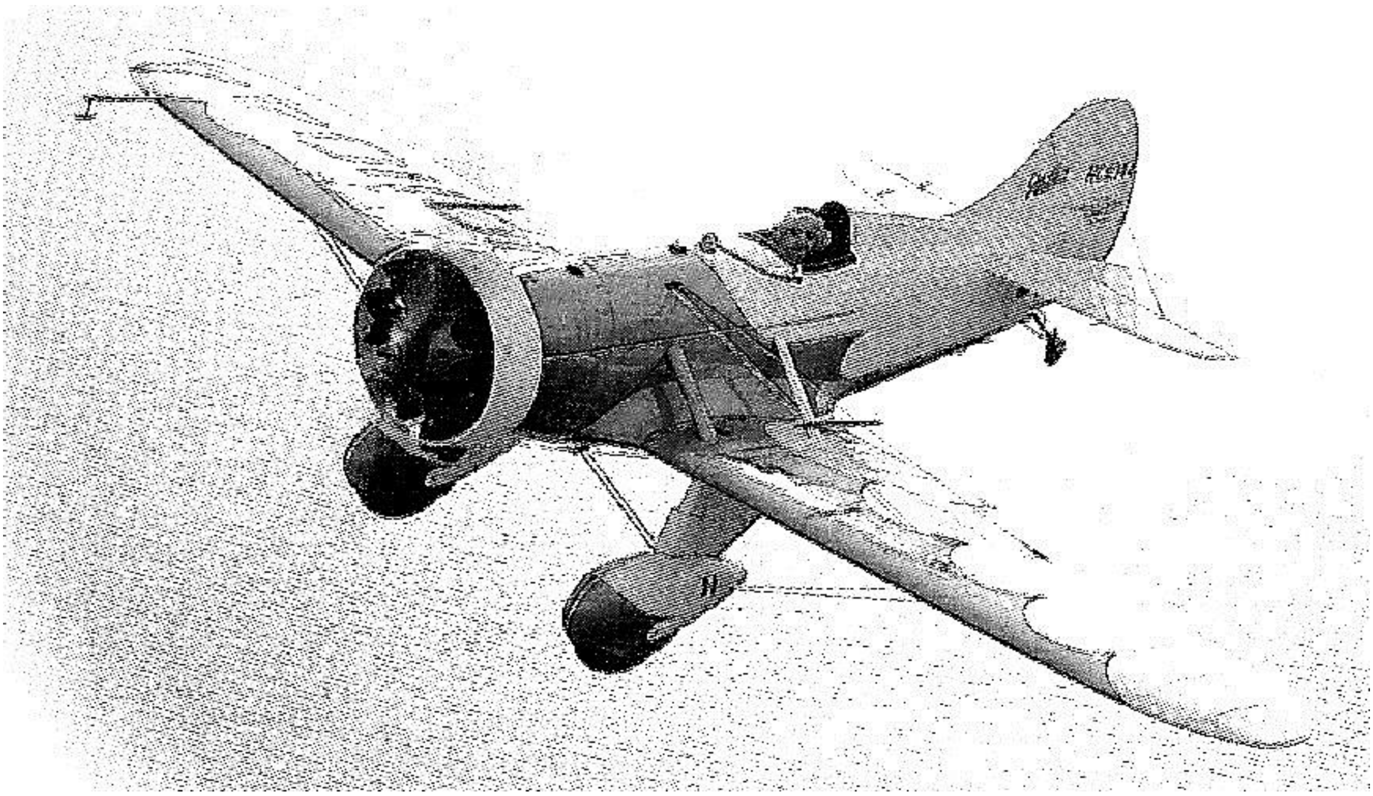
FLY BETTER

(The things you should have been taught when learning to fly.)

Book One - Fourth Edition

Aerodynamics and other Stuff



Transcripts of lectures about flying by

Noel Kruse

Founder of the Sydney Aerobatic School

Guarantee for a difficult but happy life:

1. ***Find what you want to do more than anything else in the world.***

2. ***Do it, no matter what stands in your way.***

3. ***Give the gifts of what you have learned to those others …***

…. who care enough to ask.

BOOK ONE (Fourth Edition) CONTENTS

Fourth Edition 2017

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PREFACE TO FOURTH EDITION

Since the release of Book One in August 2009 I have received a huge amount of positive feedback from aviators worldwide, ranging from low time student pilots to experienced airline captains. It seems I have been successful in filling a glaring need for aerodynamic and flight technique information which is easily understood and immediately applicable to the art of flying.

I have also been asked a number of questions by readers which have highlighted some areas where the book could be expanded. So in the second edition I improved a number of explanations within the existing lessons and added two new lessons, one on ‘Power’ and one on ‘Minimum Radius/Maximum Rate Turning’. I retained the original forward, introduction and post script.

I was also aware that a number of sailplane pilots had read the first edition of this book, so, primarily for their benefit, I added a supplement discussing the not so obvious differences between sailplanes and powered aeroplanes including details on the derivation and use of ‘Polar Diagrams’. Of course most powered aeroplane pilots can benefit from reading this supplement too.

In the third edition I tidied up some of the diagrams and added ‘figure numbers’ to them for ease of reference and added an additional Annex to the lesson on Lift which details the mathematics supporting the Momentum Theory of Lift.

I have since learned that there is still considerable confusion about ‘Minimum Radius Turning’, some of it caused by ‘authorities’ who should know better, so in this fourth edition I have expanded the lesson on ‘Minimum Radius and Maximum Rate Turning’ with the aim of removing this confusion. And I have, once again, changed the cover picture for ease of identification.

Since there has been no advertising budget, mention of this book in flying magazines and similar publications has been virtually nonexistent. Despite this I am most gratified that referrals via word of mouth, emails and the internet have ‘spread the word’ amongst those aviators who have become dissatisfied with their current training standards and want to learn about the things they should have been taught. You can help distribution of this book by simply telling all of your aviation colleagues about it.

I would also like to acknowledge the assistance I have received in the production of this book from the following people:

Phil Astley, Ron Aitken, Chris Ward, Steve Care, Andrew Sooby, and the hundreds of reader who have given me such positive and useful feedback.

Thank you all.

Noel Kruse

FORWARD

By Katrina Kruse

This is Book One of a series of books about how aeroplanes fly and how best to fly them. They are the teachings of my father, Noel Kruse, who was the creator and former Chief Flying Instructor of the Sydney Aerobatic School, a unique and widely known advanced flying school which was based in Sydney Australia for over two decades. These books are intended for people who are planning to learn to fly and for Student and Private Pilots who feel they have not been taught about the subject in a way that enables them to really understand it. It will also be useful to junior Flight Instructors who don't really know enough about the subject to teach others how to fly properly.

The style is personal because each chapter is based upon recordings of lessons and briefings given by Noel to individuals and groups comprising this target audience. Obviously some editing has been necessary to tidy the presentation, but the rhetorical style remains untouched. The annexes to each lesson come from printed material which was distributed for further reading at the end of each lesson.

The books are not just a collection of theory lessons or flying technique lectures: each lesson contains Noel's philosophy of flying, his personal experiences and opinions, including some 'pointed' comments on the current teaching methods of most flying schools.

Noel first started 'mucking around' with aeroplanes in 1960, at the age of 16, with a weekend job at the Royal Victorian Aero Club refueling and 'swinging' the propellers of their fleet of Chipmunks and Tiger Moths. A year later he gained his Private Pilot's Licence, and on his 18th birthday was accepted into the Royal Australian Air Force as a cadet pilot, graduating as a fighter pilot trainee 18 months later. Noel first flew 'supersonic' at the age of 19 and just before his 20th birthday became an operational fighter pilot with number 76 Fighter Squadron flying Sabre Jet fighters. As he gained flying experience, Noel became an 'A' category fighter pilot during a tour of duty in South East Asia (which is when I came along too). Upon returning to Australia Noel took up a position as a Fighter and Bomber Test Pilot serving under the mentorship of Sir James Rowland, one of the RAAF's finest Test Pilots. (Sir James later went on to be the Chief of the RAAF and the Governor of New South Wales and kept in touch with Noel throughout this period.)

Noel's last tour of duty as a fighter pilot was a two years 'stint' as a 'Fighter Combat Instructor' (FCI), passing on what he had learned to the next generation of fighter pilots. Then, with the phasing out of the Sabre as an operational aeroplane in 1971, Noel was 'recycled' into Tactical Transport Operations, flying the DeHavilland 'Caribou', in which he gained invaluable experience flying in mountainous terrain and operating in and out of high altitude and short airfields throughout Papua New Guinea, Irian Jaya and Sumatra. Within two years in this role Noel had qualified as a 'Check and Training Captain' on the Caribou and in 1978 he was appointed the Commanding Officer of number 38 Tactical Transport Squadron. At that time No38 Squadron was the largest operational Squadron in the Royal Australian Air Force comprising 250 men including 80 aircrew and 18 Caribou aircraft. The Squadron also maintained three concurrent overseas detachments with five of its aircraft and crews based in Pakistan, Indonesia and Papua New Guinea. This was Noel's last operational flying posting with the RAAF.

After being relegated to flying desks more than aeroplanes, as seems to happen all too soon in the air force, as promotion narrows the field of available flying jobs, Noel took up the sport of competitive aerobatic flying in his spare time and was soon coaching pilots in aerobatics and competition techniques. It was during this period that Noel became aware of need for a flight school offering a better quality of aerobatic training. After leaving the RAAF in 1983, Noel created the Sydney Aerobatic School and for the next 23 years he and his staff trained student and experienced pilots in the art of three dimensional flying. Shortly after establishing the school, Noel was certified by the Australian CAA to train and test pilots for low level aerobatic approvals down to 500ft (Noel was the first person outside of the CAA to receive this certification). This was followed a couple of years later by an approval to test all pilots to commercial pilot licence standard.

For a significant part of the period that Noel was the chief flying instructor of the Sydney Aerobatic School, his graduates dominated the winners' circles of most Australian state and national aerobatic championships, a few going on to becoming 'Unlimited' aerobatic champions. Graduates of the Sydney Aerobatic School were also prominent in selection for pilot training with the Royal Australian Air Force throughout this period, to the extent that senior RAAF instructional staff and selection psychologists visited the school on more than one occasion to ascertain what was so different and so effective about the style of training these applicants had received.

In 2006 Noel moved his home to New Zealand and now regularly fly's his own Pitts S2S out of Omaka Airfield, to "keep his hand in" and has recently completed the restoration of his 1941 Ryan STM vintage 'Warbird'.

So imagine you are attending a series of lessons by Noel Kruse about the things you should be, or should have been taught when learning to fly. Read on.........

INTRODUCTION

I have been flying for most of my life, and I continue to fly. I first underwent formal flying training in 1961 at the age of 17, and after a further 55 years I have accumulated about 18,000 flying hours, 12,000 of which have been engaged in teaching other people how to fly and not one of which has involved the use of an autopilot! I have had innumerable technical malfunctions, about a dozen forced landings and about another dozen asymmetric landings. I have survived one crash, one severely damaged aeroplane in a thunderstorm and one midair collision. Despite these adventures the only injury I have sustained is a broken finger, which occurred in Ubon, Thailand, sometime in 1967 when I used it in a failed attempt to stop the open door of our squadron crew van from swinging shut when in transit from the aircraft flight line to the bar!

Now you will note I did not say that I learned to fly in 1961; that was just the beginning. It wasn't until about six years later when I had gained some experience as a fighter pilot that I could truly say I could fly, even with a broken finger! Even so, I have never actually stopped learning. You can't; that's the nature of the 'beast'.

Along the way I have had some very good flying instructors and some that were not so good, including the one who demonstrated to me how to crash an aeroplane! But it was a particular aeroplane that allowed me to develop my own flying style and 'feel' for flying. It was a very high performance (for its day) single seat jet fighter called the CA-27 Avon Sabre, a more potent Australian development of the North American F-86F Sabre. This aeroplane 'fitted me like a glove' and ultimately became an extension of my central nervous system. I didn't fly it and it didn't fly me, I just flew. I just flew in the same way that I just walk, with no conscious thought except my goal. Being a single seater there was never another 'instructor' pilot trying to impose his ideas and techniques on me, so I was free to develop my own. Ultimately it became my turn to pass on what I had learned to others and I became a Fighter Combat Instructor. The two years that I spent in this role, helping others to fly at the edge of the 'flight envelope', are amongst the most satisfying of my life. I count myself extremely fortunate to have had the opportunity to become 'one' with such a beautiful aircraft and even though I have been able to translate what I learned to other aeroplanes since, the Sabre will always be my enduring love.

When I look back on those days I cannot recall, in the many discussions we fighter pilots had in the squadron crew rooms, of ever talking about how to fly the jet. We did talk a lot about air combat tactics and weapons delivery techniques, but not about how to fly. You see all of my squadron buddies, like me, had become 'one' with the aeroplane and the air, and no more needed to talk about how to fly it than footballers need to talk about how to run. The ability to fly was a 'given'. The talk was about how to achieve the goal.

Many years later, in 1994, I was coaching and critiquing my daughter Katrina for her first attempt on the advanced aerobatic title at the forthcoming Australian National Aerobatic Championships. She was having trouble keeping her outside loops straight as she bunted over the top of the manoeuvre. Since she was flying my school's Pitts S2S, which is also a single seater, any assistance I could give her had to be from the ground via a radio. "Use more rudder", "back off the power", "don't roll passing the vertical" and other suggestions flowed over the 'airwaves'. Eventually she said, "Look, stop talking at me and let me work on it myself". Dutifully I shut up and watched a few more off-line loops, then suddenly a straight one! Then another and another. Finally I couldn't restrain myself anymore: "They are great" I exclaimed, "What did you do?" "Oh I just figured out where to look" was her matter-of-fact reply.

Idiot! I chided myself. I was busy trying to tell her how to fly when all she needed was a way of aiming the aeroplane. Her ability to manipulate the controls was already internalized; she just needed to see the goal. A week later she took first place in every flight program and won the contest.

Since my fighter pilot days I have been able to sow the seed of real flying into many other people and helped them to 'become one' with their craft. This has also been very satisfying. In an increasingly computerized and automated world I feel I have, in a small way, kept the art of flying alive, at least in my corner of the sky.

Every year there are thousands of pilots churned out by 'Flying' Schools who view flying as nothing more than being aerial systems operators. Their heads are filled with confused theories involving vectors and pressures and other stuff which cause what I term 'analysis paralysis', which in turn gets in the way of enjoying and learning the art of flying. The term 'pilot' is applicable to them as they are merely technicians; whereas 'aviator' is the term I use to describe 'aerial artists'. I have created aviators.

Human beings are the most adaptable creatures on this planet; we, as a species, have developed the capability to do the most remarkable things with our bodies. An infant child doesn't take its first faltering steps in its attempt to walk upright until it is about twelve months old. A feat regarded by many as not very remarkable compared with many other animals which can walk within a few hours of being born. But six years later can these other animals skate board up a wall, perform gymnastics, ice skate or swim and surf or ride an 'off road' BMX bike or ride one of these other animals? Humans can, and much much more, and they do it without any theoretical knowledge. They learn to do it by simply doing it, and along the way they develop the appropriate motor skills to get better and better at it. Learning to fly is no different; it is a motor skill which is learned by doing. Nothing can replace the 'doing' of flying because nothing can replace the feel of an aeroplane in your hands and the tactile sensations, the 'G', the noise, even the smell and especially the sight of flight. And **nothing** can replace the emotional thrill of flight. Doing it is the only way to forge the new neural links and pathways in the brain as learning to fly 'takes root'.

I have taken teenagers flying who have never been in an aeroplane before and, within 15 minutes, had them looping and rolling the aeroplane themselves, whilst I recorded them doing it with their own video camera. Yet this amazing adaptability seems to be 'beaten' out of them when they take 'formal' flying lessons at a 'standard' flying school; it is replaced by a confused 'hotch potch' of do's and don'ts based upon some obscure theories and their flying instructor's own inhibitions, and it is replaced by a plethora of rules and procedures, most of which are about 'air transport' and not about 'flying'.

I was once told that the best way to destroy a golfer's 'T' shot is to ask him how he holds his golf club. The resulting 'analysis paralysis' puts him 'off' for the rest of the game. Modern flying schools are very good at putting student aviators 'off' their 'game' with analysis paralysis.

Many young people who have caught the 'flying bug' do not have much schooling in physics or mathematics, so to bamboozle them with confusing descriptions of obscure theories does not lead to understanding. Unfortunately many junior flying instructors use their incomplete knowledge of these theories to establish a sort of psychological superiority over their students, and many testing officers do the same. So not only has the poor student to learn and develop new motor skills, but has to do it without really understanding why the aeroplane flies the way it does. Their flying instructors learned the same way, and theirs, and theirs..........

Sure, it is helpful, in the early stages of learning to fly, to understand why what you do with the controls causes the aeroplane to respond the way it does, and the very best way for this information to be imparted to a new student of flight is direct description, demonstration and hands on experience under the guidance of a suitably experienced and qualified flight instructor. A much less satisfactory but often more flexible way to impart the description portion of this 'information transfer' process is through a properly written book, which explains the principles of flight in a clear and understandable way. Hopefully this is such a book. It is written in the hope that it will be read by the latent aviators out there who feel that there is something missing from their pilot training thus far, or who are suffering 'analysis paralysis' as a result of the confused way they have been taught, and also by aspiring aviators to start them on the right path. This is not a book about engines or systems or procedures; there are a number of very good books available on these subjects. This book is a collection of my lessons about how and why an aeroplane flies the way it does and key techniques that you should be, or should have been, taught about how to fly it. It contains what could be viewed by many 'mainstream' flying schools as some radical ideas.

The basic principles of flight are very simple, but they have become obscured by a fog of confused detail and erroneous ideas. I hope to clear away some of that fog and correct those ideas with this book. The descriptions and theoretical details of how aeroplanes fly contained herein are based upon extensive reading about the adventure of the development of the aeroplane, the thousands of briefings and lectures on the subject that I have given to students over the years and, of course, my own personal flying and instructing experience. I have included references to historical situations, where applicable, as I believe we have much to learn from the pioneers of flight, both those who were successful and those that weren't! I believe that understanding how modern aeroplanes and the techniques used to fly them have evolved can give an aviator a more thorough understanding of why they work the way they do without over-analyzing the subject.

In the early 1970's I became interested in the newly emerging sport of 'hang gliding'. In those days the Rogallo hang gliders, or delta kites, were the only types around. Francis Rogallo was an aerodynamicist who created this design, loosely based upon a yacht sail but inherently stable. Being a well-trained military aviator I was not going to just leap aboard one without understanding what 'made it tick', so I studied the aerodynamic principles involved and plotted many sail shapes and aerofoil sections myself. I made large flying models (one meter span) which I flew from the top floor balcony of the block of units I was living in at the time, (the neighbors must have thought I was nuts!). Finally I considered I had enough data to construct a man (me) carrying glider, but before I did I decided to talk to some of the small, but growing, band of hang glider pilots who would fly off the sand dunes at Cronulla, a southern coastal suburb of Sydney. The day I went to Cronulla there were two or three gliders ridge-soaring along the dunes at about 50ft altitude and a dozen or more nose diving into the sand at every attempted take off. The soarers obviously knew what they were doing so it was these pilots I decided to talk to. When the opportunity came I asked many questions about structure and rigging and got some useful tips, but when I asked about the aerodynamics it was a different story. I recall one question which I really needed an answer to was "to what degree is the longitudinal stability affected by the change of conical washout at the tips when the tension of the fabric is altered?"

I still remember the look I got in return. I might as well have spoken in Swahili for all he understood of my question. The more questions I asked the more the realization came to me that these guys and girls were aerial surfers; they had no more understanding of the aerodynamics of their gliders than the average surfer does about the hydrodynamics of a surf board! Yet they flew them beautifully!

I left Cronulla feeling quite confused but determined to find out how this apparent contradiction could possibly be. I built my hang glider and I flew it, then I knew. In this simple craft there is virtually no technology to get between the aviator and the air. The feel of the airflow and the feel of the movement were obvious and, with a little practice, the control of the craft was easy; and it was exhilarating. I was left with the feeling that learning to fly any aircraft should be this simple, at least to begin with, before the technological considerations of operating the machine crowd in. A few years later this was the challenge I confronted when I started my own flying school.

In 1984, having retired from the air force, I started the Sydney Aerobatic School with the intention of teaching aerobatics to licensed pilots. I found that the pilots coming to me for training were deficient in their understanding of the basic principles of flight and had been taught some poor flying techniques, so before starting aerobatic training it was necessary to teach them all of the things they should have been taught in a way they could understand them. This became a preliminary course for those who needed it. I called the course the "things you should have been taught course", hence the sub-title of this book. I soon found that they all needed this course first so I integrated it into the basic aerobatics course and renamed it the "basic aerobatics and advanced flight techniques course". I used the phrase 'advanced flight techniques' to differentiate these techniques from those taught by others, but in fact they were the basics that all aspiring aviators should be taught.

A few years later when I took on my first 'ab initio' flying student I taught him in accordance with the 'standard' training syllabus, even though I felt I was 'short changing' him. But since he was to be tested by a 'standard' testing officer I didn't want to make life difficult for him by teaching him too many of my 'radical ideas and techniques'. Ultimately he graduated and immediately signed on to learn aerobatics with me. As we progressed through the aerobatics course he kept asking me "why didn't you teach me this before?" Of course I had no good answer to that question but I vowed to never again 'short change' a flying student. I integrated the advanced aircraft control and aerobatics course with the standard private pilot syllabus and dropped my next student into the 'deep end' to see how she handled it. Handle it she did, better than the private pilots from other schools that I had been teaching as she did not have any previous flying instructor's limitations and inhibitions stamped upon her. Thirty five years later we are still good friends, and I have now been responsible for teaching a thousand or more students just like her how to really fly and be comfortable in the sky.

The course I designed starts at lesson one, effects of controls, as usual, but includes teaching the student to loop and roll the aeroplane, which is a great way to understand pitching and rolling. The manoeuvres are simple and fun to fly, and give the student great confidence in his/her handling of the aeroplane, so much so that by the time the student is flying the first solo sortie in the training area loops and rolls are on the practice schedule. Toward the end of the course, after having covered more basic aerobatic manoeuvres and spinning, I had a lesson called ‘mishandling consolidation’ wherein I set up every conceivable ‘out of control’ situation that I could think of and have the student recover. The usual reaction from the student, having returned the aeroplane to controlled flight was, “ho hum is that the worst you can do?”

I am very proud of my flying students.

Along the way I was approached by many reasonably experienced pilots who were having difficulty with things like navigation or instrument flying and in a number of cases, instructing! I quickly confirmed that the root cause of their problem was apprehension. They were simply flying afraid! Afraid of what might happen in turbulence or if the bank angle got too great in and out of cloud, or if their student did something unexpected in flight and put them in a situation they had never been in before. In each case their confidence level improved significantly after completing my course and their problems in these seemingly unrelated areas simply went away.

These are just a few examples of situations which underline my basic teaching philosophy, which is that anything that you do in an aeroplane will be done better if you are comfortable in the air in all three dimensions, and the best way to get comfortable in the air is to make the sky your playground and go play in it, often.

Unfortunately I can’t fly with all of you to show you my playground, or show you how to find your own, but I do hope that you will be able to glean something to assist you in finding it for yourself from reading my books.

So, let’s get into it....what follows are the things you should be taught when learning to “fly better”.

UNITS and JARGON

Along with the development of the aeroplane aviators have produced a plentiful and colourful jargon. The average general aviation aeroplane contains a pot pouri of units of measurement, some of which the new student aviator may find quite bewildering and probably has never heard of before. Since I will be using some of these units in the following lessons I should explain or define a few of them, so here goes…..

Altitude is expressed in 'Feet' unless you are flying an old soviet 'War bird'; then it is expressed in 'Meters'. The sea level pressure datum from which altitude is measured is expressed in 'Hectopascals' in European and Australasian aeroplanes (it used to be in 'Millibars', a Millibar being 1000th of a 'Bar' and a 'Bar' is the pressure of one atmosphere). In American aeroplanes atmospheric pressure is expressed in 'Inches of Mercury' when set on the altimeter and is also expressed in pounds per square inch in the old imperial system (lb/inch^2 or 'psi') for other purposes.

Whilst 'Altitude' is the way of expressing how high an aeroplane is as measured using sea level as the datum, the height of an airfield above sea level is called its 'Elevation' whilst the height of structures in the vicinity is expressed as their 'Height' above the surrounding terrain.

Airspeed is expressed in 'Knots' (a 'Knot' is a nautical mile per hour) in European and Australasian aeroplanes and in 'Miles per Hour' (MPH) (which is statute miles per hour) in American aeroplanes, whilst the old soviet War bird expresses it in 'Kilometers per Hour' (KPH). However, an aircraft's airspeed is either 'True' airspeed, which is how fast it is really going through the air, 'Indicated' airspeed, which is how fast it 'thinks' its going through the air (depending upon the air density), or Ground speed, which is its true airspeed adjusted for the effect of wind, which helps you figure out when you are going to get to where you are going, and in which direction to point your aeroplane to get there.

Manifold Air Pressure (MAP), which is an expression of engine power setting, is expressed in American-made aeroplanes in "Inches of Mercury Absolute" whilst English aeroplanes with superchargers call it 'Boost' and express it in "Inches of Mercury Relative", that is inches plus or minus standard atmospheric pressure (which they express in Hectopascals!!).

Confused yet? Well don't worry, you are not alone. But it doesn't end there.

Fuel Capacity can be in either 'Liters' or 'Imperial Gallons' or 'US Gallons' or 'Pounds', whilst Oil Pressure is in 'Pounds per Square Inch' (psi) or 'Kilopascal's and Gyro Suction is in 'Bars'!

Aircraft weight and load are expressed in ‘pounds’ or ‘Kilograms’, often interchangeably, so be very careful of this one.

Temperature of course can be expressed in degrees ‘Fahrenheit’ or degrees ‘Celsius’ (formerly ‘Centigrade’).

‘Air Density’ is the mass of air in a particular volume. Now the ‘Mass’ of anything is measured by a unit with a strange name, a ‘Slug’! A Slug is the weight of the thing being measured divided by the acceleration due to gravity. (Since ‘weight’ involves gravity.) So density is the number of ‘Slugs’ in a particular volume. Air density at sea level is its weight (.0765 lb/ft^3) divided by the ‘gravitational constant’ (32.2 ft/sec/sec) which equals .002376 Slugs per Cubic Foot (Slug/ft^3).

When navigating, an aircraft’s position can be expressed by ‘Cartesian co-ordinates’ such as ‘Latitude and Longitude’ or by ‘Polar co-ordinates’ as bearing and distance from a known point, whilst the direction it is going is either its ‘Heading’ or its ‘Track’ (Heading corrected for wind drift) and is measured in ‘Degrees Magnetic’ (which allows for the difference in the position of the north magnetic pole and the true north pole) or ‘Degrees True’ which makes no such allowance. Oh, and the Americans call ‘Heading’, ‘Course’.

There are many more, but they are the main ones. Let’s now turn to the Jargon.

Aviation Jargon will be forever indebted to the Royal Air Force which, prior to World War Two, created a thing called the ‘Operational Brevity Code’ which was peppered with wonderful words like ‘Bogies’ and ‘Bandits’ and ‘Tally-Ho’. This code was supposed to simplify radio transmissions and confuse the enemy (often the reverse was the case). When I started operational flying in the Royal Australian Air Force in 1964 (19 years after the end of the war) much of this code was still in use and it was quite common to hear a young fighter leader, having broken cloud after a QGH (VHF-DF letdown) call to his wingman, “Tally Ho home plate, QSY Tower for pancake”. A translation of which meant “I can see the airfield so let’s change radio frequency now to the control tower for landing.” This of course was after ‘Base Oranges’ was determined!! (The terminal weather).

Some of this wonderful ‘aviator-speak’ even survives in general aviation to this day. When we set the altimeter datum pressure we say (in Europe and Australasia) that we set the QNH or the QFE. These letters are the remains of the ‘Q’ code which was originally developed to be sent via aerial telegraph but was later verbalized as part of the operational brevity code. I have heard many young instructors try to give words to these code letters but the fact is they were a code designed to confuse the enemy, and they are still confusing these instructors today. In the USA, these particular code letters have been replaced by the simple and self-explanatory phrase, “Altimeter Setting”.

The code word which has survived completely intact and will probably continue to survive (because nobody can think of a better word for it) is “Squawk”. ‘Squawk’ is what you do when you activate the aircraft’s radar transponder. The radar transponder was invented in England shortly after the invention of radar itself, as a result of a couple of lethal ‘friendly fire’ incidents during the early days of WW2. It was a means by which the radar operator could differentiate between the good guys and the bad guys and it was called **IFF**, which stood for ‘**I**dentification **F**riend or **F**oe’, but was code named a ‘Parrot’! So, what do parrots do? They “Squawk”.

I grew up with feet and inches and even though I have made the conversion to the metric system on the ground, I still think in the old system when flying, so many of the units I use in these lessons may be a throwback to the imperial system so here is a conversion table to assist you in getting your ‘head around’ the relationship of the more common units.

CONVERSION TABLE

Units	**Multiply by**
Pounds to Kilograms	0.4536
Kilograms to Pounds	2.2046
MPH to Knots	0.8684
Knots to MPH	1.1515
Kilometers per Hour to Knots	.540
Knots to Kilometers per Hour	1.852
Feet to Meters	.3048
Meters to Feet	3.2808
Imperial Gallons to Liters	4.546
Liters to Imperial Gallons	0.220
US Gallons to Liters	3.785
Liters to US Gallons	0.264
Inches of Mercury to Hectopascals	33.84
Hectopascals to Inches of Mercury	0.0295

Lesson One

THE AIR IN WHICH WE FLY

I am always intrigued when I hear of complaints by members of the general public about low flying aircraft. Sure, in some cases they are justified when some aberrant pilot does something really stupid in an aeroplane, but the majority of complaints are usually about a light aeroplane seen flying at 500 feet many hundreds of yards from the complainants' house. The pilot was probably just practicing some training exercise or going about his or her normal business.

The same complainant will happily drive down a road at 100 kilometers per hour, passing traffic doing a similar speed in the other direction with only one or two meters gap between them and separated by nothing more than a white line painted on the road, without a moment's thought of the hazards of such an activity. Often the opposing traffic is a 30 wheeled 'B double' Mac truck, but this still causes no concern to the complainant who may be preoccupied talking on a cell phone and driving with only one hand at the time!

Why this double standard? If the aeroplane fell out of the sky at the point of closest passage to the complainants' house it probably wouldn't hit the house, and even if it did would probably not injure the occupants of the house: whereas, if the Mac truck driver only sneezed and momentarily veered across the line many motorists could be smeared over the road like strawberry jam! Cars, trucks and aeroplanes have been around for about the same period of time (Henry Ford introduced the 'T' Model five years after the Wright brothers' first flights). Our attitude to cars and trucks has become complacent with familiarity, but the average citizen still fears aeroplanes because he or she does not understand them or how they are controlled. In the entire history of aircraft accidents, the total number of people killed is a miniscule percentage of the total number of people killed in automobile crashes worldwide in only the last few years! Yet complaints to aviation authorities about the proximity of aeroplanes continue to be made.

We are regularly treated to a 'late breaking' news story on television of a light plane crash and how the hapless pilot will be subject to investigation possibly resulting in his or her perpetual 'grounding'. Meanwhile, a number of people die on the roads during the time of the telecast and we never hear about them. The news media love aeroplane crashes as they enable them to play on the fears of the general public and sell more newspapers or TV time. They certainly do not help raise awareness of just how safe a modern aeroplane, properly flown, is.

Most people's fears come from a singular lack of understanding of what keeps an aeroplane 'up there', yet they will watch the latest television newscast of the damage and devastation caused by hurricane 'Fred' or typhoon 'Mabel' with scenes of garage roofs flying through the air and trees being flattened because the wind speed was a terrific 120kph; they will shrug and say "of course, not much can withstand such wind forces", without realizing that that is only the lift off speed of the average light aeroplane. At wind speeds of 120kph it is not a question of what keeps it up there, but of what keeps it down! At 120kph most things that are not 'bolted' down - and many things that are - have a tendency to fly, the fundamental difference between garage roofs and light aeroplanes being that the aeroplanes are controllable in flight whilst garage roofs aren't!

I have often had people say to me "but the air is so thin, I cannot perceive how it is capable of holding such a heavy thing up there, especially something the size of a jumbo jet." But the air is not thin, it is in fact quite thick but we don't notice it because we have evolved to live in it. At the bottom of the deepest oceans of the Earth live fish that are subject to pressures equal to many hundreds of atmospheres, yet they swim around quite happily going about their business without noticing it because they have evolved to live in that environment. Bring them to the surface and they blow up like a balloon and explode! We live at the bottom of an ocean of air only about 100 kilometers (60 miles) deep and are subjected to a pressure of about 15 pounds on every square inch of our body! That is a total pressure on the average size body of 60,000 pounds or 30 Tons! If we were brought to the surface of our ocean we would blow up and explode too! The people who do venture to the surface of our atmosphere and beyond have to be enclosed in special garments called 'Pressure Suits', to stop them exploding. I am of course talking about Astronauts and Cosmonauts and high altitude aviators.

This ocean of air in which we live is not very deep; 100km when compared to the diameter of the Earth is miniscule. To give you an idea of this relationship, imagine that the Earth is about the size of a soccer ball. Now give the ball a coating of leather-preserving wax and rub it well in. The thickness of this wax coating is proportionally the same as the thickness of the Earth's atmosphere! We are all aware of mankind's journeys into space over the past few decades and perceive space to be a great distance away, but it is not, it is only about one hours drive away - if your car could drive straight up!

Despite the fact that this air mass is not very deep, it is very dense, and when it starts to move it can exert tremendous pressure on anything in its way (like a garage roof) or when anything moves through it, it again exerts tremendous pressure on that thing (like an aeroplane). Whether the air moves, which we call 'Wind' or whether an aeroplane moves through it, which we call 'Flying', the pressures are the same. It is the relative motion of one to the other which creates this pressure.

Air is compressible, that is, it can be squeezed into a confined space, and as a result of this squeezing the pressure it exerts on whatever is confining it and whatever is in that confined space with it, increases. If we were to squeeze a given volume of air, say all the air in the room you are sitting in right now, into a room with only half its volume, its temperature would double, the pressure it would exert on the walls and on you would double and its density would double. (Air density is defined as the number of air molecules within a given volume. Therefore if you squeeze the same number of molecules into half the volume the air ‘density’ doubles.)

Now all the molecules of air surrounding the earth have weight and are stacked up one on top of the other so they push down on the ones beneath them which push down on the ones beneath them and so on. By the time we get to the bottom of the atmosphere we find that the bottom layers of molecules have been squeezed significantly so the density and the temperature and the pressure of the air have increased considerably. This is, as I have said, where we live.

As we climb higher and higher the density, temperature and pressure of the air get less and less, so the force it can exert gets less and less. A garage roof in a 120kph wind at the top of Mount Everest would experience much less force than it would in the same wind speed at the bottom of the mountain and an aeroplane moving through the air at this altitude experiences less and less force too. Indeed, an aeroplane flying only a little higher than Mount Everest (about 10 kilometers high) can go twice as fast as it could down at sea level without experiencing any greater pressure. This effect has interesting implications when it comes to measuring how fast an aeroplane is really flying through the air compared with how fast it ‘thinks’ it is flying. We will discuss this in some more detail in Annex B to this lecture. Also, I have outlined the properties of the ‘standard’ atmosphere in more detail in Annex A.

Flying is both the science of harnessing these varying air forces and the art of controlling them. Both the science and the art of flying are things which mankind has mastered extremely well over the last 100 years, thereby allowing us virtually unlimited three dimensional freedom of movement within our ocean of air with safety.

List of Annexes to the lesson on: The Air in which we Fly

Annex A. The Standard Atmosphere

Annex B. Measuring Air Speed

Annex A

The Standard Atmosphere

Each evening, whilst sitting in front of the television, we see at the end of the news bulletin the latest weather forecast with its schematic 'synoptic charts' showing high and low pressure systems as they drift across the continent. These 'Highs' and 'Lows' and the lines surrounding them (called isobars) represent the changing sea level atmospheric pressures that can be expected at the various locations on the chart because, due to naturally occurring turbulence within the atmosphere; there are continual changes in pressure (and temperature) every day. Way back in the 1930's the National Advisory Committee for Aeronautics (USA) defined a 'Standard Atmosphere' based upon an average of all of these fluctuations over time. They called it the 'International Standard Atmosphere' (ISA) and this standard has been adopted worldwide. The 'ISA' gave them, and those who venture into the atmosphere, a datum to work from when figuring out the effects that all of these changes have on their activities.

The performance of aeroplanes and their engines is very dependent upon the density of the air in which they operate. The density of the air is the number of air 'molecules' contained in a particular volume, but since there are a 'gazillion' molecules in the atmosphere their numbers are too huge to use in any calculations of density, so each group of a 'squillion' (or so) molecules is called a 'Slug'. 'Slugs' reduce the numbers involved to a more manageable size so we now express air density as so many 'Slugs' per unit volume. Because air density depends upon its pressure and its temperature, the aviator should have an understanding of the 'ISA' so that he or she can understand how deviations from this standard affect their aeroplane's performance.

The International Standard Atmosphere starts at sea level with a temperature of 15ºC (Celsius) and a pressure of 1013.2Hp (Hectopascals) or 29.94 Inches of Mercury in the USA. A cubic foot of air under these conditions weighs 0.0765 lb and has a Density of .002376 'Slugs' per cubic foot. The amount of water vapor in the atmosphere causes a slight variation to this weight, 'damp' air being a little lighter than 'dry' air, but we are going to ignore this difference as it has no significant effect on aircraft performance.

As we climb up into the 'standard' atmosphere we will find that for each 30ft of altitude gained the pressure drops 1Hp initially and for every 1,000ft of altitude gain the temperature drops 2ºC. This temperature drop per 1,000ft is quite uniform up until about 35,000ft but the altitude-per-1Hp drop expands a little as we get higher so that at 35,000ft a 1Hp drop equals 50ft altitude gain. What this all means is that at 35,000ft it is damn cold, minus 55ºC to be exact and the pressure is down to about one quarter of the sea level pressure.

Long before we get to 35,000ft the temperature and pressure have dropped to a point where a human body can no longer survive without assistance. The upper limit for unaided human survival is only 10,000ft; which is about a two minute drive straight up. But don't make the drive at night because your night vision begins to deteriorate after only 45 seconds due to oxygen deprivation.

We live in a very thin blue line of air at the bottom of 'our ocean'.

An aviator can operate for a short time at 40,000ft, breathing 100% oxygen and wearing very warm clothes. Beyond this altitude the aviator must also wear some sort of pressure garment or be enclosed in a pressurized cockpit. For the human body 40,000ft (an 8 minute drive straight up) is the beginning of 'Space'. Think about that the next time you are gazing out the window of a Jet airliner cruising at 38,000ft with a cabin pressure equivalent to an altitude of only 7000ft. (Because the cabin has been pumped full of compressed air.) Don't lean on that window too hard!

The predicted performance of aeroplanes is based upon the standard air density change within the ISA. If the atmospheric conditions on any particular day deviate from the ISA, the aeroplane's performance will deviate from that expected. The performance charts contained within the 'Flight Manuals' of each aeroplane allow the aviator to calculate the aircrafts 'standard' performance and the degree of performance deviation if the actual pressure and temperature are known.

Also, back in the 1930's the NACA created another concept that an aviator could use when making these performance calculations to assist him or her get a better 'feel' for the expected deviation in performance when ISA conditions did not exist. Let me explain this concept.

Imagine that you are holidaying at a beach house (at sea level, obviously) for a few days. Nearby is a large hill climbing 3000ft above the beach. On this particular day you decide to climb the hill but before you do you note the temperature and pressure at the beach using a convenient, portable, thermometer and barometer. You note that it is 15ºC and 1013.2Hp, "exactly ISA", you muse to yourself. Later upon reaching the summit of the hill you note that the temperature has dropped to 9º and the pressure is 913.2Hp, "exactly what the ISA scale says it should be", you muse some more. "Obviously the density of the air up here is less than down at the beach" you go on, "so my aeroplane would not perform as well up here as it would down at the beach. The power output of the engine would be less and if there was a runway up here my aeroplane would use more of it to take-off and its ability to climb after take-off would be degraded".

The next morning, having climbed back down the hill, you note that overnight that approaching ‘Low’ that you saw on the television has caused the temperature to drop to 9º and the ‘barometric’ pressure to drop to 913.2Hp. “What a coincidence” you declare, “that’s the same temperature and pressure that I experienced yesterday on top of the hill. This means that the air density down here now is the same as it was on top of the hill yesterday, and because of this reduction in air density my aeroplane’s performance down here now will be degraded the same as if it were on top of the hill in an ISA”. So due to the drop in density it would be as if it were operating at 3000ft ISA.

This is the concept that helps aviators assess their aircraft’s performance when the atmospheric conditions where they are, differ from sea level ISA. It is called ‘Density Altitude’, and the formal definition is: “Density Altitude is the air density that exists at a given place expressed as an altitude equivalent on the ISA scale.”

So if on a particular day you are taking off from an airfield at sea level but the ‘Density Altitude’ of the field is 3000ft, your aeroplane is only going to perform as if it were taking off from an airfield 3000ft above sea level ISA. This concept also applies if the actual elevation of the field is above sea level but the temperature and pressure there are not what they would be at that altitude on the ISA scale. So an airfield at an actual 1500ft elevation could have a density altitude of 3000ft if the current temperature and pressure at the field were the same as 3000ft on the ISA scale, and once again the aeroplane would perform as if it was at 3000ft ISA.

The concept of Density Altitude is a very handy concept and one that you, the budding aviator, should get a good ‘feel’ for.

Annex B

Measuring Air Speed

One of the most vital pieces of information an aviator can have about his aircrafts performance is its speed through the air. An aeroplane's performance, range, endurance and handling depend upon how fast it is going. However the measurement of this speed and the way it is presented to the aviator is not as simple as you are used to in a motor car.

A car speedometer is related to the number of revolutions the wheels make in a given time when in contact with the road, whereas an aeroplane's airspeed is determined by the air pressure it encounters as it moves through the air, which we call 'dynamic air pressure'. Herein is a problem, because this dynamic air pressure is dependent upon the density of the air, which is determined by the atmospheric pressure (static air pressure) and temperature. As we climb the aeroplane higher and higher the air density reduces and the cockpit 'Air Speed Indicator' (ASI) starts to 'under-read' the 'True Air Speed' (TAS). By the time we reach 35,000 ft the 'Indicated Air Speed' (IAS) is about half the TAS!

An extreme example of this is illustrated by the NASA Space Shuttle, which leaves Earth as a rocket but returns as an aeroplane. On approach to land the Space Shuttle pilot uses the ASI in the same way as the pilot of any other aeroplane, but when in orbit at 15,000kts the ASI is 'reading' zero! (Because there is no air in space, and no one can hear you scream.)

At the altitudes that a student pilot operates when learning to fly this IAS/TAS difference is not so great. A light aeroplane flying at 3-4,000ft at 110kt IAS will have a TAS of about 120kts. I say "about" because the actual difference will depend upon the 'Density Altitude' at the time.

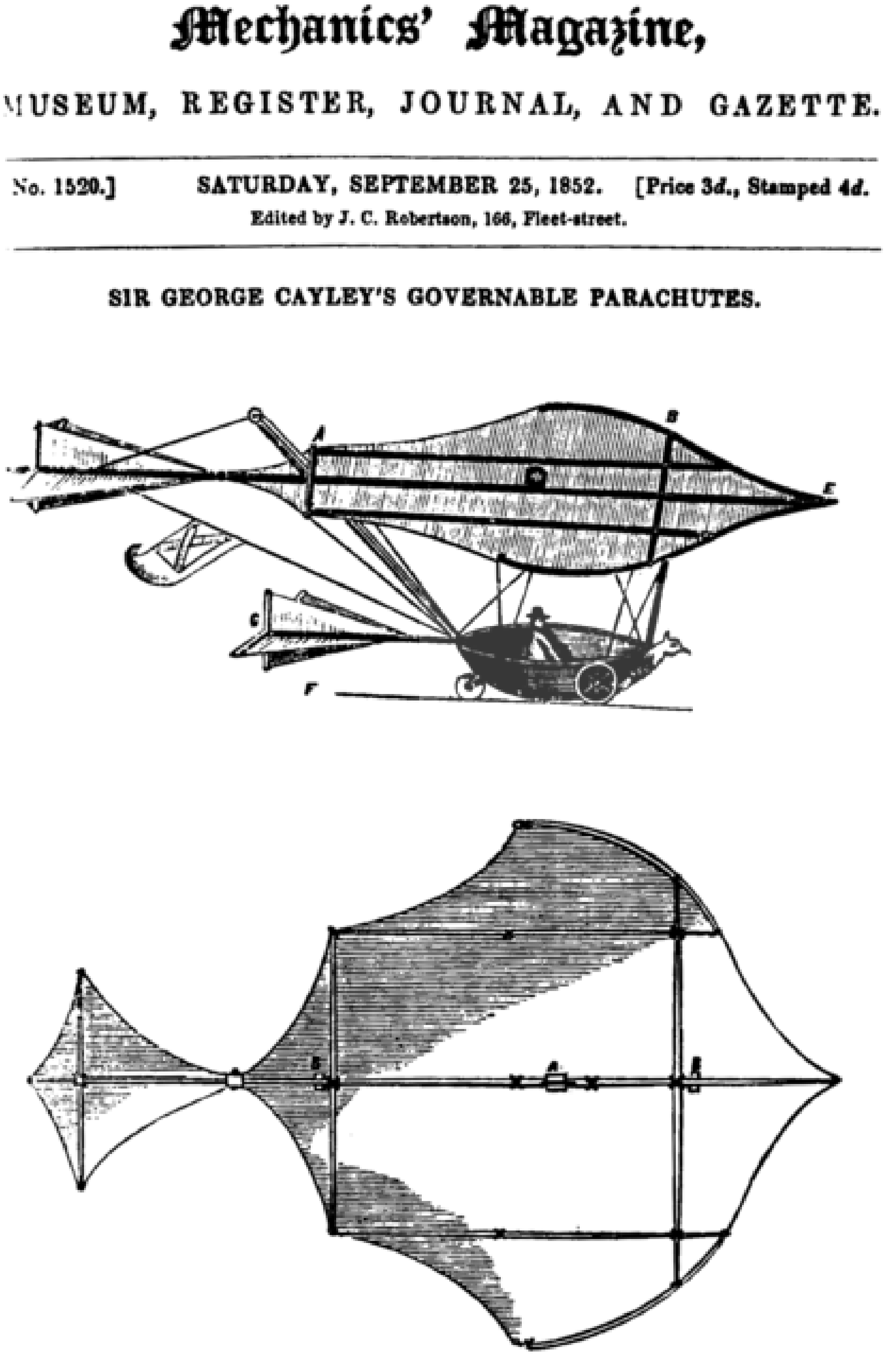
Knowing the aeroplane's TAS is important when calculating its 'Ground Speed' (GS) when navigating from one place to another and when calculating its range. There are simple procedures for making these calculations which you will learn when learning to navigate. The 'good news' is that the speed you see on the airspeed indicator is the one you need when flying the aeroplane. How so?

The aeroplane's lift, drag and thrust depend upon the density of the air in which it is flying too, so the IAS gives the aviator the correct information about the handling of his aircraft. If you are flying at 120Kts IAS then the aeroplane will handle like it should at 120Kts IAS, even if you are at 35,000ft doing an actual 240Kts TAS! In the forthcoming lessons about how aeroplanes fly, when I mention airspeed, I will be referring to IAS. If I use True Airspeed at any point I will use the abbreviation 'TAS'.

Lesson Two

LIFT

Why start with Lift? Because, as I said in Lesson One, most people when confronted with an aeroplane in flight first ask "what keeps it up there?" So I guess answering that question makes this a good place to start. So what does 'keep it up there'? Let's go back to the beginning of it all.



Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1520.] SATURDAY, SEPTEMBER 25, 1852. [Price 3*d.*, Stamped 4*d.*

Edited by J. C. Robertson, 166, Fleet-street.

SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Developed design for a man-carrying glider, called a "governable parachute"; facsimile of the illustrations as they appeared in the *Mechanics' Magazine*: 1852.

In 1852 an English gentleman named Sir George Cayley invented a glider which he called a “Governable Parachute” and which his coachman flew (under duress) a short distance across a valley. As a result George declared “the problem of flight is solved”. He then spent considerable time during the rest of his life trying to invent an engine to power his ‘air-craft’. The internal combustion engine had yet to be invented - by someone else - and unfortunately George’s efforts came to nothing. From that time forward the understanding of the solution to the ‘problem of flight’ has become more complex.

By the time World War One had ended the aeroplane had proven itself a formidable weapon demanding further development. Also, visionaries predicted air transport possibilities beyond imagination. Proper scientific and engineering methods were introduced into its development. Fluid dynamics experts explored the miniscule airflow patterns around a huge array of aerofoil and aerodynamic shapes. They employed various esoteric fluid flow theories such as, ‘Bernoulli’s Principle’, ‘Reynolds Number’, and ‘Prandtl Circulation Theory’. They used bigger and better wind tunnels to test and experiment with their designs. The result was a range of data which was extremely useful to aircraft designers and engineers, but which confused the hell out of the average aviator and obscured the fundamental simplicity of “what keeps it up there”.

Today that confusion continues. The average student pilot, who may have little or no education in basic physics (mechanics), or if he has, has forgotten most of it, is confronted with:

1. Bernoulli’s theorem.
2. Laminar flow.
3. Turbulent flow.
4. Moving centers of pressure.
5. Pressure gradients.
6. Boundary layers.
7. Separation points
8. Tip vortexes.
9. Stall flow patterns.

Some of these are aerodynamicists’ tools and most are unnecessary for a basic understanding of “what keeps it up there”.

So, what does “keep it up there”?

In 1687 another English gentleman named Isaac Newton proclaimed three essential principles (Laws) pertaining to the motion of particles of matter of any mass, from grains of sand to suns and planets. These principles apply to all molecules of matter be they solids, liquids or gasses (although the existence of molecules wasn’t known in 1687). Here they are:

Principle One: ‘Things’ remain stationary or keep moving in a straight line until pushed upon by an external force. (This is called the principle of ‘Inertia’.)

Principle Two: ‘Things’ will move from their stationary position or be sped up (or slowed down) along their line of motion or be deflected from their line of motion, by applying an external ‘push’. The degree of speed or direction change is proportional to the mass of the thing and the size and direction of the push. (This is the principle of ‘acceleration’).

Principle Three: For every ‘push’ on something, the something pushes back with an equal and opposite ‘push’. (Action – Reaction.)

I would also like to define three other terms at this point as I will be using them regularly throughout this and subsequent lessons. The first is ‘Velocity’. Most people use the words ‘velocity’ and ‘speed’ to mean the same thing, but in fact velocity has an added factor and that is ‘direction’. So velocity is speed in a particular direction. When we use the term velocity, we not only have to define how fast a thing is going but also in what direction it is traveling.

The second is ‘Acceleration’. Most people are familiar with this term in one sense and that is as a change of speed. When driving a motor car the speed can be changed by adjusting the ‘accelerator’ (‘Gas Pedal’ in the USA), but acceleration is not just a change of speed but a change of velocity. This means that a car is also accelerated when its direction of motion is changed without its speed changing. We do this every time we drive the car around a bend at constant speed. (Newton’s second principle is about acceleration.) This is an important point which I will be returning to in the lesson on Manoeuvring.

The third is ‘Momentum’. The Momentum of something in motion is the product of its mass and its velocity (M x V). This means that a small mass traveling very fast can have the same momentum as a large mass traveling slower. If we wish to change the momentum of a moving ‘thing’ we can do it by changing its mass or its velocity and, as we have just seen, we can change its velocity by changing its speed **or** its direction of travel (or both simultaneously). So the previously mentioned motor car going around a corner is changing its momentum at constant speed. Air molecules have a very small mass, but if moved quickly can have a large momentum, and changing this momentum is the key to answering the question, “what keeps it up there?”

So, to begin with, let’s focus on Newton’s third principle. If we can somehow push molecules of gas one way, we will experience a push back the other way with an equal force. The simplest example of this is the rocket, (solid fuel rockets were invented by the Chinese over a thousand years ago). In a rocket, fuel is burned in a confined space (combustion chamber) and the gas produced ‘whooshes’ out a hole in the chamber (action). The chamber and the vehicle attached to it experience a force propelling them in the opposite direction (reaction). The first successful operational liquid fuel rocket was the German World War Two V2 rocket which produced 56,000 pounds (25,400 KG) of thrust. Twenty five years later the Saturn V rocket propelled the Apollo Astronauts to the Moon with seven million pounds (3.17 million KG) of thrust produced this way! Note the expanding, ‘whooshing’ gas doesn’t push against the air: its motion out of the hole is itself the ‘action’ and the rocket’s movement is the ‘reaction’. This is how rockets can operate in the vacuum of space.

In the Earth’s atmosphere, if we can push air molecules down we will experience an upward ‘lifting’ reaction which will enable us to fly! How did George Cayley and his successors accomplish this? Simple, they moved an inclined flat surface through the air at a speed which pushed air molecules down hard enough, (that is, changed their ‘momentum’ by ‘accelerating’ them) to produce a reaction force strong enough to sustain them in the air. Now I am about to draw a diagram to show you what I mean (Figure One), but I want you to note that I am changing perspective for ease of drawing. I am going to draw the end view of an inclined stationary flat surface and the air molecules moving past it in ‘streamlines’. Either way the relative motion between them is the same and that is what is important here:

Figure One – Deflecting a ‘stream’ of air molecules

In Figure One the solid line is the end view of the flat surface (flat plate) inclined at a small angle to its line of motion (right to left) and the other lines are the lines of four of the millions of air molecules streaming past it as a result of this motion (left to right). You will note that molecules 3 and 4’s paths are deflected down by the angled flat plate but what about molecules 1 and 2? They say that “nature abhors a vacuum” and since we have pushed molecules 3 & 4 down we have tended to make a ‘hole’ in the air above the flat plate, so molecules 1 & 2 don’t just go sailing merrily on by, they ‘fall’ into the hole!

Here is the complete picture (Figure Two):

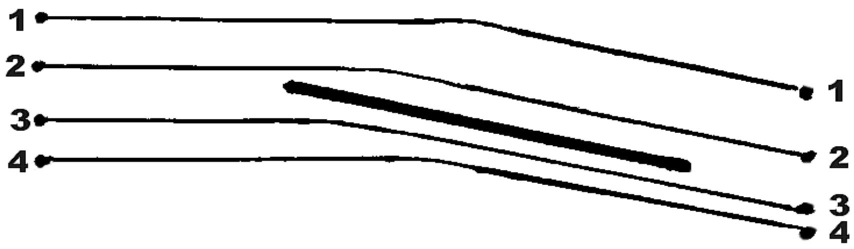


Figure Two – Deflecting both 'streams' of air molecules

So you can see that the flat plate has deflected all four molecules (and millions of others too) down. Now let's reverse perspective again and look at a before and after scenario from the 'point of view' of the molecules (Figure Three):

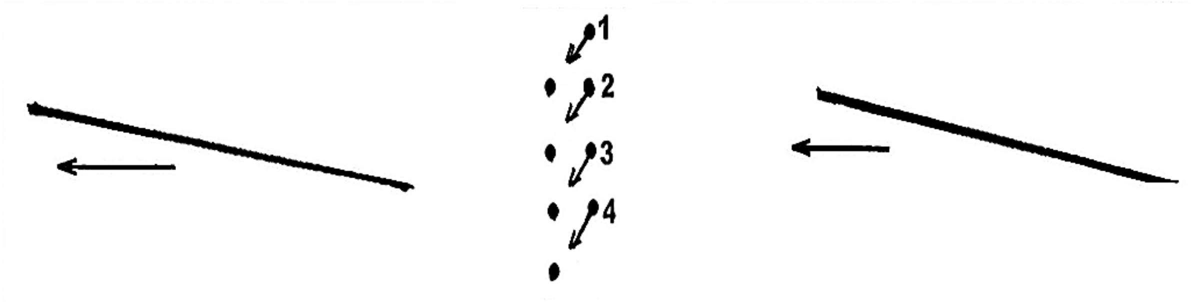


Figure Three – Pushing air molecules down and forward

Here we see the flat plate moving from right to left past the four molecules and you can also see that the molecules have not only been pushed down but also slightly forward, that is, in the direction of motion of the flat plate. As a result the reaction to this is not quite straight up but inclined slightly back; indeed the reaction is at about 90 degrees (90º) to the plate. Going back to the original perspective again, here is the same picture (Figure Four):

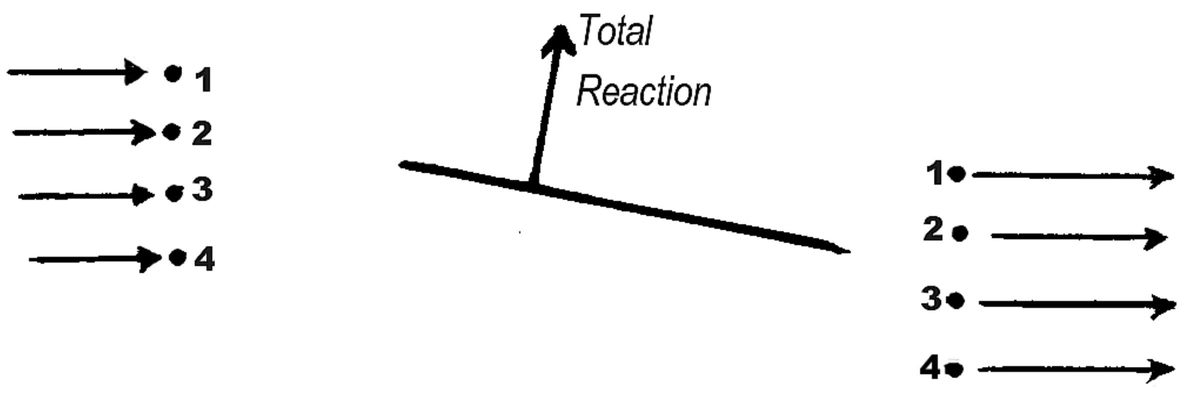


Figure Four – Total Reaction

Note that I have labeled the reaction force in the diagram the "Total Reaction". Why? Because, as I have said, we aren't just affecting the momentum of four molecules but millions of them and each one produces its own tiny reaction; here is a diagram of just a few (Figure Five):

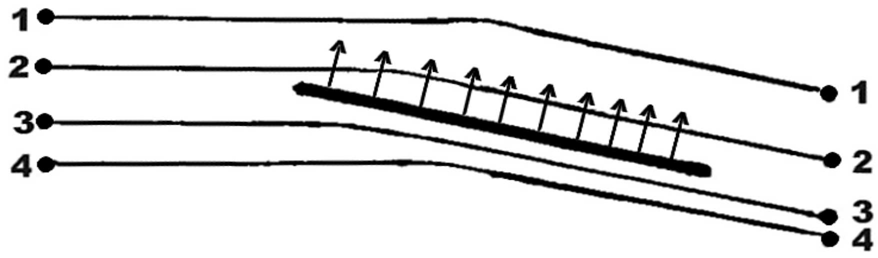


Figure Five – Individual reactions

For simplicity we lump all of these reactions together into one big reaction and we position this "total reaction" arrow about a quarter of the way back from the leading edge of the plate (centre of reaction), for reasons I will explain later.

Remember I said the Total Reaction is about 90º to the flat plate. Why "about", why not exactly? Well, if air molecules had a perfect elastic rebound (bounce) when struck by the wing the Total Reaction would be at exactly 90º but air molecules are rather 'squishy'. Let me explain. Imagine you are playing billiards and you play a shot off the side cushion of the billiard table. The ball will come off the side cushion at the same angle that it hit it (angle **A** = angle **B** in Figure Six below) because the ball and the cushion have a near perfect elastic rebound.

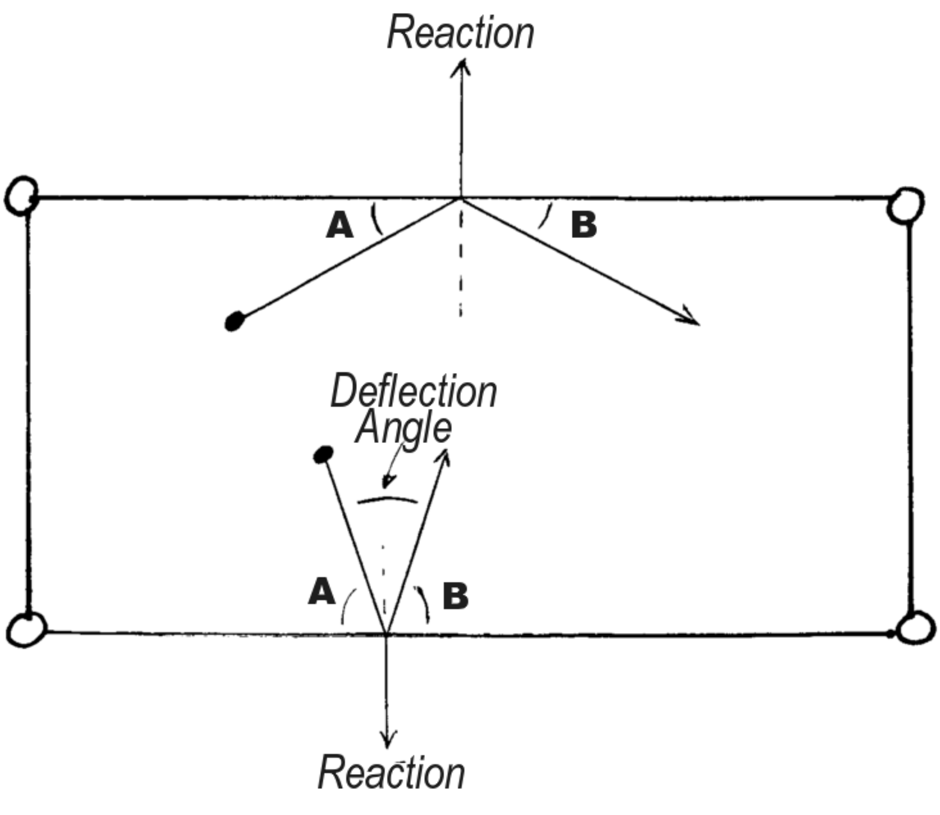


Figure Six – Billiard ball reactions

The force of this deflection is absorbed by the side cushion and the direction of the force is the opposite of the bisector of the angle of deflection, which is always 90º to the cushion. So if air molecules behaved the same way in my airflow diagrams as billiard balls, my diagrams would look like this and the total reaction would be at 90º to the wing (Figure Seven):

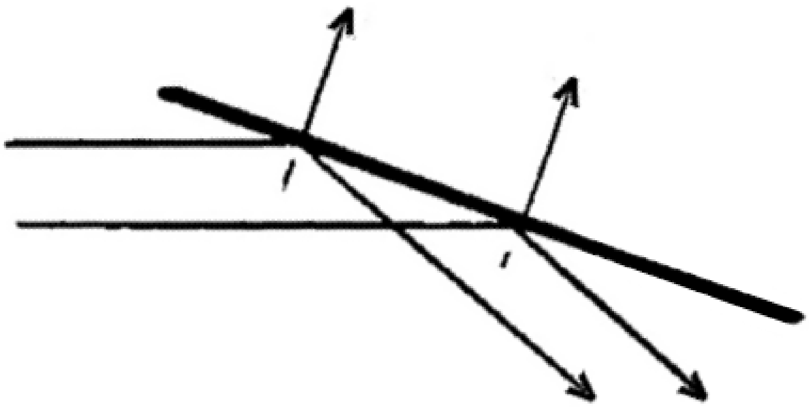


Figure Seven – Billiard ball molecules

But, as I said, air molecules are 'squishy' and bounce more like a squash ball than a billiard ball. So this is how they 'bounce' off our flat plate (Figure Eight):

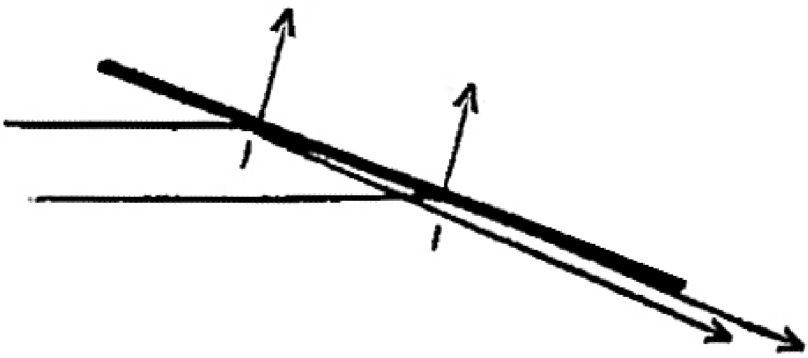


Figure Eight – Squash ball molecules

Whilst the Total Reaction is still the opposite of the bisector of the angle of deflection, the angle of deflection is not as great as the perfect elastic rebound so the Total Reaction is a little forward of 90º as you can see.

Many years ago when 'super' balls first came on the market, they were small and black and looked a lot like squash balls and a friend and I tried one out on a squash court. The rebound off the first serve was lethal and had us both diving for cover! (And there is not much 'cover' on a squash court.) That is when I learnt why squash is called squash. So if you want to get a 'feel' for the difference between air molecules (Squash Balls) and molecules with a near perfect elastic rebound (Super Balls), try them out on a squash court yourself, but I suggest you wear protective padding and a crash helmet!

The inclination angle that the flat plate makes to the airflow is called the ‘Angle of Attack’ and if we vary the angle of attack of the flat plate to this ‘squishy’ airflow we will vary the number of molecules and amount that the molecules are deflected, and therefore the size of the total reaction. In general terms, if we double the angle of attack we will double the total reaction, three times the angle will produce three times the total reaction etc. But there is a limit to how far we can go with this before we reach what is called the ‘critical angle’. For a flat plate the critical angle of attack is about 10º. Beyond this angle the air flowing over the top doesn’t ‘fall’ smoothly into the ‘hole’, it becomes turbulent and isn’t deflected down. At the critical angle of attack the total reaction reaches its maximum and then starts to get less. More about this later (note, the angles used in my diagrams have been exaggerated for clarity). The following diagram (graph) shows this Angle of Attack versus Total Reaction relationship (Figure Nine):

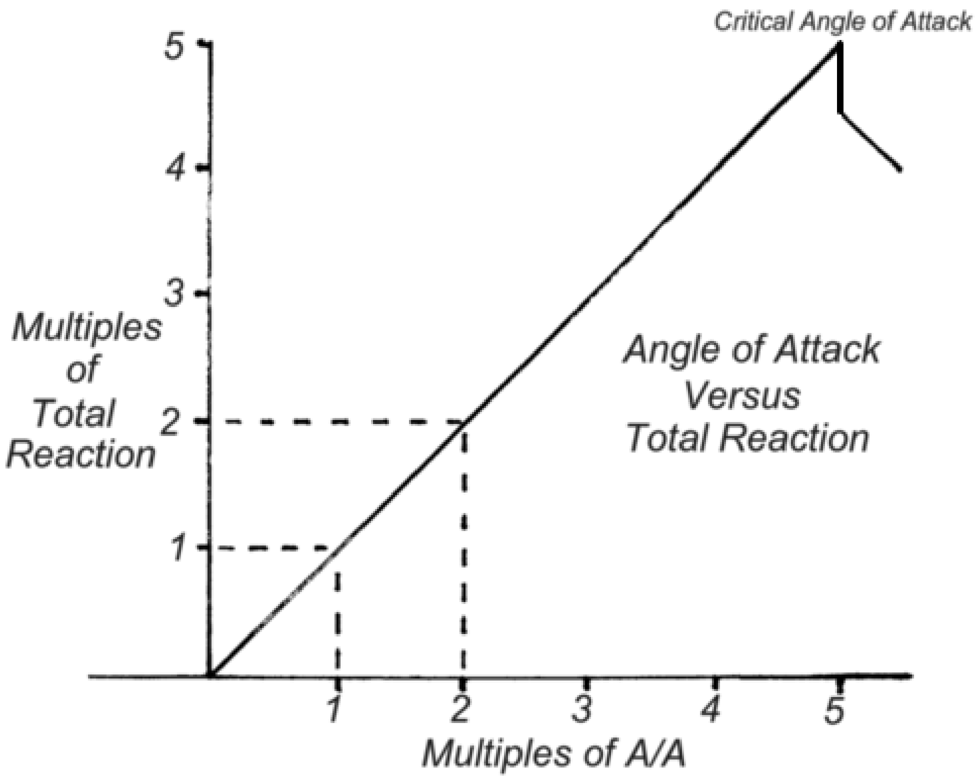


Figure Nine – Angle of Attack versus Total Reaction

Another way that the total reaction can be changed is by changing the air speed. If we push our flat plate through the air faster we will push the air molecules down harder and get a greater total reaction, in fact, if we double the speed we get four times the total reaction! A simple way to think of this is that in a given time we hit and deflect twice as many molecules twice as hard, so the total reaction varies as the ‘square’ of the airspeed. The following diagram is a graph showing this Airspeed versus Total Reaction relationship (Figure Ten):

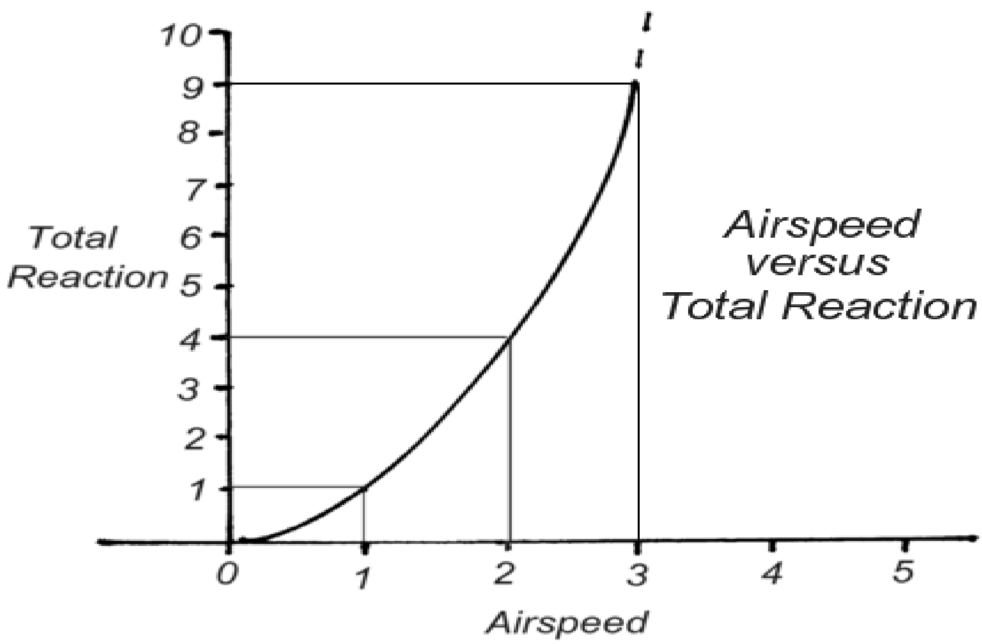


Figure Ten – Airspeed versus Total Reaction

These two variables can be controlled by the aviator to keep the reaction force in balance with the weight of the aircraft for level flight or create an excess total reaction for manoeuvring. We will be discussing manoeuvring a whole lot more in later lessons, but for now we can simply say that the aviator has control of the total reaction by virtue of his or her ability to control the angle of attack and the airspeed.

The other factor involved in all of this is of course the number of molecules being hit, that is, the mass of air being deflected, and as we have seen from Lesson One, this will depend upon the density of the air we are flying in at the time.

So we can now say that the total reaction produced by a wing (which is what our flat plate really is) depends upon the mass of the air encountered by the wing, and the velocity of the encounter, which is its ‘Momentum’ (MV), and the degree of deflection (acceleration) of this airflow. Deflecting the airflow means we change its momentum, and if we change its momentum we create a reaction force which we have labeled ‘Total Reaction’. For those who are mathematically inclined I have indulged in the mathematics of this process in Annex B.

What I have described here is called the ‘Momentum Theory’ of lift and Momentum theory when applied to a wing is “what keeps it up there”.

Now so far I have been using the term ‘Total Reaction’ and not the term ‘Lift’, because lift is only one component of the total reaction. Let me explain.

Imagine a wing moving horizontally at an angle of attack to the airflow as shown in the following diagram (Figure Eleven):

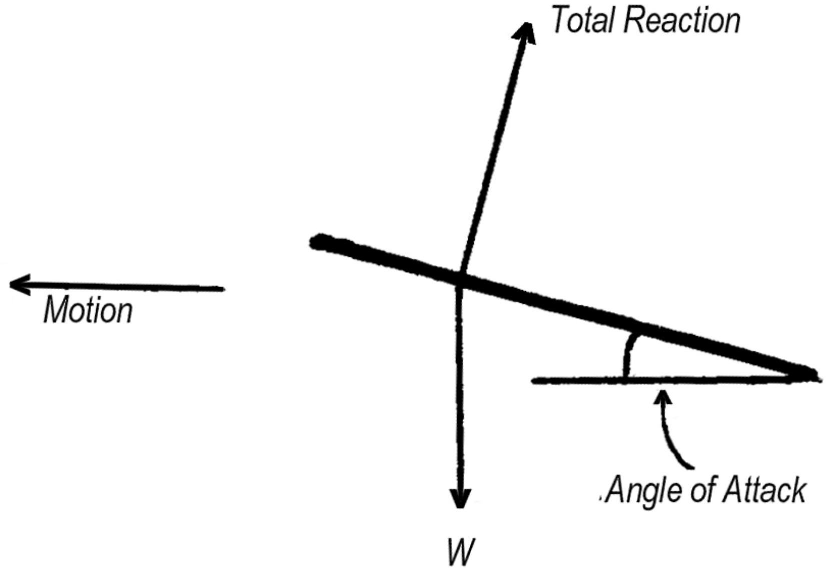


Figure Eleven – Total Reaction versus Weight

The weight of the wing, **W**, (and the aeroplane it is supporting) is vertically down but the total reaction, being about 90º to the wing, is therefore angled back by an angle about equal to the angle of attack, so it does not directly oppose the weight. Therefore the total reaction has to be split into two components, one vertically UP to balance the weight, which is called 'Lift' and one horizontally back opposing the forward motion, which is called 'Drag'. Figure Twelve shows the total reaction split into these two components. (I have used the common abbreviation A/A for 'angle of attack' in this diagram too).

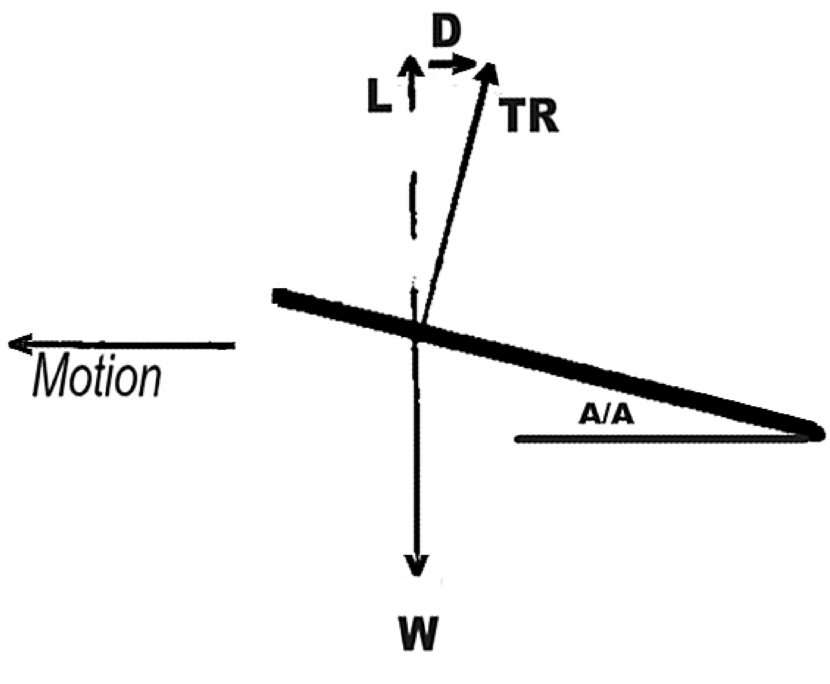


Figure Twelve – Lift and Drag Components

There is a whole lesson to come on this drag component, so no more about it here. Let's just focus on the lift component.

Early experimenters with gliders in the late 1800's - J. J. Montgomery in the USA, Percy Pilcher in England and Otto Lilienthal in Germany - did not use flat plates for their wings. A long time before, George Cayley noticed that a bird's wing, whilst essentially a flat plate, has the front or 'leading edge' curved down so that the airflow over the top surface did not have to negotiate such a sharp corner when it first encountered the wing, it curved smoothly around the forward part of the wing. All of these early experimenters used curved (cambered) wings (Figure Thirteen):

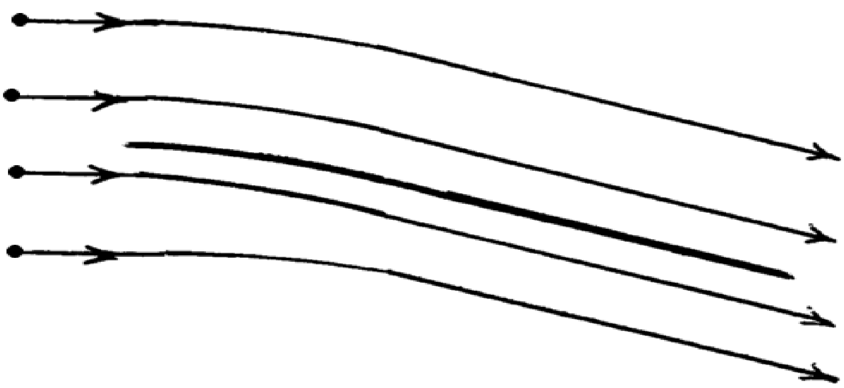


Figure Thirteen – Airflow around a Cambered Wing

This curvature significantly delayed the angle of attack at which the airflow 'breaks away' becomes turbulent and stops being deflected. That is, the critical angle of attack is increased from about 10º to about 16º! Which means a much greater total reaction can be achieved. This curvature wasn't much, about 3 or 4 percent of the width of the wing (nowadays called the 'Chord' of the wing) and finishing about 20% of the way back from the leading edge. Note from Figure Thirteen that most of the 'curving' or 'turning' of the airflow is achieved by the forward half of the wing, which is why the total reaction arrow on previous diagrams is positioned around 25% back from the leading edge (center of reaction). Also the amount that the total reaction arrow 'leans forward' from 90º on a cambered wing is a little different to a flat plate wing too, and differs with the amount of camber.

Otto Lilienthal made thousands of successful glides using his cambered wings and recorded much useful data about their performance.

In 1900 two bicycle manufacturers from Dayton Ohio USA decided to experiment with flying machines. They were Wilbur and Orville Wright, the Wright brothers. The Wright brothers used Lilienthal's data, did gliding experiments between 1900 and 1902 and modified their designs as a result of these flights and tests on wing section shapes in a 'Wind Tunnel' they developed themselves. They invented a means of three - axis control, built their own light weight engine and designed and built their own propellers: they were two exceptionally gifted men. On the 17th of December 1903 they made history with several powered controlled flights in one day, the longest being about a half kilometer into a 20 knot headwind! The Wrights wing section had a 3% camber with the curvature ending at about 20% chord.

The reason the Wrights invented the 'Wind Tunnel' was to explore a phenomenon they had noticed involving the position of the centre of reaction moving in what seemed an illogical manner as they changed the wing's angle of attack. They had assumed that their cambered wing would exhibit the same centre of reaction movement that a flat plate does as the angle of attack is changed, but it didn't! Let me explain.

A flat plate at 90º to the airflow has a centre of reaction in the middle, or to put it another way, 50% of the chord from the leading edge, as shown in the following diagram (Figure Fourteen):

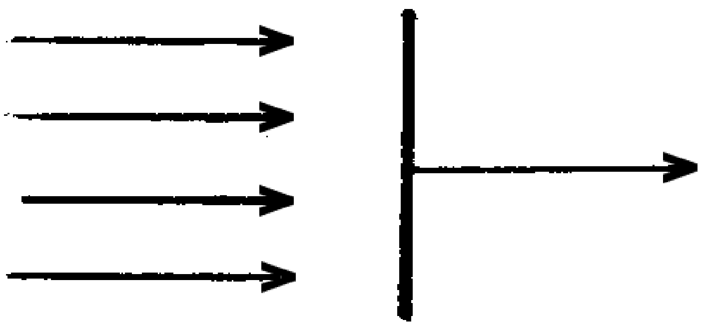


Figure Fourteen – Centre of Reaction at 90º A/A

As the angle of attack of a flat plate is reduced the centre of reaction moves progressively toward its leading edge (Figure Fifteen):

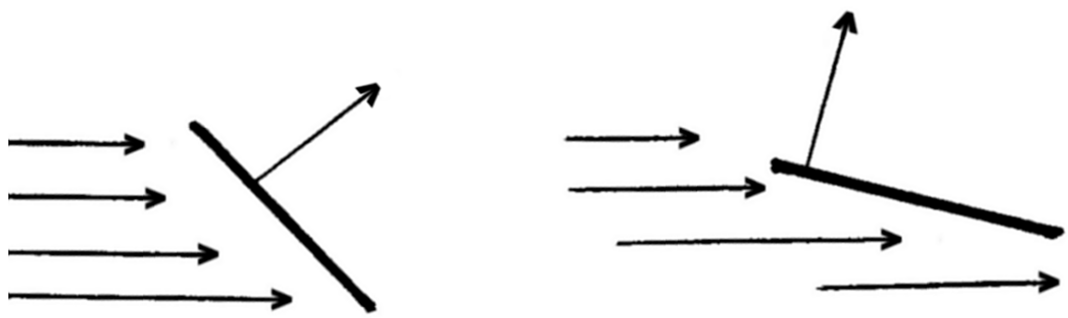


Figure Fifteen – Centre of Reaction moving forward

But the Wrights discovered that at angles less than the critical angle, a cambered wing has the reverse of this tendency. That is, the centre of reaction moved back as angle of attack is reduced and forward as angle of attack is increased, which seemed rather odd! (Figure Sixteen):

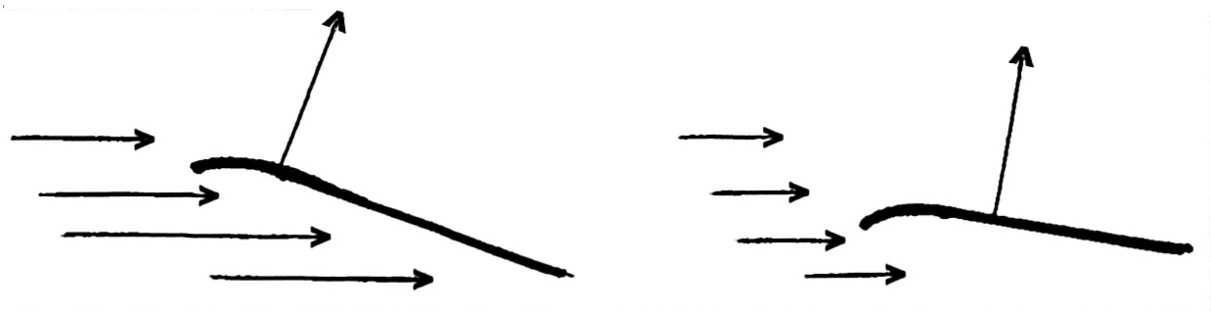


Figure Sixteen – Centre of Reaction moving back

But once the A/A increased beyond the critical angle a cambered wing acts like a flat plate again and the centre of reaction moves back again as angle of attack is increased further.

This moving around of the centre of reaction caused some consternation amongst early aircraft designers, because in order for an aeroplane to be reasonably controllable the centre of reaction should remain quite close to its centre of gravity (point of balance). But the damned thing wouldn't hold still!

As I have said, after World War One a lot of effort was put into the development of the aeroplane and this moving centre of reaction was high on the list of problems to be solved. It did not take long for one bright aerodynamicist to reason that if the centre of reaction moves one way on a flat plate and the other way on a moderately cambered surface when the A/A is changed, there must be subtle curved shapes between the two on which it doesn't move at all! Wind tunnel tests revealed a range of curved wing sections which continued to deflect airflow efficiently but on which the centre of reaction did not move with changing angle of attack right up to the critical angle. These wing sections are used today on most modern aeroplanes. (Some special purpose 'high lift' wings still suffer the problem slightly.)

Effectively the problem has been solved; no longer does the centre of reaction move about. Which of course raises the question: "why do most student pilot theory texts still say that it does?" (See Annex A for the complete performance data of a modern wing section, on which you will note the stationary centre of reaction.)

It might be worth mentioning at this point that many pilots confuse the curvature of the wing that they see with its actual camber. The camber of a wing is defined by a line drawn halfway between the top and bottom surfaces of the wing and you can't see this line on a modern wing.

Until the end of World War One, biplanes dominated the skies. A biplane gets its structural strength from struts and wires external to the wing, so the wing itself can be quite thin and its section can resemble those sections I have used in the foregoing diagrams. But struts and wires come at a cost - 'drag' - the resistance to forward speed through the air. By the early 1930's aircraft structures had improved to the extent that 'cantilevered' wings were becoming common, that is, wings strong enough to 'stick out' of the side of the fuselage without external support. Obviously these wings carried their support internally via one or two very strong lateral 'spars' and cross bracing. The wing had to be thick enough to accommodate this structure, so the wing section was surrounded by a 'streamlined' shape causing a flat plate wing to look like this (Figure Seventeen):

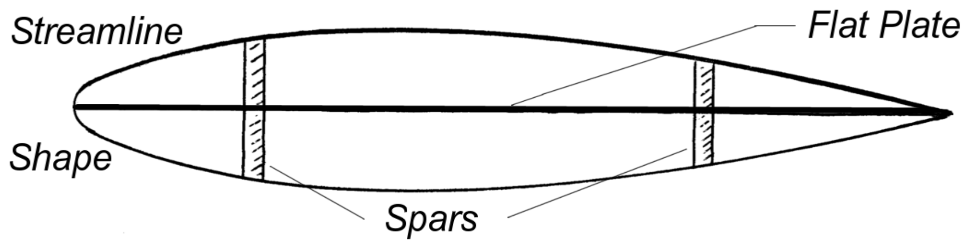


Figure Seventeen – Streamlined Flat Plate Wing Section

Note that the wing is curved top and bottom by the same amount, but the camber is zero. A highly cambered wing looked like this (Figure Eighteen):

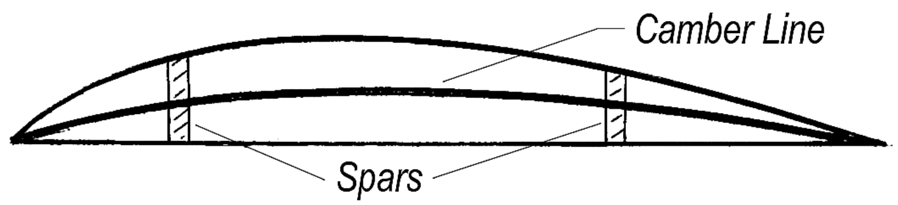


Figure Eighteen – Streamlined Cambered Wing Section

And a modern wing with a subtle (2%) camber looks like the section shown in Figure Nineteen: (also showing the 'chord' line, which is a straight line drawn from the leading edge to the trailing edge of the wing section and its difference to the 'camber' line):

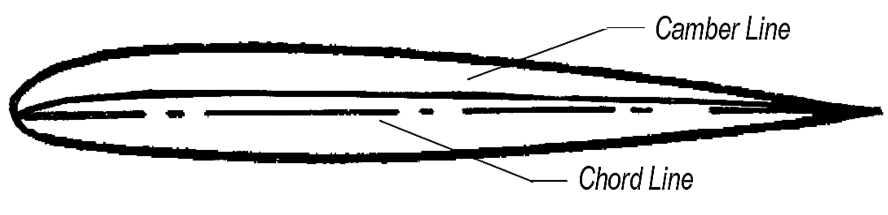


Figure Nineteen – Modern Wing Section

Note that as the curvature of the top of the wing is much greater than the camber, it gives the illusion of a highly cambered wing; but the actual camber, whilst positive, is much less than it may appear. Indeed modern wings have only about 2% camber, which is not too different to the wing section the Wright brothers used on their successful aeroplanes.

This streamlined enclosure also has the advantage of giving the flat plate wing an increase in critical angle as it allows the airflow a smoother encounter with the wing's leading edge. Most modern high performance aerobatic aeroplanes utilize 'streamlined' flat plate wings like this, nowadays called 'symmetrical' sections. Supersonic jets use similar wing sections too.

Unfortunately it doesn't end there, there are added complications. As has been stated previously, in order to create a total reaction the wing has to deflect the airflow and this deflection results from turning the airflow from its initial path (Figure Twenty):

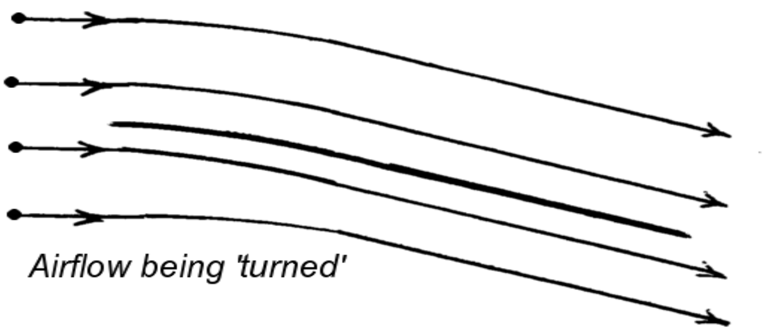


Figure Twenty – Airflow being 'Turned'

Now Newton's third law of motion doesn't just apply to linear situations but also to angular situations. That is, if an airflow is turned one way then the wing that turned it experiences an equal and opposite turning force. In general situations this is called a 'torque reaction', but in the case of a wing it is called a 'pitching moment' (Figure Twenty One).

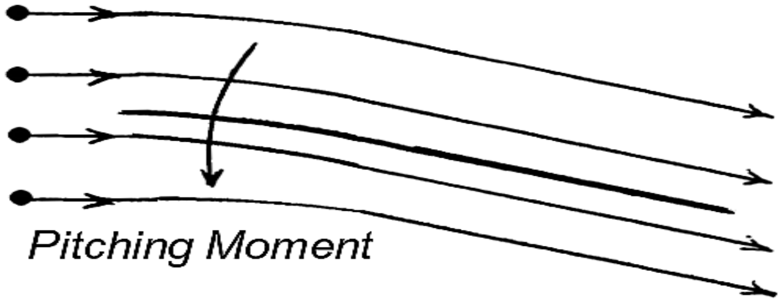


Figure Twenty One – Wing Pitching Moment

This 'pitching moment' will cause a disembodied wing, presented to the airflow, to pitch leading edge down and reduce its angle of attack to zero lift. (The effects of the wing's pitching moment will be discussed further in the lectures on 'Stability & Control' and 'Propellers'.)

Okay, by now the pilots amongst you are crying out "hang on, what about this Bernoulli guy's principle I was taught about?" Good question. Let's take a look at Bernoulli and where current student pilot aerodynamic theory has come 'off the rails'. It all started in 'Wind Tunnels'. Figure Twenty Two is a diagram of a 1920's wind tunnel; note its complexity:

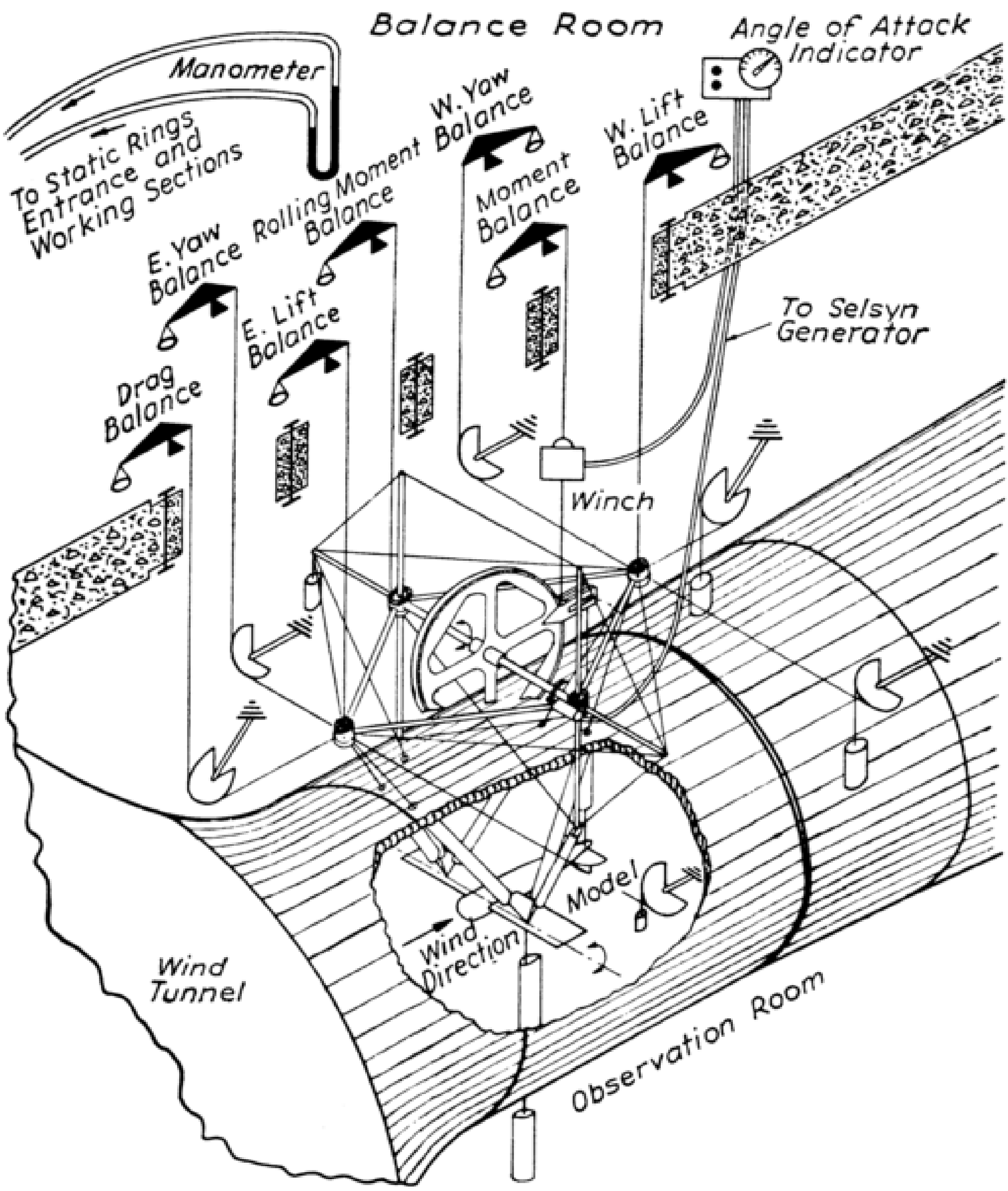


Figure Twenty Two – Early Wind Tunnel

After World War One, in order to experiment with shapes in faster and faster airflows, wind tunnels had to become more 'sophisticated'. The 'Wrights' wind tunnel had various shapes suspended on one end of a beam balance in order to measure the reaction forces. The balancing/measuring apparatus was in the wind tunnel too. For about the next 20 years this was the general design of the few wind tunnels used in aerodynamic experiments. Indeed, in 1962 when I was a cadet pilot in the RAAF this was the style of desk top 'wind tunnel' we used to conduct learning experiments in aerodynamic theory. The problem with this system was that as the airflows became faster and faster in these tunnels, the measuring apparatus interfered with the smooth airflow and corrupted the results of the experiments. (The friction of the wires and pulleys would not have helped the accuracy of the measurements either!) The apparatus had to be removed and some other method of measuring the results incorporated. Enter Bernoulli.

Daniel Bernoulli (1700-1782), a Dutch physician and mathematician, who had obviously passed on long before the aeroplane was invented, formulated a simple theorem which applied the general principle of 'conservation of energy' to fluid dynamics. He used it to measure the flow of blood through patients' veins! His principle simply stated that "the total pressure in a steady fluid flow within a tube is constant".

Now in any fluid flow the total pressure of the flow is made up of two components, the 'Static pressure' (the pressure on your body right now as you sit at the bottom of a 100km deep ocean of air reading this book) and 'Dynamic pressure' (the pressure that you feel on one side of your body when you stand out in a wind). Bernoulli's principle requires that, since total pressure can be sub divided into 'Static' and 'Dynamic', in order for it to remain constant, the size of the static and dynamic components must be proportionally interchangeable. That is, if dynamic pressure increases, the static pressure must decrease proportionally and vice versa. Let me now redraw a previous diagram of airflow around a wing section (Figure Twenty Three):

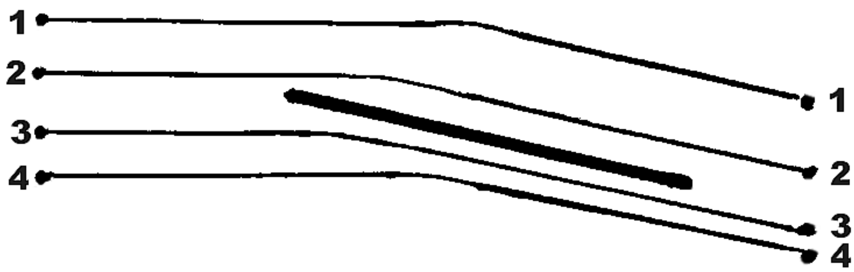


Figure Twenty Three – Figure Two Revisited

Notice that our four favored molecules are a certain distance apart before encountering the wing. This represents their static pressure (assuming that the density and temperature remain constant for the time it takes the wing to pass by). Now look at what happens upon encountering the wing. The wing, whilst pushing molecules 3 & 4 down causes them to squeeze together, whilst molecules 1 & 2 move further apart as they, in turn, fall into the 'hole' created in the air. Now not all of the millions of molecules deflected by the underside of the wing actually come into contact with it; a large proportion of them just 'squish' up against the ones closer to the wing and are deflected and the next ones out 'squish' up against them and so on. Conversely, over the top of the wing, as each molecule close to the wing falls into the 'hole' it leaves its own 'hole' for the next one further out to fall into (a fraction of a second later due to its inertia) and so on. The end result is that molecules 3 & 4 and their millions of 'buddies' are compressed and have their static pressure increased, whilst molecules 1 & 2 and their millions of 'buddies' are expanded and have their static pressure decreased. So, in accordance with Bernoulli's principle, the airflow under the wing must slow down (dynamic pressure proportionally decreased) and the airflow over the top surface must speed up (dynamic pressure proportionally increased). This should be starting to sound familiar to all of those readers who are Bernoulli fans, but note the reversal of the chain of events.

Because of Bernoulli's principle, aerodynamicists now had a way of measuring reaction forces in a wind tunnel without the clutter. They simply measured the static pressure through tiny holes positioned all over the shape under investigation, compared these readings with the free stream total pressure and by applying some simple mathematics could calculate the aerodynamic characteristics of the shape. The following is a diagram of a typical early static pressure measuring system (Figure Twenty Four):

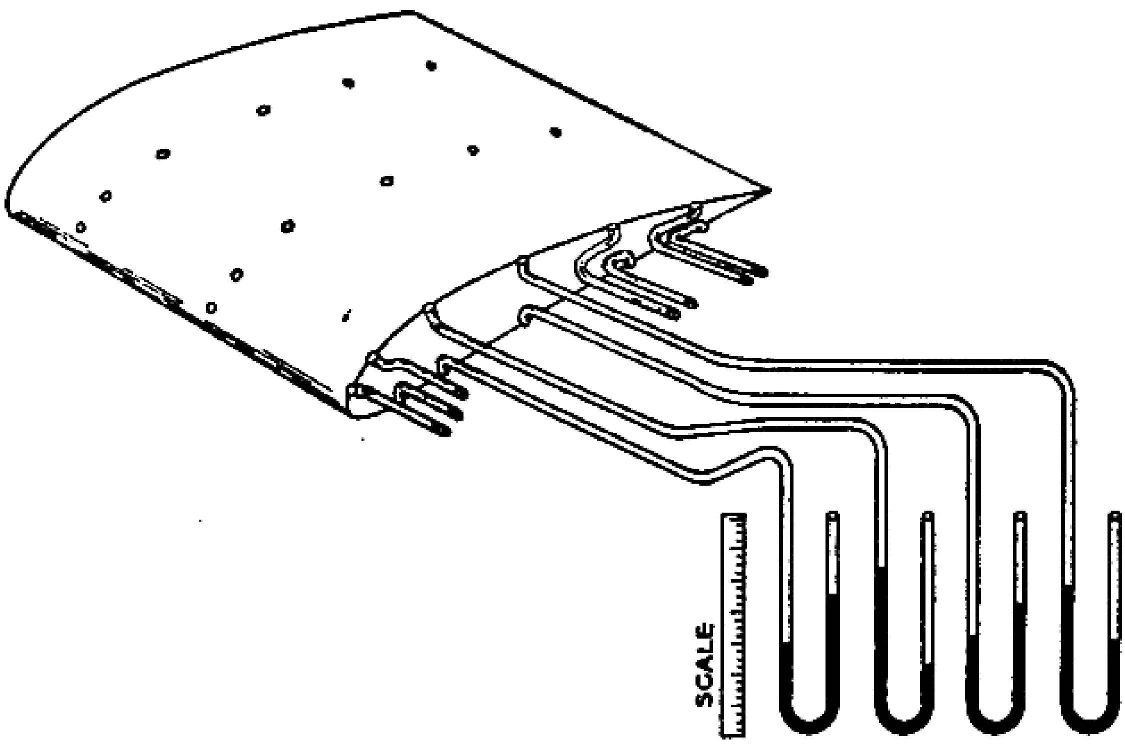


Figure Twenty Four – Static Pressure Measuring System

The tiny holes in the wing attached to the static pressure measuring equipment ('Manometers') reveal a static pressure distribution around the wing section similar to that shown in Figure Twenty Five. (This diagram will be familiar to those who have already been exposed to the Bernoulli 'theorem' of lift production but it can now be put into its correct context.)

Figure Twenty Five – Static Pressure Distribution

Because of this new measuring system aerodynamicists called the centre of reaction the 'Centre of Pressure'. This term is now used in student pilot aerodynamics texts and contributes to the current misunderstanding, but the main confusion is the reversal of cause and effect which has occurred. Let me put it simply**:**

Lift comes from deflecting airflow down. Deflecting air down with a wing <u>also</u> causes air pressure differences around the wing, and these air pressure differences are proportional to the amount of airflow deflection and the lift created. So the pressure differences did not <u>cause</u> the lift they <u>resulted</u> from it being created by other means!

It is not clear when the misuse of the Bernoulli principle first started. I have a copy of the 'Technical Manual on the Theory of Flight' issued by US war department and authorized by General George C Marshall, Chief of Staff dated 24 February 1941 which was the official manual on the subject used by the US Army Air Corps when training its pilots throughout Word War Two. It unequivocally states: ***"The resultant dynamic reaction upon an airfoil (wing), is a force accompanying a change of momentum of the air. This force depends upon the mass of air deflected and the acceleration imparted to that mass of air and Newton's laws of motion are directly applicable in the determination of its magnitude."*** So we can't blame the US Army.

I also have a first edition copy of a book entitled "Stick & Rudder" written by Wolfgang Langewiesche, a US civilian Test Pilot, and published in 1944, in which within the first few pages he says, ***"Forget Bernoulli's Theorem, a wing keeps the aeroplane up by pushing air down."*** This implies that somewhere between 1941 and 1944 the so called 'Bernoulli Theorem of Lift' production was being somehow introduced and confusing many pilots. Why else would Wolfgang come out so strongly against it? Unfortunately, despite the fact that his book has remained in publication to this day, very few pilots appear to have read it or understand it, because in the minds of most pilots today, Bernoulli rules!

I strongly recommend that all aviators obtain and read a copy of "Stick & Rudder" by Wolfgang Langewiesche.

The Bernoulli principle is a great tool for aerodynamicists and aircraft designers. It is totally unnecessary for an aviator's understanding of how to fly and control his/her aircraft. The 'Momentum Theory' of deflected airflows utilizing Newton's laws of motion provide the aviator with a clear, simple and easily visualized understanding of what keeps the aeroplane "up there".

For those of you who are still not convinced I have indulged in some simple arithmetic concerning the Bernoulli principle at Annex D. If you are convinced or are not 'into' arithmetic you may skip the annex as it doesn't change anything of what I have already said.

I would now like to 'back up' a bit. Now that you have a clear picture of how lift is created by a wing, I wish to develop your understanding just a little further. I mentioned earlier that the curvature near the leading edge helps the airflow to negotiate the 'corner' it encounters. How?

Early in the 20th century a gentleman named Henri Coanda noticed that moving fluids, water and air in particular, tend to 'stick' to curved surfaces placed in their path provided the curvature wasn't too severe. This has become known as the 'Coanda Effect'. Figure Twenty Six below illustrates what I mean:

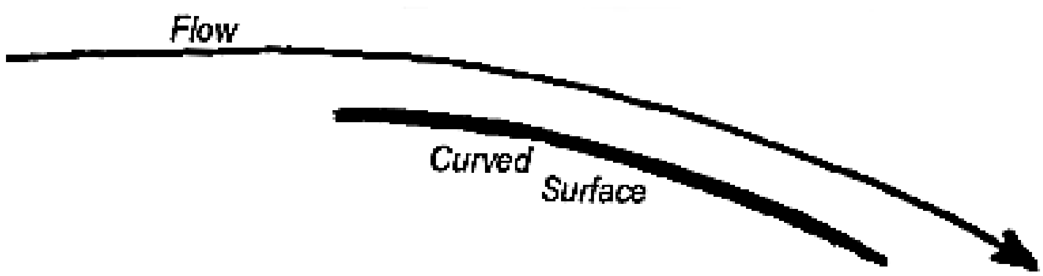


Figure Twenty Six – Airflow 'sticking' to curved surface

You can observe this effect yourself quite simply. Hold a teaspoon near a stream of tap water as shown in the next diagram (Figure Twenty Seven) and let it swing freely between your finger and thumb. Now move the head of the spoon close enough to the stream for it to just touch the spoon. The instant the spoon touches the water the Coanda Effect causes the water to 'stick' to the surface of the spoon and curve away from its previous vertical stream:

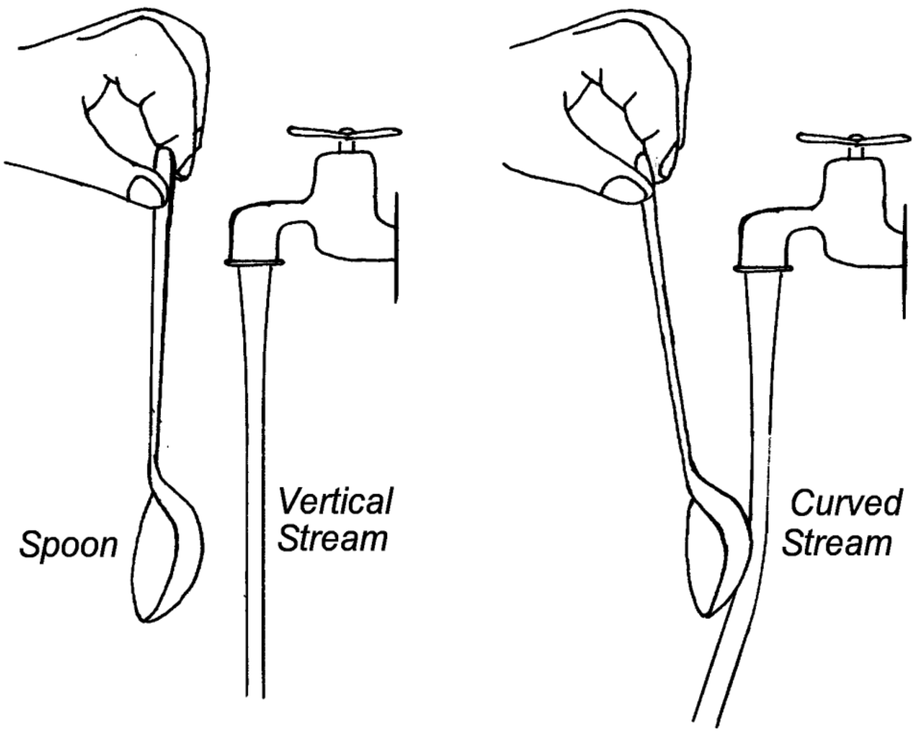


Figure Twenty Seven – The spoon and water experiment

Here is another example. Take a piece of typing paper about A4 size and fold a thin lip along one of the shorter edges. Hold it horizontally by this lip and let the paper curve down under its own weight. Now bring it up to your lower lip whilst blowing straight out against your other hand. The instant the surface of the paper touches the airflow from your mouth you will feel the airflow against your other hand disappear! Now drop this hand down and you will feel the airflow again much lower. This is because the airflow has followed the curved surface due to the Coanda Effect (Figure Twenty Eight):

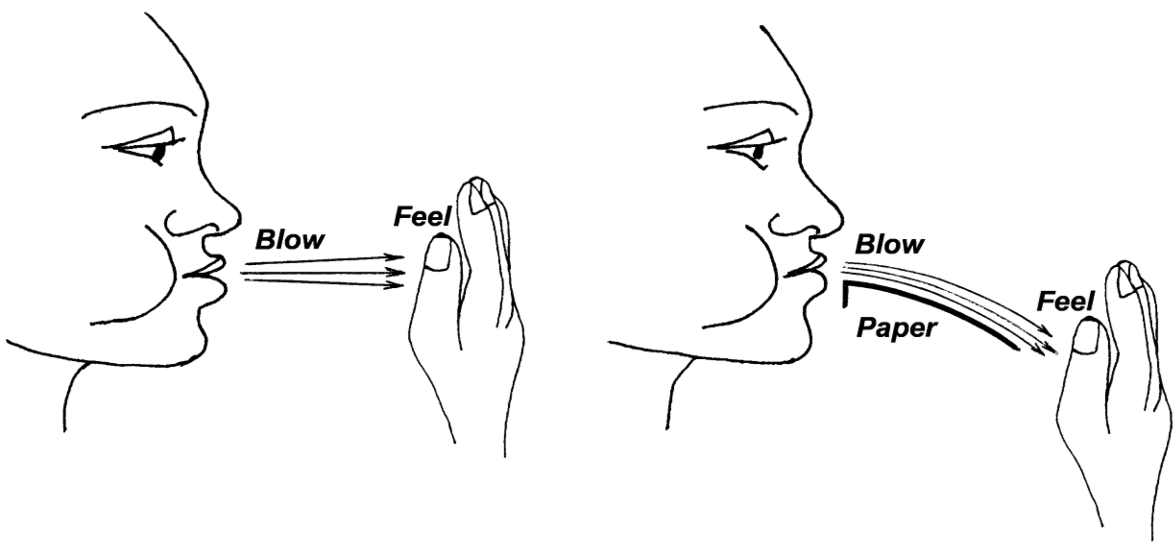


Figure Twenty Eight – The blowing over curved paper experiment

Henri Coanda attempted to develop this principle into a method of propulsion. Indeed his creation could be classified as the first ‘Jet’ engine. He had a piston engine drive a centrifugal compressor and ducted the airflow created via a small annular slot over the curved cowling of the engine. Fuel was mixed in this airflow and ignited in an attempt to accelerate it further. The airflow and the flames turned almost 90° and were supposed to provide thrust to drive the aeroplane (Figure Twenty Nine):

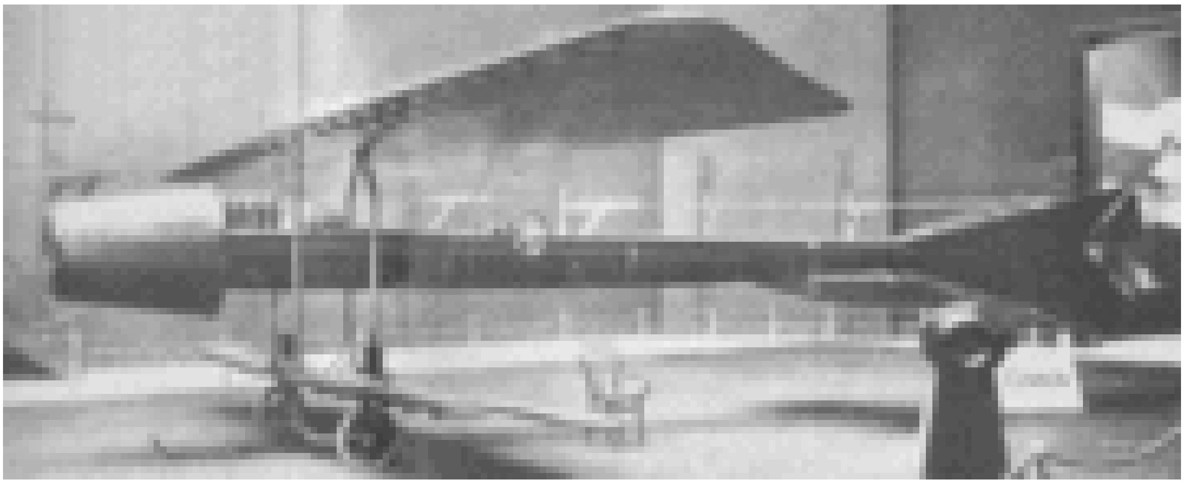


Figure Twenty Nine - Coanda’s ‘Jet’ Aeroplane

We will never know how well Henri’s aeroplane could have worked because it caught fire and was destroyed and he never continued its development. Figure Thirty below is his original patent for this engine detailing his ‘Coanda Effect’.

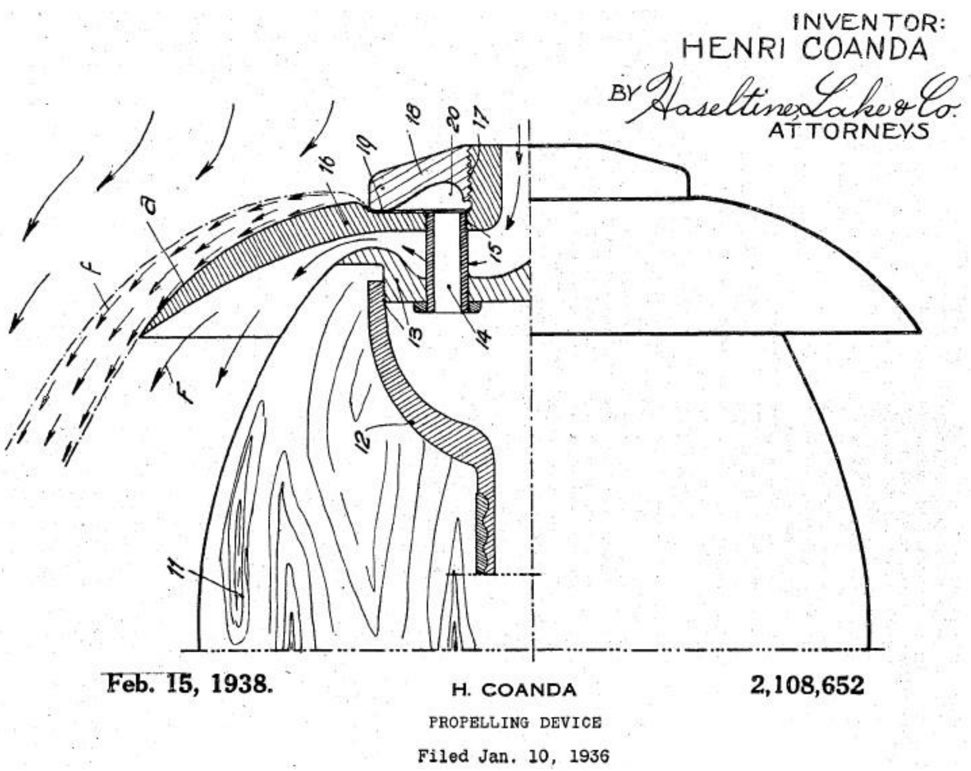
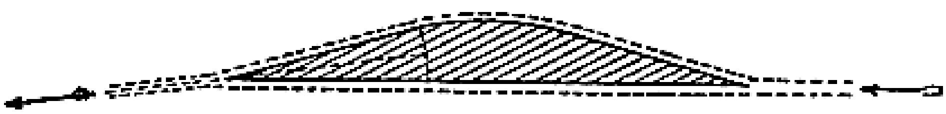


Figure Thirty - Henri Coanda’s Patent

When conducting these experiments with the spoon and the water or blowing air over paper, you will also note another phenomenon. The spoon will swing further into the water stream of its own accord and the sheet of paper will float up against its own weight. **This is the effect of total reaction before your very eyes.** The airflow coming off the ‘trailing edge’ of the piece of paper or a wing is moving down relative to its original direction. This is called ‘Downwash’ or ‘Rotor wash’ or ‘Slipstream’, depending upon whether we are referring to an aeroplane’s wing, a helicopter’s rotor or a propeller. It makes no difference because they are all doing the same thing, deflecting airflow. It is difficult to feel the downwash off a wing as the aeroplane would have to be flying very low over your head, but stand behind a whirling propeller or near a helicopter when it is lifting off or alighting and you will feel it. For a more immediate demonstration, go and switch on your electric fan. Feel the breeze? That is the downwash I am talking about. Fortunately the electric motor driving your fan is not too powerful, if it was the whole device would take off across the room and crash into the wall! (Action - Reaction!)

The following is an extract from a very old book entitled “How to Fly” which was published in 1910. Note the opening statement which says that “the action of the air when surfaces are driven through it is not fully understood”, which is an honest admission. It then goes on to discuss the “Aeroplane Paradox” and suggests that further investigation be undertaken (Figure Thirty One):

The action of the air when surfaces are driven through it is not fully understood. Indeed,



Section of the "paradox" aeroplane.

the form of plane shown in the accompanying figure is called the aeroplane paradox. If driven in either direction it leaves the air with a *downward* trend, and therefore exerts a proportional lifting power. If half of the plane is taken away, the other half is pressed downward. All of the lifting effect is in the curving of the top side. It seems desirable, therefore, that such essential factors should be thoroughly worked out, understood, and applied.

Figure Thirty One – The Aeroplane Paradox

This ‘paradox’ is an excellent example of the ‘Coanda Effect’ as it causes downwash and a total reaction if the ‘wing’ is moving in either direction. This effect was observed long before it was completely understood or called the ‘Coanda Effect’. I expect that you would now be able to explain the ‘paradox’ to the author.

The Coanda ‘paradox’ effect is what enables a cambered wing to develop some lift at zero degrees angle of attack; indeed to reduce the lift to zero on such a wing the wing would have to be set to a slight negative angle of attack. This negative angle of attack is often referred to as the ‘zero lift angle of attack’. The following diagram (Figure Thirty Two) shows a graph of the lift due to camber and the lift due to angle of attack of a typical cambered wing section. Note the positive lift at zero degrees angle of attack:

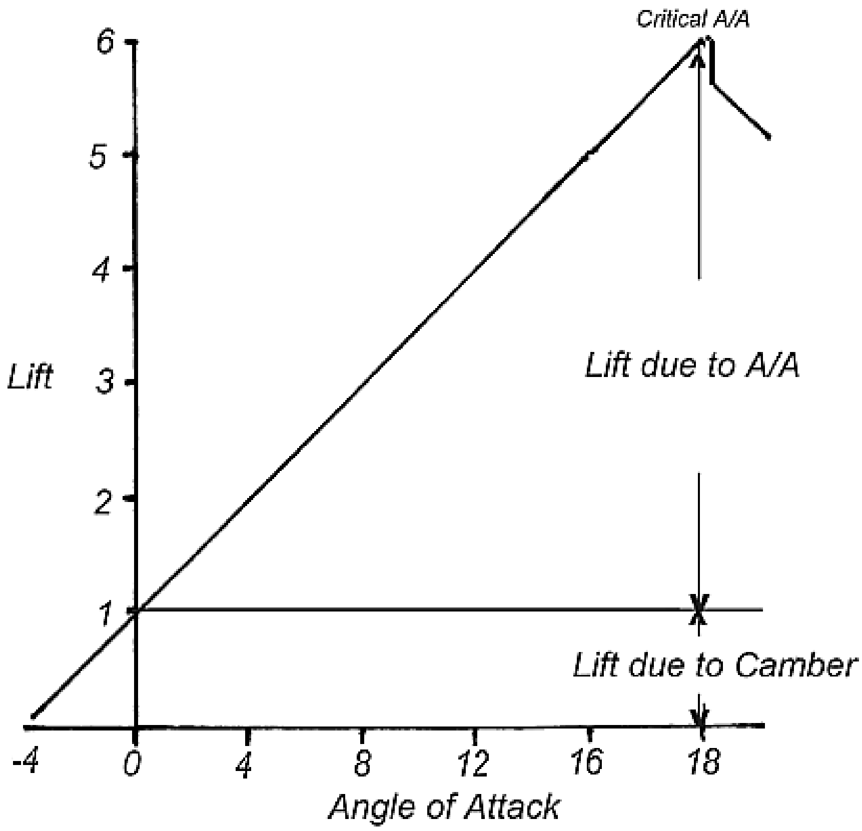


Figure Thirty Two - Graph of a Cambered Wing’s Lift

Now when the angle of attack of a wing is taken past the critical angle the Coanda Effect ceases because the angle of encounter is too great. The airflow over the top surface doesn’t follow the curve and separates. The downwash is significantly reduced as is the total reaction and the lift. This whole process is called an ‘aerodynamic stall’, nowadays shortened to just ‘stall’. To maintain level flight whilst slowing down, an aviator should increase the angle of attack to compensate for the loss of lift, but there is obviously a minimum speed at which the compensating angle of attack becomes critical and the wing stalls. This minimum speed is called the aircrafts ‘Stall Speed’. In order to fly slower, various devices can be attached to the wing to enhance the Coanda Effect.

Before the Second World War, the Handley-Page Aeroplane Company in the UK designed a device which attached to the leading edge of each wing and formed a 'slot', through which the airflow was directed around the leading edge at high angles of attack, thus delaying separation. The following diagram shows a wing section at 20° angle of attack without any airflow separation from the top surface (Figure Thirty Three):

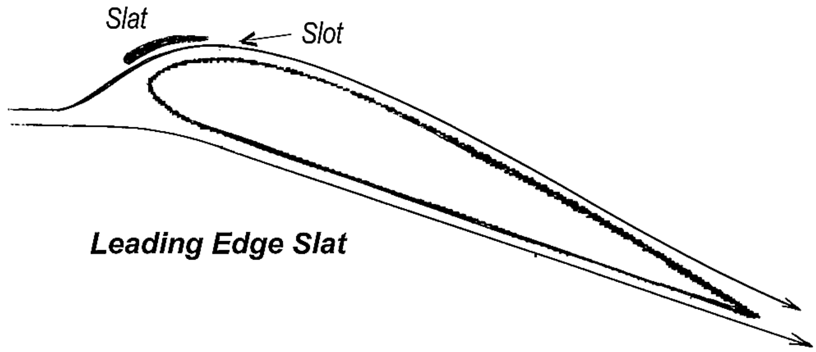


Figure Thirty Three - The Handley-Page Slat & Slot

The device was called a 'Slat'. Slats are not seen on many aeroplanes any more, but the venerable old Tiger Moth wears them proudly. The following Lift versus A/A graph shows that the Slats extend the graph and increase the critical A/A and the resulting lift (Figure Thirty Four):

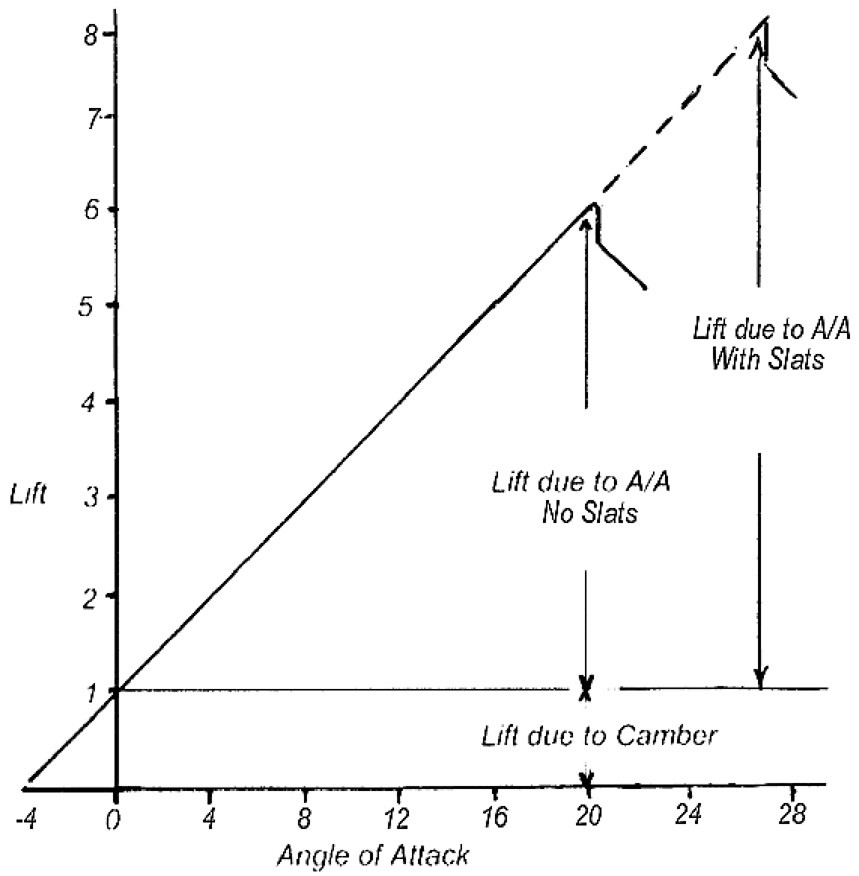


Figure Thirty Four – Effect of 'Slat' on Critical Angle and Lift

Another device which is in common use is the 'Flap'. A simple flap is just an adjustable 'drooping' trailing edge which gives the airflow a second deflection after it has settled down from the first one (Figure Thirty Five):

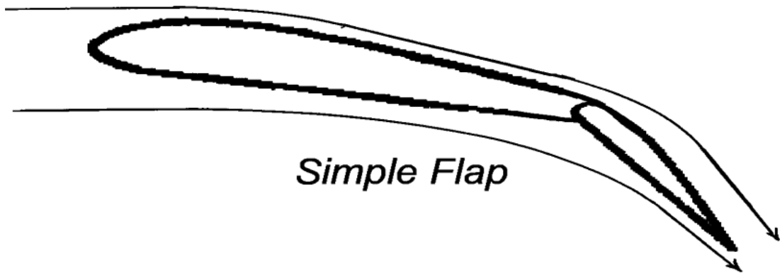


Figure Thirty Five – Simple Flap

Normally, when simple flaps are used to improve the lifting capabilities of a wing, they don't 'droop' more than about 30º from the wing chord line (when lowered further than 30º the affect is mostly increased drag. There will be more about this in the lesson on drag). Flaps are mounted on the inboard section of the trailing edges of both wings and move together so that their effect on the lift on each wing of the aeroplane is symmetrical. The following Lift versus A/A graph shows the effect of Flaps on the critical A/A and the resulting lift. Note that in this case the effect is to raise the whole graph up thereby increasing the 'Lift due to Camber' component of the total lift (Figure Thirty Six):

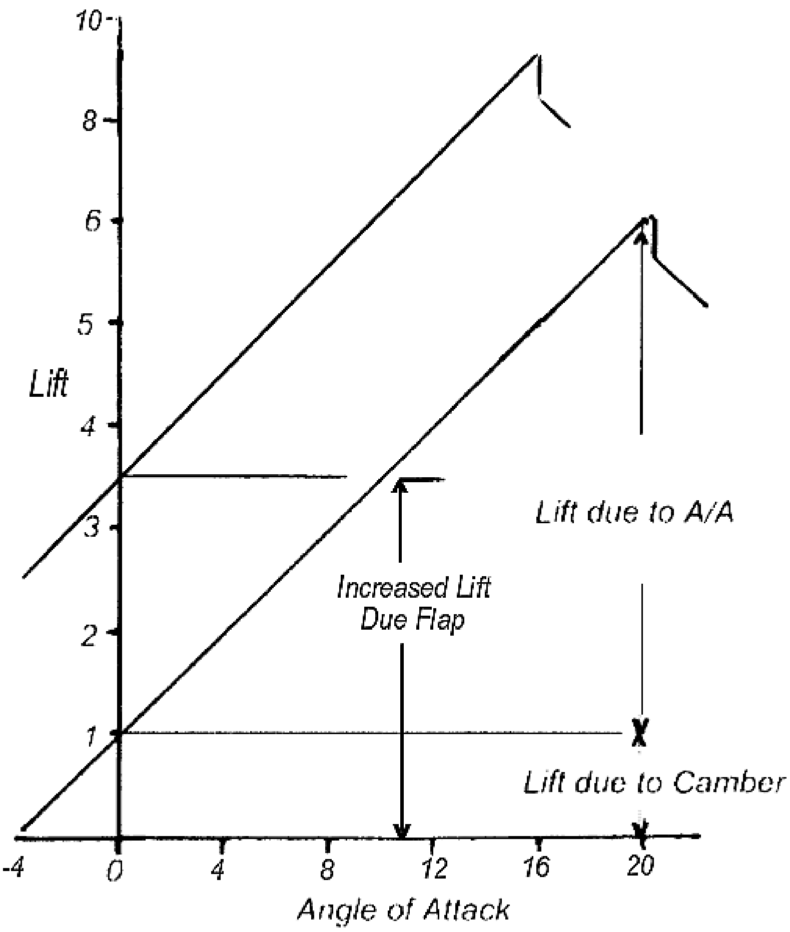


Figure Thirty Six – Effect of Flaps on Critical Angle and Lift

Similar devices mounted outboard on the trailing edge of each wing, called 'Ailerons' work in a similar fashion except that each aileron moves opposite to the other, that is, when one goes down the other goes up. This causes a significant difference in the lift produced by each wing and causes the aeroplane to roll. There will be more about ailerons in the lesson on Stability and Control.

Another common type of flaps is the 'Fowler Flap'. This flap moves back as it goes down and increases both the camber and the wing area (Figure Thirty Seven):

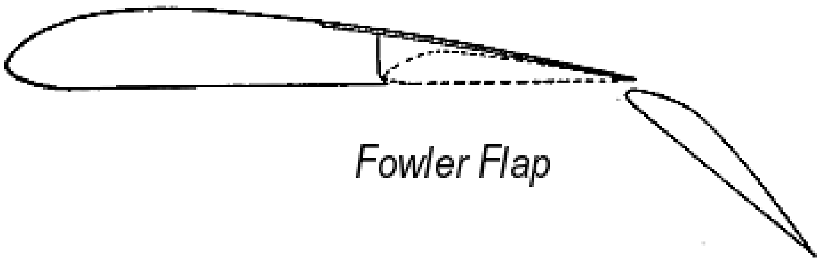


Figure Thirty Seven – Fowler Flap

Many modern aeroplanes combine flaps and slots into what are called 'slotted flaps'. As the flap is activated it opens up a slot to assist the airflow around the second 'corner' (Figure Thirty Eight):

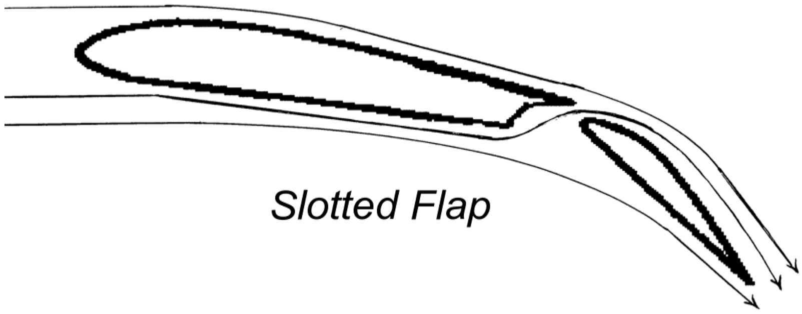


Figure Thirty Eight - Slotted Flap

This slot effect enables the flaps to be 'drooped' more than a simple flap thereby deflecting the airflow more and providing a greater total reaction. There are plenty of aeroplanes around with slotted flaps. (Indeed most modern Jet Airliners have Slotted Fowler Flaps to safely reduce their landing speeds.)

All of these devices help to deflect the airflow by greater and greater angles without separation, thereby enabling the aeroplane to fly slower and slower. Great if you want to land a heavy aeroplane in a small space. I once flew the DeHavilland DH-4 'Caribou'. It had full span (98ft) double slotted flaps, the inboard sections of which could be set to an angle of 80º from the chord line! It could fly and land very slowly for an aeroplane of its size and weight. I have landed that aeroplane on 'cricket pitches' on the sides of mountains all over South East Asia (Figure Thirty Nine):

Figure Thirty Nine - Caribou full span double slotted flaps

What happens if, despite all of these devices, we slow down and increase the angle of attack beyond the critical angle? Well, not very much. The wing loses about half its lift and the aeroplane starts to 'sink', which means you had better be only a few centimeters above your chosen landing point or high enough in the sky to recover from the situation. If you are somewhere in between these two situations, your life will become very interesting for a while. This is why 'stalling' and the recovery from a stall is the subject of a whole separate lesson.

Throughout this lesson we have been looking at the wing 'end on' as we have discussed the airflow around the various wing sections and lift augmentation devices and I pointed out that the majority of the 'curving' of an airflow around a wing section takes place in forward part of the wing, and this suggests that if we could have a longer and narrower wing it would encounter and deflect more air than a short and broad wing of the same area and therefore be more effective at producing lift. And this is the case; the shape of the wing in 'planform' also has a bearing upon its efficiency. The following diagram (Figure Forty) shows three wing planforms of the same area and same aerofoil section. Note that the ratio of the wing span to the wing chord is significantly different in each case and we call this ratio the wings 'Aspect Ratio'.

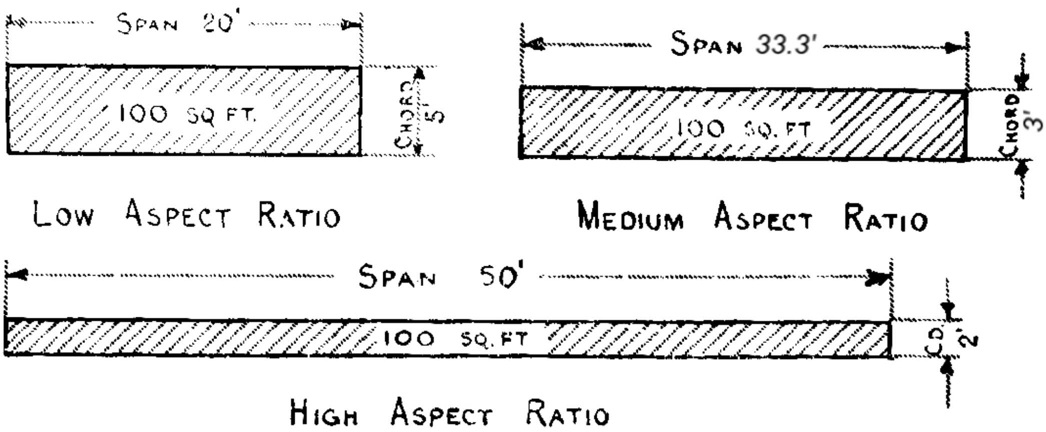


Figure Forty – Aspect Ratio

In Figure Forty the 'Low Aspect Ratio' wing has a ratio of 20/5 or **4**, the 'Medium Aspect Ratio' wing has a ratio of 33/3 or **11** and the 'High Aspect Ratio' wing has a ratio of 50/2 or **25.**

A high aspect ratio wing affects a greater volume of air as it moves through it, which means it can generate the same total reaction as a wing of lower aspect ratio but at a slightly reduced angle of attack, thereby reducing the drag component in relation to the lift component. (I will have a lot more to say about the drag component in the lesson on drag.) The disadvantages of a high aspect ratio wing are its reduced structural strength and its reduced roll rate. The forthcoming lessons on 'Aircraft Structural Limits' and 'Manoeuvring' will expand on these points.

The following diagram shows a comparison between the 'lift graphs' of two wings with the same area and aerofoil section but with different aspect ratios. Note that the high aspect ratio wing attains its lift at lower angles of attack (Figure Forty one):

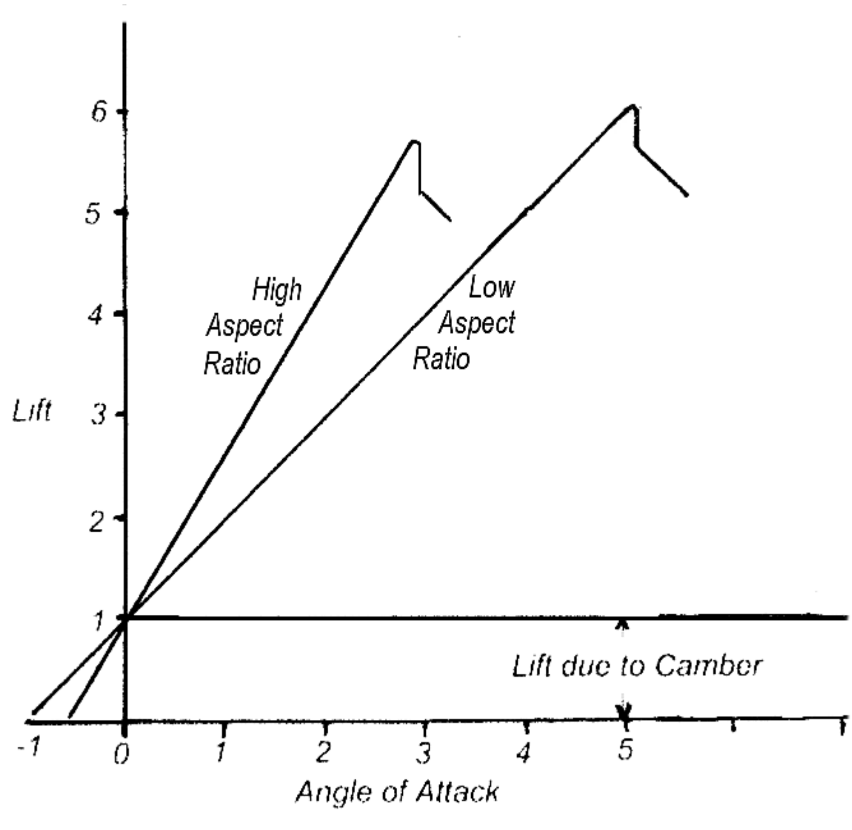


Figure Forty One – Graph of Lift of two Different Aspect Ratio Wings

Picking the aspect ratio most suitable for the purpose of the aeroplane is the designer's job. A modern light training aeroplane usually has an aspect ratio of between 6 and 8. A modern Jet Fighter has an aspect ratio of about 3, whilst a high performance 'sailplane' can have an aspect ratio as high as 40!

Okay that concludes the lesson on lift, but there is one last thing I need to mention. I have avoided confronting you with a formula that flight instructors love to present to their students at an early stage of their training. It is usually presented during their description of how lift is created by a wing, and since you will encounter it, I have put it into Annex C with a full description of how it is derived, the meaning of each term, and its applicability, from an aviator's point of view, in actually flying an aeroplane.

List of Annexes to the lesson on: LIFT

Annex A. A Modern Wing Section

Annex B. Momentum Formula

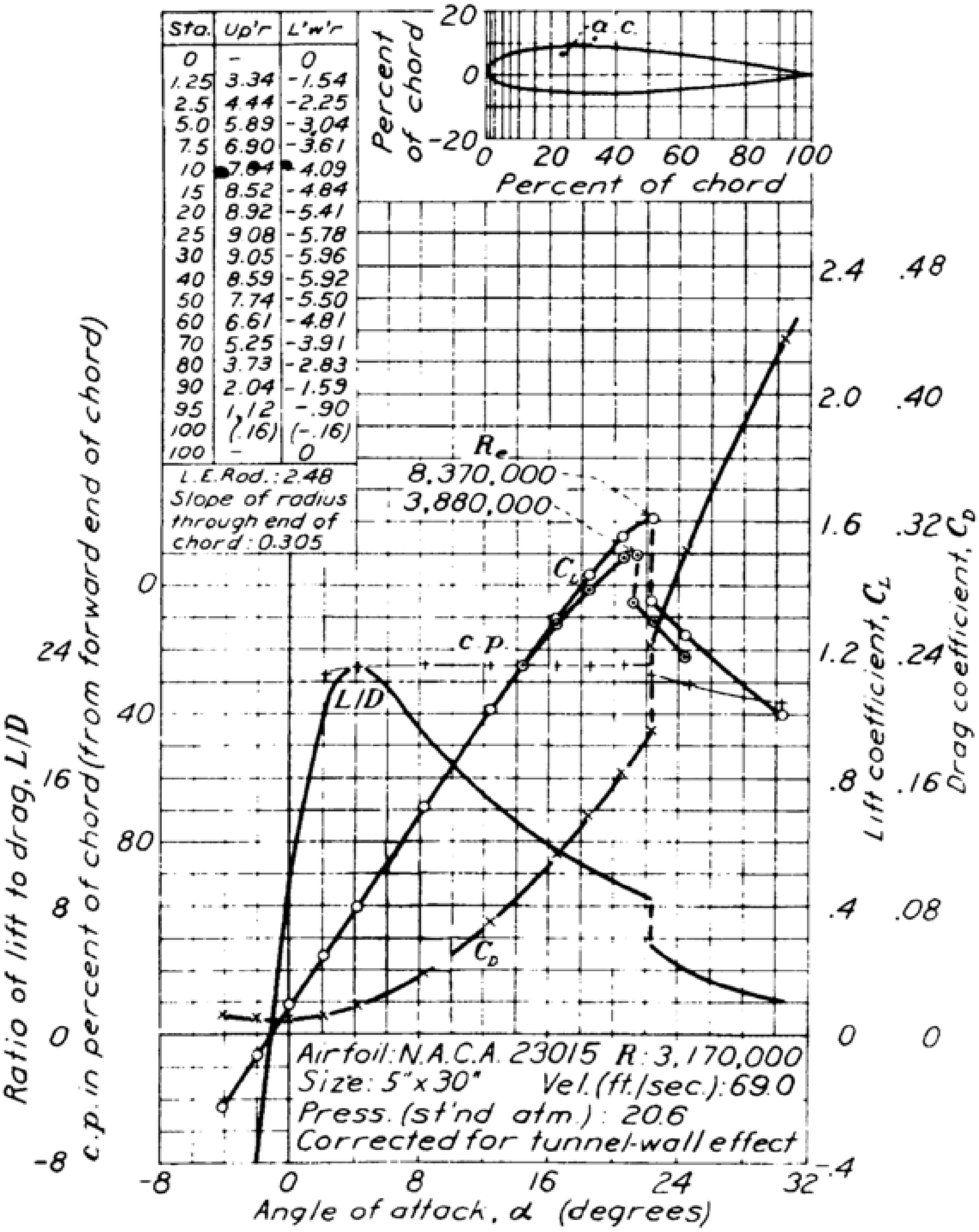
Annex C. The Lift Formula

Annex D. The Bernoulli Principle revisited

Annex A

A Modern Wing Section

Note the completely flat graph of the position of the Centre of Pressure (CP).



N.A.C.A. 23015

N.A.C.A stands for 'National Advisory Committee for Aeronautics' and the number 23015 assigned to this wing section means is has 2% camber (first digit) reaching this amount 30% of the chord back from the leading edge (second and third digit) and the whole wing section has a 15% 'thickness/chord' ratio (fourth & fifth digits). This wing section and its slightly thinner brother the 23012 section have become very popular on modern light aircraft because of their predictable and benign characteristics at all angles of attack. (Note that the 'zero lift A/A' is about -2º.)

Also note what happens to the lift and the drag at and beyond the critical angle of attack. The two 'peaks' in the Lift graph depict the two different 'Reynolds Numbers' at which the wind tunnel tests were conducted.

I guess at this point I should explain as simply as I can what Reynolds Number means. Reynolds Number is a number used primarily when conducting wind tunnel experiments on aerodynamic shapes (like wing sections or whole aeroplanes) to establish a reference point for the size of the curved surface the airflow is following (referred to as the 'scale effect') and the 'viscosity' (stickiness) of the air! It is a number that represents the ability of the air to stick to a curved surface (the Coanda effect) and not separate. It depends upon the velocity of the airflow, and the density and viscosity of the air, and the size of the curved surface it is following. The Reynolds number (**R**) is determined by the following formula:

$$\mathbf{R} = \mathbf{V}\, \boldsymbol{l}\, \boldsymbol{\ell}/\boldsymbol{\mu}$$

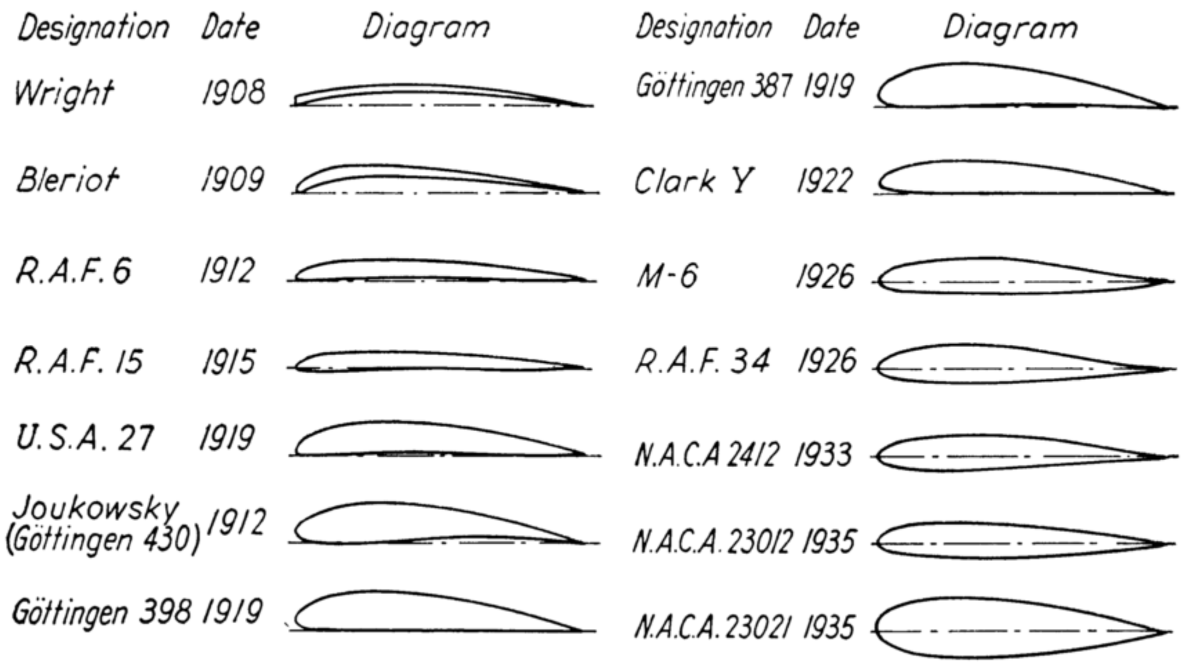
Where **V** is Velocity, ***l*** is a representative dimension of the aeroplane (usually the wingspan), ℓ is the density of the air and μ is its viscosity.

In a wind tunnel small models of aeroplanes are used. These models may resemble their much larger counterpart but can be a hundred times smaller, so air molecules, which don't change size, react differently when flowing around a model compared to when they flow around the real thing. You can see from the formula that if a smaller wingspan is used for ***l*,** **R** will be less, but if the density of the air is increased, **R** can be brought back to the original value. So by adjusting the density of the air in the wind tunnel to produce the same Reynolds number as the full size aeroplane would have in the atmosphere, similar results can be obtained in wind tunnel tests to those that would be obtained on the full sized aeroplane. (The density of the air is increased by using compressed air.)

Also the higher the Reynolds number, the longer the airflow will 'stick' to the top surface of the wing before separating, which means the greater the angle of attack which can be achieved before the wing stalls. So aeroplanes which operate at high speed will have a greater critical A/A than a slow speed aeroplane using the same wing section.

For a light training aeroplane the air density doesn't change too much from day to day within the height band in which they operate, and the airspeed range is not that great either! So we can safely say that the Reynolds Number of a light training aeroplane is always reasonably constant, so variations in wing performance because of changing Reynolds Numbers in the atmosphere are negligible. However it does have an effect on propellers and that will be covered in the lecture on 'Thrust'. (Also the lower 'peak' of the lift curve of the high aspect ratio wing seen in Figure Forty Two in the main lecture is because the 'scale effect' of the wing section causes its Reynolds number to be lower.)

As mentioned in the lesson, the development of 'aerofoil' sections to improve their lifting capability and to remove the wandering centre of pressure was rapid after World War One and by the mid 1930's the sections in current use on modern light aeroplanes had evolved. The following chart shows the development of wing sections from the early Wright section of 1908 up until the NACA sections of the mid 1930's. The 1935, 23012 section is a close relative of the 23015 section shown earlier in this annex. Both are used extensively on modern light aeroplanes:



Historical sequence of airfoil sections.

Annex B

Momentum Formula

The Momentum principle of lift is based purely on Sir Isaac Newton's three principles of motion.

From Newton's second law of motion; when a force (F) is applied to a mass (m) the mass is accelerated (a). This law is expressed by the simple formula **F=ma**. Now acceleration is a change of velocity and velocity is a vector which has both speed and direction. So, to change either the speed or the direction of an airflow you must apply a force, and when either the speed or the direction of a flow does change as a result of this force, an equal and opposite reaction force will be generated in accordance with Newton's third law.

The acceleration (a) experienced by changing the direction of a vector can be calculated by dividing the square of the velocity (v) by the radius (r) of the 'turn', therefore **$a=v^2/r$**. So by substituting **v^2/r** for '**a**' in the first formula we get:

$$\mathbf{F = mv^2/r}$$

The equal and opposite reaction to **F** in the foregoing formula is the total reaction experienced by a wing when it changes the direction of an airflow and can be expressed as:

$$\mathbf{Total\ Reaction = mv^2/r}$$

The lift component of the total reaction is perpendicular to the initial airflow direction and the drag is along the airflow direction. For a given radius of deflection the lift and drag components have a fixed relationship to each other, so, ignoring the drag for the moment, the forgoing formulae can be re-written as:

$$\mathbf{Lift = mv^2/r}$$

It's that simple!

The Facts at a glance

1. Force = mass x acceleration. (F = ma)
2. Acceleration is a change of velocity.
3. Velocity has both speed and direction.
4. A change of direction (turn) is an acceleration.
5. The acceleration of a turn = velocity squared / radius of turn. ($a = v^2/r$)
6. Changing the direction of a fluid flow generates a reaction force.($F = mv^2/r$)
7. Lift is a component of the reaction force generated by changing the direction (turning) of a moving fluid (air), therefore ($L = mv^2/r$).

Annex C

The Lift Formula

Despite the simplicity of the momentum formula detailed in Annex B the 'Lift Formula' presented to student pilots is a little different. This is how it is derived.

The total reaction of a wing comes from changing the momentum of a relative airflow. This relative airflow has 'Energy' by virtue of its motion and this is called 'Kinetic Energy'. Energy is the ability to do work and the work to be done in this case is to lift the aeroplane up against the action of gravity.

From the branch of Physics called 'Kinematics' (detailed in all high school basic physics books) we get the following formula for 'Kinetic Energy' (KE), it is:

$$\mathbf{KE = \tfrac{1}{2}\, MV^2}$$

(Where **M** is the mass of the air deflected by the wing and **V** is the velocity of the airflow, that is, its **TAS**.)

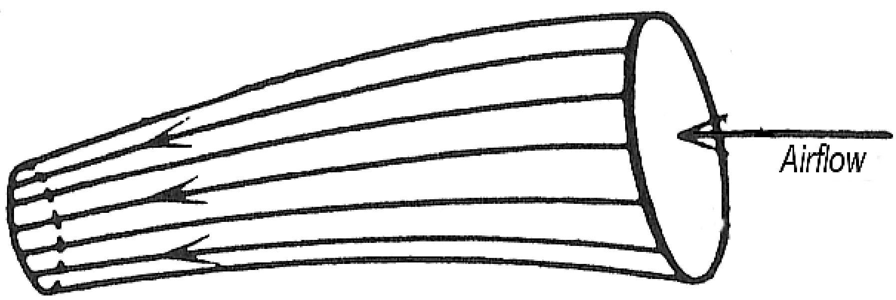
Therefore the 'Total Reaction' of a wing when the Kinetic Energy of the airflow is used to do the work of lifting an aeroplane can be expressed as:

$$\mathbf{TR} = \tfrac{1}{2} \times \mathbf{M} \times \mathbf{V^2}$$

Now the **V^2** is easy to determine, but how do we calculate the Mass of the air deflected by the wing? If we multiply the density of the air by the volume of air deflected we would get it - right? So the formula would now look like this:

$$\mathbf{TR} = \tfrac{1}{2} \times \ell \times \mathbf{Vol} \times \mathbf{V^2}$$

(ℓ is the Greek letter 'Rho' pronounced "Row". It represents the air density.)
But we have only shifted the question haven't we? The question now is "how is the volume of air deflected by the wing determined?" Consider the following diagram:



Aerodynamicists call this a 'Stream Tube' and it represents the volume of air which flows past the wing and is deflected by the wing in a certain time. The length of the tube can be calculated by dividing the velocity of the flow by the time (V/t), but determining the area of the end of the tube is rather difficult. This area is influenced by the surface area of the wing (S) and its angle to the airflow (frontal area) and its aspect ratio, whilst the curvature of the tube is influenced by the angle of attack and the camber of the wing.

Also this 'stream tube' only represents the volume of air directly in the path of the wing and takes no account of the air out side of the 'tube' which is also influenced by the wings passage out to some distance. So all we can say is that the volume of air deflected is 'somehow influenced' by the wing area (S), which is fixed, and the A/A which isn't. So putting the fixed component (S) into the formula we get:

$$\mathbf{TR = ?} \times \tfrac{1}{2} \times \boldsymbol{\ell} \times \mathbf{S} \times \mathbf{V^2}$$

The question mark is the effect that the A/A has on the volume, but before we try to include it we must also take into account the effect of the wing camber. Trying to come up with a mathematical way of measuring the effect of A/A and camber on volume and deflection angle in the final calculation of TR is a difficult job, so this unknown combined value is added to the formula as a 'coefficient' (C). (A coefficient is defined as a "factor that measures a property." Meaning "we don't know what the hell it is but let's give it a symbol!"). So now we have:

$$\mathbf{TR = C} \times \tfrac{1}{2} \times \boldsymbol{\ell} \times \mathbf{S} \times \mathbf{V^2}$$

But we still don't know the value of 'C' do we? So how can we work out TR!? The value of 'C' is measured in a very practical way. Since all of the other factors in the formula are known and can be set up pretty accurately in a wind tunnel, the aerodynamicists, having set them up, position the wing at a particular A/A, run the tunnel and measure the actual total reaction force being created and then work the formula backwards to determine 'C' at that A/A, like this:

$$\mathbf{C = TR} \div \tfrac{1}{2} \times \boldsymbol{\ell} \times \mathbf{S} \times \mathbf{V^2}$$

If this is done over a range of angles of attack, **'C'** can be determined and recorded for each angle. Using this recorded data the TR can be calculated for each angle of attack when any of the other factors in the formula vary without having to resort to wind tunnel testing all of the time. Here is the formula again:

$$\mathbf{TR = C\ \tfrac{1}{2}\ \boldsymbol{\ell}\ V^2\ S}$$

But it is not quite over yet! Having a way of calculating the Total Reaction still leaves us with the question "which component of TR is Lift and which is Drag?" If the TR was at exactly 90º to the chord the answer could be calculated using simple trigonometry but as we have already learned, the 'squishiness' of the air and the camber of the wing section cause it to be at an angle other than 90º and we can't be sure exactly what it is. So how do we calculate it? We don't! Since the Lift and Drag produced by a wing are components of the Total Reaction it follows that their coefficients must be components of **'C'**, so when the aerodynamicists run the wind tunnel they don't just measure the Total Reaction they measure the force 90º to the airflow, which is Lift and the force parallel to the airflow, which is Drag and assign a different coefficient to each of them. So 'C' for Lift becomes 'C_L' and 'C' for Drag becomes 'C_D'. This approach splits the TR formula into two formulas, one for the Lift component and one for the Drag component, and they are:

$$\mathbf{L = C_L \tfrac{1}{2} \ell V^2 S}$$

$$\mathbf{D = C_D \tfrac{1}{2} \ell V^2 S}$$

$\mathbf{C_L}$ is called the 'Coefficient of Lift' and $\mathbf{C_D}$ the 'Coefficient of Drag'.

When these wind tunnel measurements are done throughout the full range of angles of attack a 'C_L versus A/A' graph can be plotted as can a 'C_D versus A/A' graph (we will deal with C_D in a later lecture). Now we have already seen this 'C_L versus A/A' graph a few times in the main part of the lecture except that I simplified it and called it a 'Lift versus A/A' graph. (This is legitimate if none of the other factors in the formula change.) Also the chart at Annex A is an example of an actual 'Wing Characteristics Chart' showing these graphs (and some more we will come to in a later lecture).

These charts define the lift and drag characteristics of a particular wing section and the data contained therein can be extracted and applied to wings of different sizes and at different speeds and air densities as required. Obviously this process has to be carried out for every different wing section and the current range of 'Wing Characteristics Charts' created by aerodynamicists would fill a large telephone book! These charts enable the designers of aeroplanes to choose a wing section that best suits the type of aeroplane they are designing.

So having seen how this formula is created, of what use is it to an aviator? Or to put that question another way, which parts of this formula does the aviator need to concern himself with and which parts does he have control over whilst in flight?

S? No, except for the possibility that the aircraft is fitted with Fowler flaps.

V? Yes, all of the time.

ℓ? No, except for the choice of altitude to fly at.

C_L? Yes, all of the time through control of the A/A and when the flaps are used.

The aviator has immediate, direct, and very positive control of C_L, primarily by way of control of the angle of attack of the wing, but also, in a limited sense, its camber when flaps are used. The aviator also has immediate and direct control of the airspeed, so from an aviator's perspective the formula could be written in a more usable form as:

$$\mathbf{L \propto A/A} \times \mathbf{V^2}$$

Obviously the lift is now only 'proportional' to **A/A** and **V** as the aviator has no way of calculating the actual lift force without knowing the other factors. But there is no need to; he or she already knows how much lift is being developed by the wing, because when the aeroplane is flying level the lift equals its weight, and the lift will vary as a factor of this weight in accordance with this simplified formula when either A/A and/or airspeed are varied. <u>That is all the aviator needs to know.</u>

Annex D

The Bernoulli Principle revisited.

In the main text of this lesson I said that the air flows around the wing in such a way that the *static* pressure over the top of the wing decreases and underneath the wing it increases. Bernoulli's principle therefore requires the *dynamic* pressure over the top of the wing to increase, that is, speed up, whilst the *dynamic* pressure under the wing must decrease, causing it to slow down. This is the reverse of the current, common and incorrect way that it is expressed in student pilot texts. Let me restate the correct sequence of events so there is no confusion. *"The static pressure changes caused by deflecting the airflow cause the speed changes"*. NOT the other way around!

The current teaching in most flying schools is that the air molecules flowing over the longer top surface of a wing have to go faster in order to meet up with those they were with before they were split up and which are now flowing under the shorter lower surface and as a result there has to be a static pressure change and the difference in the two static pressures is the lift!

Why do they have to meet up again? Are they married or do they just have a 'date'? There is no scientific principle that supports this supposition, and don't blame Bernoulli, he never said it.

But let us, for a moment, go along with this molecular 'dating' principle. The supposition is that the top molecules have to accelerate to a higher speed because the distance over the top of the wing is further than under the wing, which completely ignores symmetrical wing sections, yacht sails and birds wings, but we have already decided to play the 'dating game' so let's see how much further they have to go.

To aid the arithmetic I am going to create a simple cambered wing section from the segment of a circle (Similar to the 'Paradox aerofoil' of 1910).

If we take a circle and divide it up into six segments we get a hexagon. Now the sides of a hexagon are the same as the radius of the circle we have just created, so if we use just one segment of the circle as our wing section it has a chord equal to the radius and an upper curve equal to one sixth of the circumference as shown in the following diagram (Figure One):

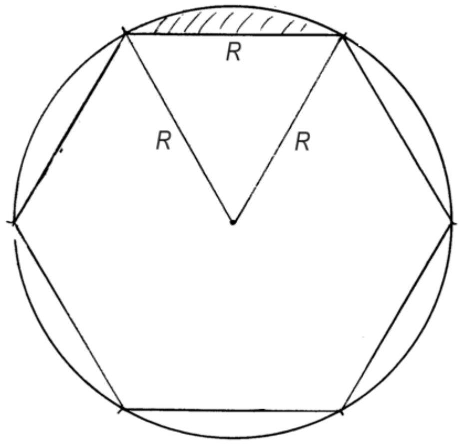


Figure One – Segments of a Circle

The circumference of the circle is given by the formula C = 2πR which is very nearly 6.28 times its radius so 1/6 of this is 1.047. This means that 1.047 is the ratio of the distance over the top of our wing to the distance along the bottom (Figure Two).

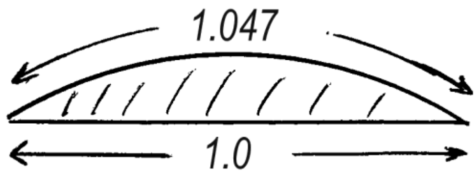


Figure Two – Top to Bottom Distance Ratio

Putting that another way; the top surface is 4.7% longer than the bottom surface, which means that in order not to be late for their 'date' the top molecules have to go 4.7% faster than those 'cute' bottom molecules (Figure Three).

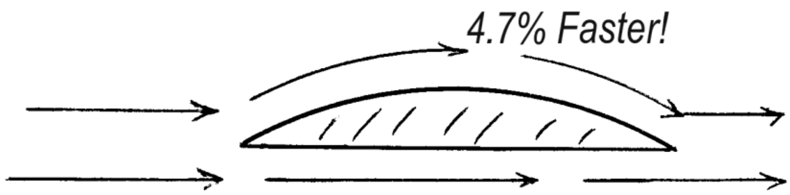


Figure Three – Top to Bottom Speed Difference

This wing section that we have created also has a thickness/chord ratio of 13% and a camber of 6.5%, so it is a pretty 'fat' wing by modern standards.

Now dynamic pressure increases as the 'square' of the speed increase, so this means that the airflow over the top of the wing will have a 22.09% increase in the dynamic pressure (4.7 x 4.7 = 22.09).

In the earths atmosphere the average sea level pressure is 14.7 pound per square inch (psi) which equates to 2116.8 pound per square foot (psf), so we can say that the static pressure portion of the total pressure surrounding our wing is 2116.8 psf and to that we have to add the dynamic pressure component caused by the air speed in order to arrive at the total pressure on the wing. The dynamic pressure is obtained with the formula; **$\frac{1}{2} \rho V^2$**, where 'ρ' is the air density and 'V' is the True Airspeed in feet per second (Knots x 1.69 = feet per second).
Now since air density is proportional to its weight it is necessary to involve the acceleration due to gravity when defining it. Since Mass is expressed in units with a rather odd sounding name, a 'Slug', so air density which is Mass/Volume is expressed as 'Slugs' per cubic foot! The air density (ρ) at sea level is the weight of one cubic foot of air at sea level (0.0765 lbs) divided by the acceleration due to gravity (32.2 ft/sec/sec) which equals 0.002376 'slugs' per cubic foot. If you are not mathematically inclined and are feeling a little 'lost' at this point, don't panic we are through the worst of it.

Now let's assume that our aeroplane is doing 120kts TAS, so putting all of these numbers into the formula we get the following:

$$\begin{aligned}
\text{Dynamic pressure} &= \tfrac{1}{2} \rho v^2 \\
&= \tfrac{1}{2} \times .002376 \times (120 \times 1.69)^2 \\
&= \tfrac{1}{2} \times .002376 \times (202.8)^2 \\
&= \tfrac{1}{2} \times .002376 \times (202.8 \times 202.8) \\
&= \tfrac{1}{2} \times .002376 \times 41127.84 \\
&= \tfrac{1}{2} \times 97.72 \\
&= 48.86 \text{ lb/ sq ft}
\end{aligned}$$

Therefore an aeroplane doing 120 knots TAS experiences a dynamic pressure of 48.86 psf. So we add the result of this formula to the static pressure to get a total pressure of 2165.66 psf (2116.8 + 48.86). With me so far?

The dynamic component of the total pressure is 2.25% (48.86 ÷2165.66) and the difference in dynamic pressure of our 'dating' molecules is 22.09% of this 2.25% which is .497% of the total pressure, or 10.76 psf. Therefore the difference in static pressure created between the top and bottom of our wing is also 10.76 psf. And that is Bernoulli's principle. Follow that?

What all this means is that every square foot of the wing is supporting 10.76 lb, so to be able to support and aeroplane of 2000 pounds weight it would have to have a wing area of 186 square feet.

This calculated wing area is about what you would expect to find on the average 2000lb aeroplane. However, the wing we have created has a 6.5% camber whereas the modern wing section detailed in Annex A has only 2% camber, which means our 'dating' top molecules don't have as far to go on this 'real' wing and yet somehow they must speed up just as much?

The sums don't add up, do they? Maybe they aren't dating?

Of course all of these sums were just figuring out the amount of lift needed for level flight (at zero degrees A/A for this highly cambered wing). When we need to manoeuvre the aeroplane we need a whole lot more lift (for reasons I will explain in the lesson on manoeuvring) and we get that extra lift by increasing the angle of attack. To double the lift of the wing using this 'Bernoulli Theory' the top molecules would have to have twice the dynamic pressure they have in our calculations (and therefore proportionally less static pressure) which means they would have to travel 41% faster and therefore travel 41% further wouldn't they? Somehow the camber would have to increase dramatically (and those bottom molecules would need to get a whole lot 'cuter').

How does that happen? What path do the molecules follow to achieve this extra speed? The answers to these questions are not taught in most flying schools because their 'Bernoulli Theorem' falls down at his point and won't give them the answers!

What actually happens is that the increasing angle through which the airflow has to turn as the A/A increases causes the static pressure under the wing to increase and the static pressure above the wing to decrease, which then causes a dynamic pressure decrease under the wing and a dynamic pressure increase above the wing such that at twice the angle of attack the airflow over the top of the wing is 41% faster. All of this is in accord with Bernoulli's principle and all of this occurs as a byproduct of creating more and more lift by deflecting the airflow more and more. (Once again the angles are exaggerated for clarity. Figure Four.)

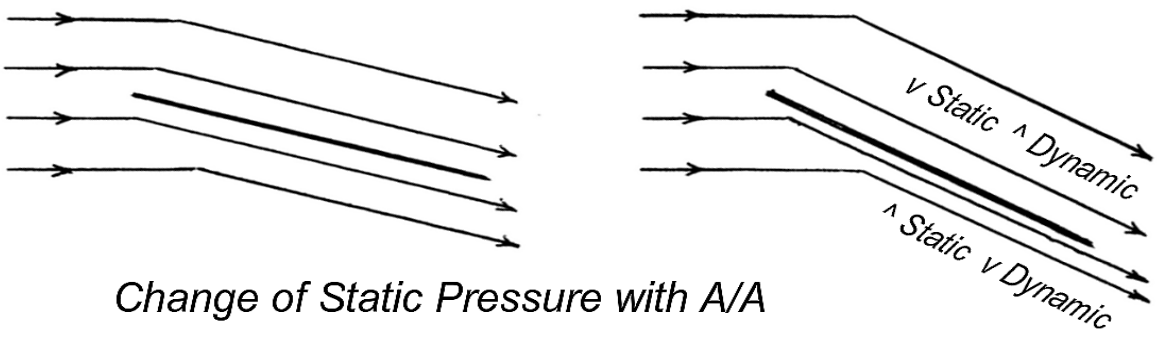


Figure Four – Change of Static & Dynamic Pressure with A/A Change

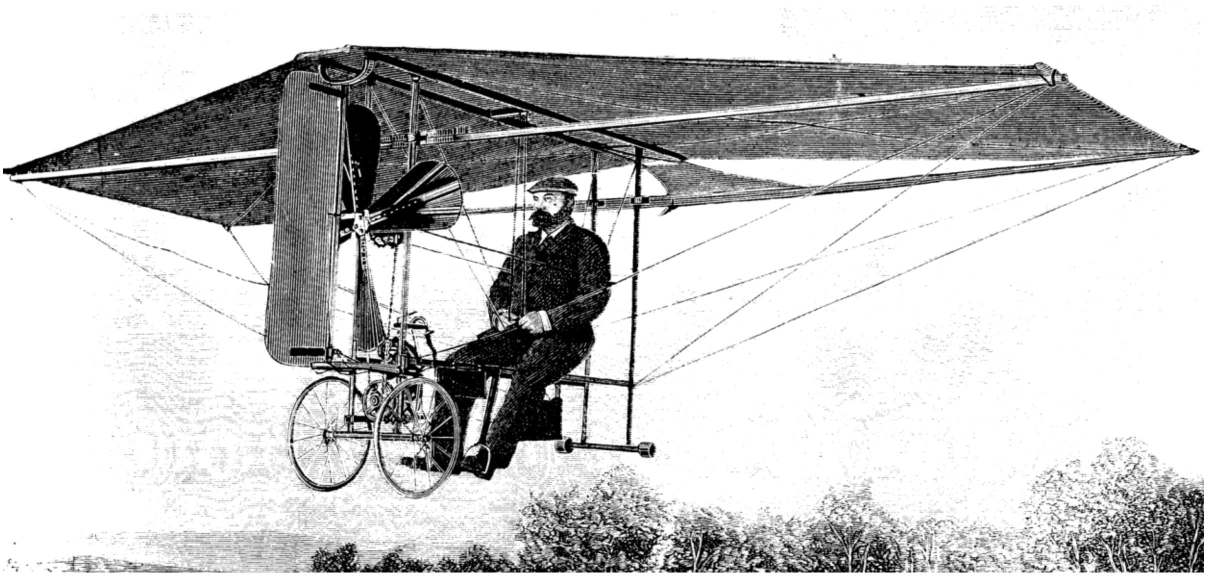
Unfortunately the 'Bernoulli Theory' of lift production which has been taught by many generations of flight instructors has taken on the character of a 'paradigm' and any alternative view is vehemently resisted by its proponents.

So, if for no other reason than ease of instruction, let me say to future generations of flight instructors that the ‘Momentum Theory’ of lift production is easier to teach because it is based upon the more general principles of motion and forces and cause and effect that are a common part of everyday life. (Even if students are unaware of Newton’s Laws of Motion as written, they have certainly experienced them every day of their lives.)

Flying Instructors: one of the first principles of teaching anything is to ‘work from the known to the unknown’. The so called ‘Bernoulli theory’ of lift violates this most fundamental teaching principle because virtually no one, prior to entering a flying school for the first time, has ever experienced or has the foggiest idea who or what Bernoulli is!

Lesson Three

DRAG



The early pioneers of aviation called the resistance to their headway through the air, ‘Head Resistance’, which I think is a great term because it needs no further explanation. We are all familiar with it; ride a bicycle on a still day and feel the relative airflow around you resisting your ‘headway’ (forward movement). Pedal twice as hard and note you are not going twice as fast. There is that ‘squared’ function again, just like we saw when developing lift. So to go twice as fast you will need to pedal four times harder! Gasp! In the case of an aeroplane this ‘pedaling’ has to be done another way, that is, by some means of thrusting the aeroplane along against this resistance. How this is done will be covered in the lecture on Thrust, but for now I simply want you to understand that the thrust must equal the resistance if the aeroplane is going to maintain its speed. So as we talk about the various types of drag bear in mind that this also means ‘thrust required’.

Nowadays the ‘head resistance’ of an aeroplane has been divided up into various categories and given various names like:

1. Profile Drag or Form Drag - terms given to the drag caused by the general size and shape of the cyclist or aeroplane pushing through the air.

2. Skin Friction - a term given to the drag caused by the surface texture of the cyclist’s clothing or the aeroplane’s skin causing friction with the air.

3. Parasite Drag - a term given to the drag caused by ancillary devices which ‘stick out’, like rear view mirrors or radio antennas.

4. Interference Drag - a term given to the drag created by the junction of two parts of the aeroplane, where airflows of different speeds meet and cause turbulence, e.g. where the wings join the fuselage.

5. Leakage Drag - caused when air flows out of gaps in the airframe and meets the surrounding airflow, causing turbulence.

6. Propeller Drag - this one comes and goes because, when the engine is delivering power, the thrust produced by the propeller balances the drag, but when the engine is throttled (or failed!) the ‘wind milling’ propeller produces a significant amount of drag. (More on propellers in the lesson on Thrust.)

There are other categories too esoteric to list. I believe that most of them are rather academic and unnecessarily confusing.

An aeroplane in a vertical dive experiences all of these different sorts of drag to some degree or another and only these. Why a vertical dive? Because in a vertical dive the wings are set to an angle of attack where they are not generating lift (Zero Lift A/A). If they were, the vertical flight path would be deflected from the vertical (Newton’s second Law), but it is not, so they aren’t. So what? Well when wings generate lift they also generate another unique sort of drag that I want to exclude from the discussion for the moment. (I will come back to this type of drag shortly.) So our vertically diving aeroplane is experiencing all of those previously mentioned types of drag at zero lift, so I am going to lump all those drag categories and names together and give them an all-encompassing and more modern name, “Zero Lift Drag”.

Now as I have said, zero lift drag (ZLD) increases as the square of the airspeed. To help you picture this I have drawn a simple graph of this drag and how it increases with increasing airspeed. (See Figure One.) Note that at 50kts the aeroplane has a ZLD of ONE, but by the time it has accelerated to 100kts (twice as fast) this drag has increased by a factor of FOUR (2^2) and at 150kts (three times as fast) it has increased by a factor of NINE (3^2). If the aeroplane was capable of flying to 200kts, that is, four times as fast as its starting speed the ZLD would have increased 4^2 times, a factor of SIXTEEN! (The graph at Figure One showing this would be off the chart and at about the top right hand corner of the page.)

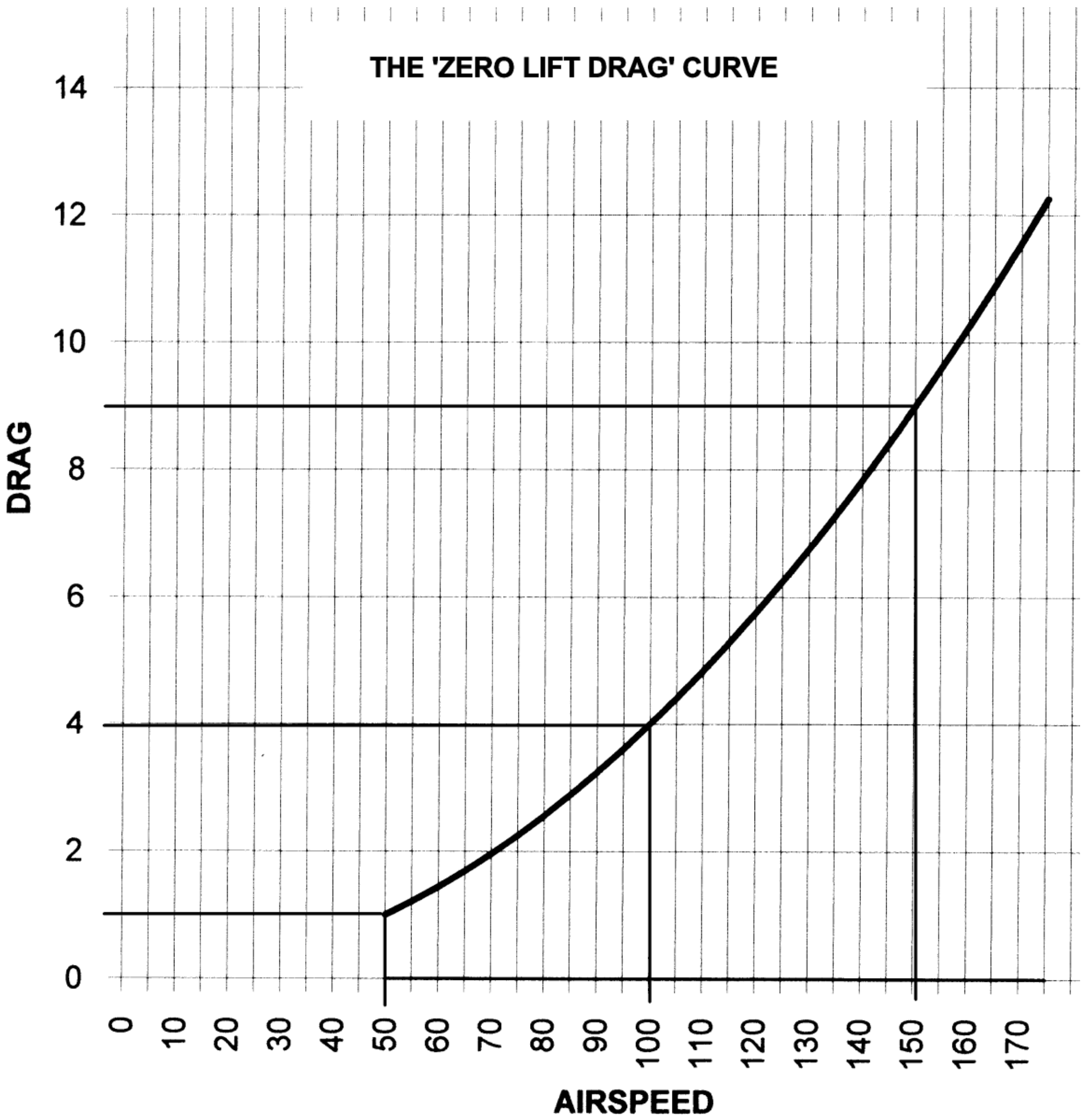


Figure One – ZLD Increase with Increasing Airspeed.

Now remember, this graph also represents the thrust required to fly at these various airspeeds, so if we double the thrust from our engine/propeller we will only go 40% faster! By the end of World War Two piston engine fighters were nearing the limit of their speed capability and a newer, more powerful, form of thrust was required. The turbojet engine filled that requirement but there is still an upper limit to the speed which can be efficiently attained in the earth's atmosphere. At three times the speed of sound the skin friction component of the zero lift drag causes temperatures so high that aluminium aeroplanes melt! So there are only a few very special aeroplanes that fly that fast. The MiG31, the Lockheed SR71 'Blackbird' and the Space Shuttle are all that come to mind. There is a formula for calculating the actual zero lift drag of an aeroplane which I have detailed in Annex B.

What about this other type of drag which comes from creating lift? I alluded to it in the lecture on Lift. It is the rearward component of the total reaction. Here is a repeat of one of those lift diagrams showing this unique drag component (Figure Two).

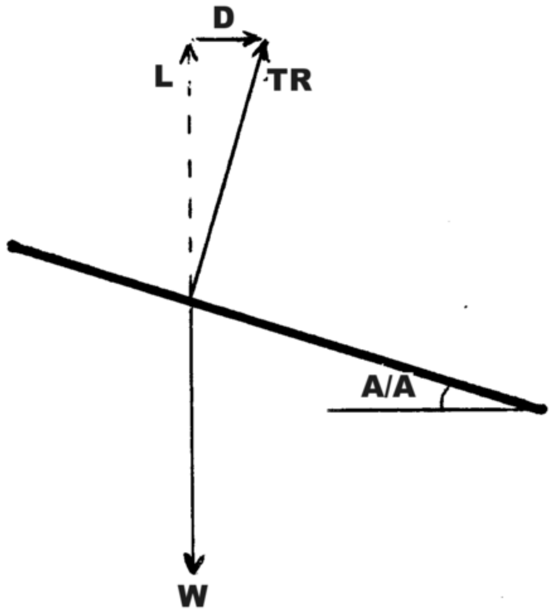


Figure Two – Drag Component of Total Reaction

The drag component of the total reaction was once called the ‘Drift’ and the ratio of Lift to Drift was (and still is) a measure of the efficiency of a wing. The Wright brothers would fly their 1900 glider like a kite and measure the angle of the kite ‘string’ at different angles of attack. The angle of the ‘string’, with the help of simple trigonometry, gave them the Lift to Drift ratio. (Like I have said previously, “clever guys”.) See Figures Three and Four.

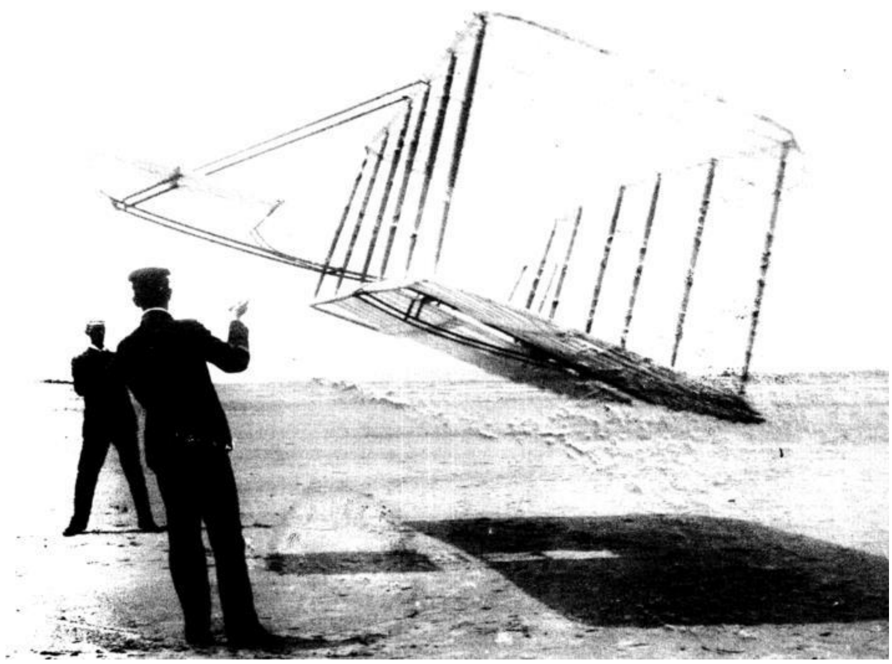


Figure Three – Kite Flying, Wright Brothers Style.

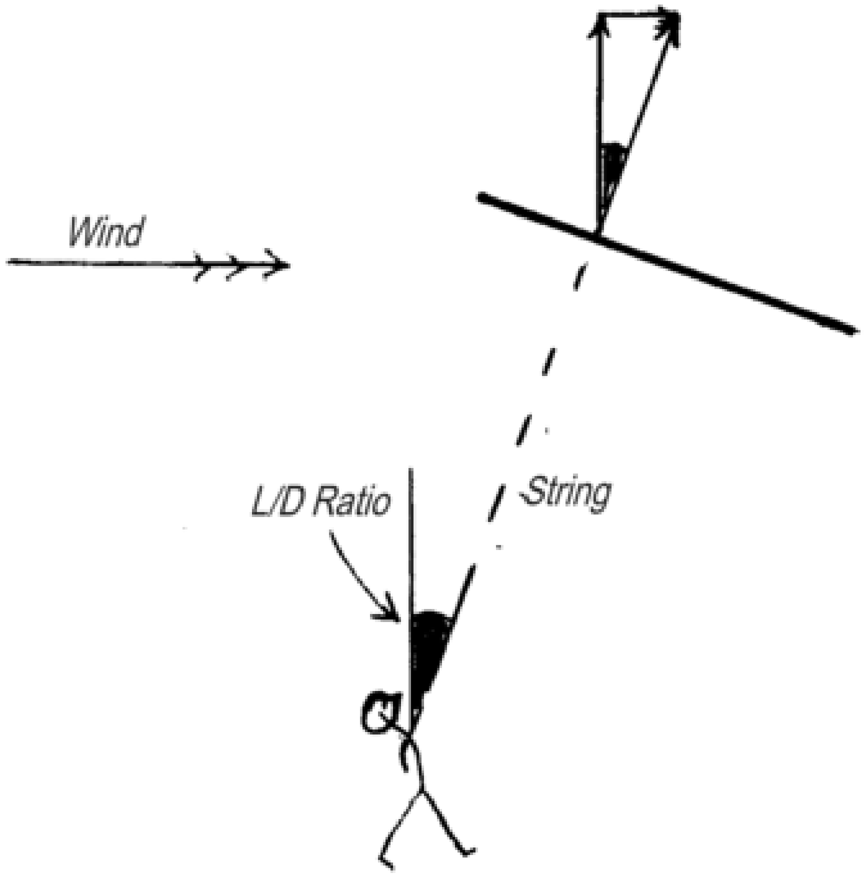


Figure Four – Measuring the Lift to Drift Ratio.

I love the terms 'head resistance' and 'lift to drift ratio' as I think they are more descriptive than the modern terms. Indeed I am going to keep using the term 'lift to drift ratio' in order to remove an area of confusion which is still prevalent amongst pilots, and which I will come to a little later.

Nowadays the drag component of the total reaction is called 'Lift Dependent Drag' or 'Lift Induced Drag' (LID), usually shortened to just 'Induced Drag'. (Which tends to remove its meaning don't you think?) Induced drag is a byproduct of producing lift with a wing. It cannot be made to go away with the addition of winglets or special wingtips as some people would have you believe because it comes from the entire wing and the only way to make it go away is to make the total reaction go away, which kind of defeats the whole purpose of the wing in the first place! I will discuss what happens at the wing tips a little later.

We have already seen how the formula for calculating the actual induced drag is derived in Annex B to the lesson on 'Lift'. But remember this derivation applies only to Induced Drag. Here it is again:

$$\textbf{Induced Drag} = C_D \tfrac{1}{2} \ell V^2 S$$

Now pay attention, this next bit is very important. As we vary the angle of attack of the wing we not only vary the lift but also the induced drag, and unfortunately it varies more than the lift; which can be a bit of a nuisance at times. Here is another exaggerated diagram (Figure Five).

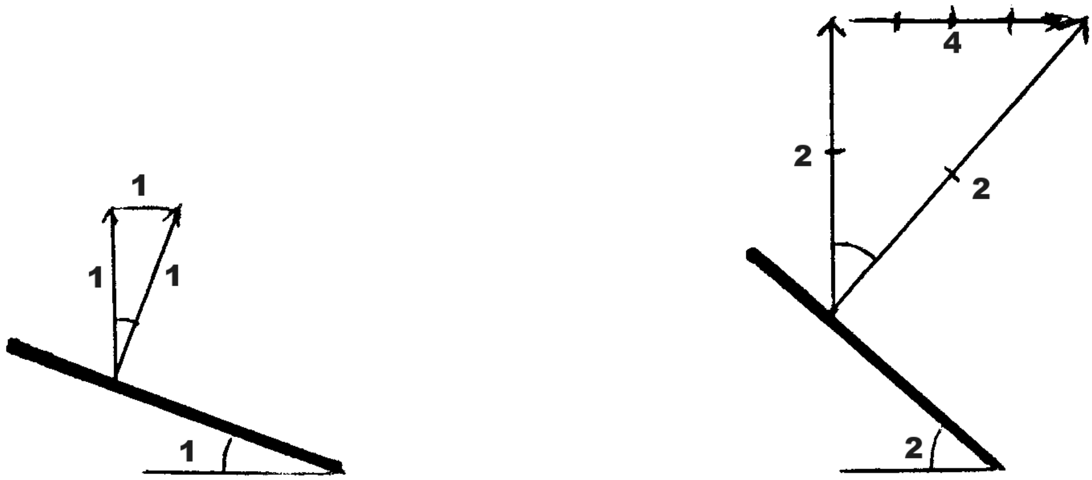


Figure Five – Induced Drag Increase with Increased A/A

Note that if we double the angle of attack, the lift component doubles, but the induced drag component increases four times! This is because the Total Reaction vector both doubles in length and angles back twice as much. So if we want to double our lift to do a tight turn we had better have plenty of thrust on hand to overcome the increased induced drag! (More about the drag effect of turning in the lesson on Manoeuvring.)

Picture an aeroplane flying straight and level at low speed. Because it is flying slowly it must have a high angle of attack and therefore very high induced drag. Now if it speeds up, the aviator, in order to compensate for the increasing lift so that it will remain in level flight, must progressively reduce the angle of attack. This will cause the induced drag to diminish rapidly. "What's that?" you say! The drag reduces as we go faster!! Yes.....I told you it was unique. Here it is graphically at Figure Six. (I have drawn this graph on the same scale as the ZLD graph for reasons which will become apparent shortly.) Note that at 50kts airspeed the drag is FIVE, but at 100kts (double speed) the drag has diminished to 1¼ ($5 \div 2^2$):

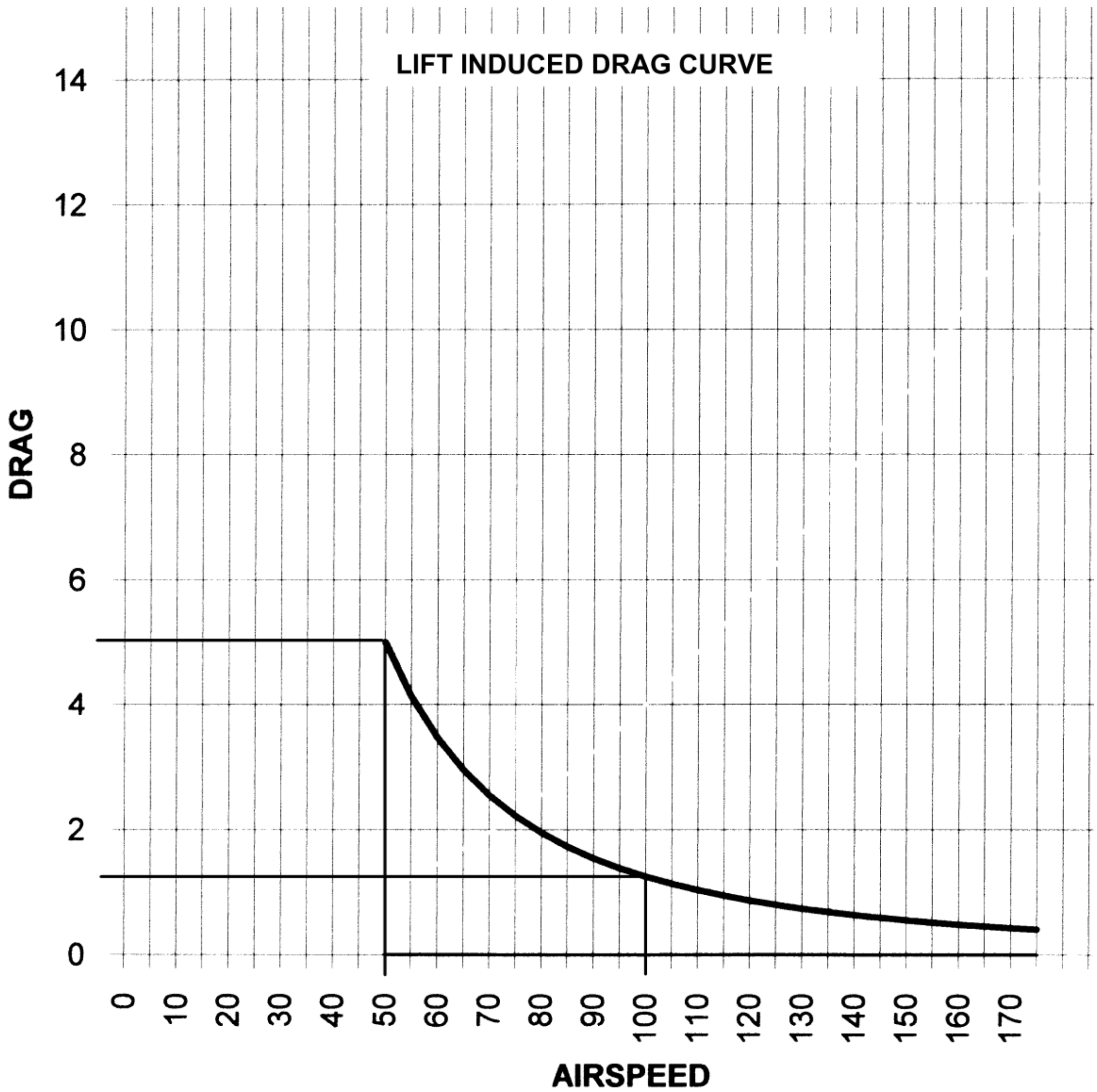


Figure Six – Lift Induced Drag versus Airspeed Graph

Interesting huh? I lied about this effect being unique; there are other craft that experience it - craft that use hydrodynamic lift like a water ski. Put a water ski on and step off the jetty, you will sink. A water ski develops hydrodynamic lift by being pulled across the surface of the water at speed. It only develops its total reaction by deflecting water molecules with its bottom surface, but since water is much denser than air (more molecules in a given volume) it works well enough. (If you do a deep water start on a single water ski you will feel the induced drag as the boat tries to pull your arms out of their sockets!)

An aeroplane in flight at any particular speed is experiencing, simultaneously, head resistance and drift – sorry, Zero Lift Drag and Lift Induced Drag. So to get a clear picture of the total drag acting upon the aeroplane at any speed we have to superimpose the two graphs upon one another and see what we get. Here is that graph (Figure Seven).

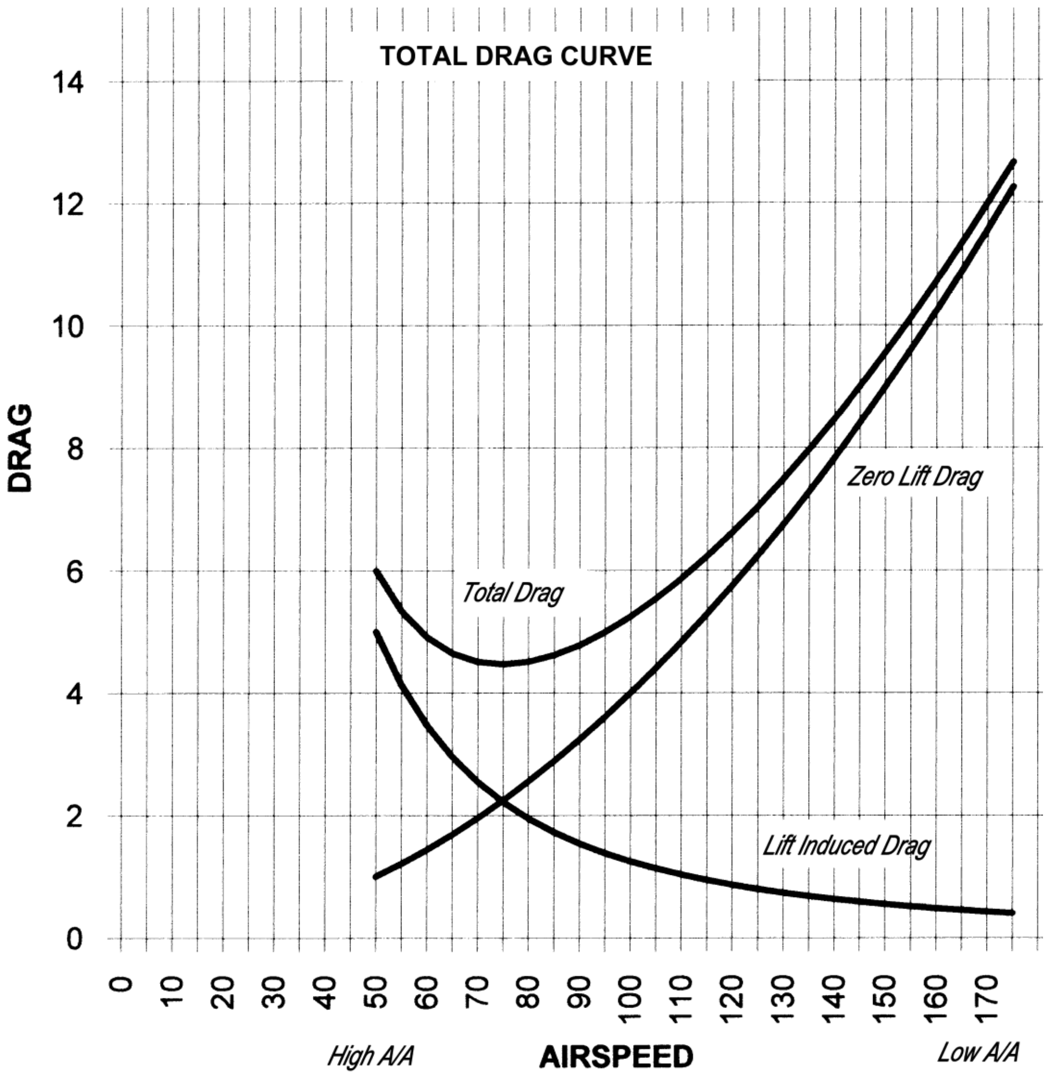


Figure Seven – ZLD, LID and Total Drag Graph

The third line in the graph, which I have labeled "Total drag", is just that, it is the sum of the ZLD and the LID at any speed. It is interesting to study this graph for a little while. It is obvious that on the right side of the graph (the so called 'front side') the increasing total drag places a limit on how fast we can fly, but interestingly the increasing total drag on the left side (the 'back side') places a limit on how slow we can fly too! This is a strange situation where we need more thrust to fly slowly at 50kts than we do at 75kts! Early pioneers of flight would get airborne on the 'backside' of this drag curve and find the drag reduced as they got faster. This was completely counter intuitive and it took them a while to figure out what was going on. I once had a friend who was, in his youth, a very 'gung ho' fighter pilot, who once declared, "You haven't lived until you have had to 'light up' full afterburner whilst turning final!" He obviously got too slow and too far onto the 'backside' of the drag curve and needed all of the thrust at his command to accelerate out of trouble. Pilots continue to get into trouble with this phenomenon because they don't understand it and therefore can't anticipate it. There will be more about this in the lesson on manoeuvring.

It follows from the shape of this total drag curve that there is a speed at which the drag is at a minimum, which is at the bottom of the curve. This speed is called the “minimum drag speed”. (At last, a descriptive term that has survived modernization!) The minimum drag speed of your aeroplane is a handy speed to know because it is the speed where you need minimum thrust to fly straight and level and it is also the speed to fly at for maximum range. (See Annex A to the lesson on Power for a more details on Range and Endurance.) You should also note that at the minimum drag speed the ZLD and the LID graphs cross, which means they are equal to one another and each make up 50% of the Total Drag.

Now since the aeroplane is flying straight and level throughout the speed range of the graph, lift is being maintained at a constant, so the Total Drag curve also represents the Lift to <u>Total</u> Drag Ratio (L/D Ratio) throughout the speed range and the minimum drag speed is the speed at which the **best** Lift to <u>Total</u> Drag ratio is attained. The graph at Figure Eight illustrates this.

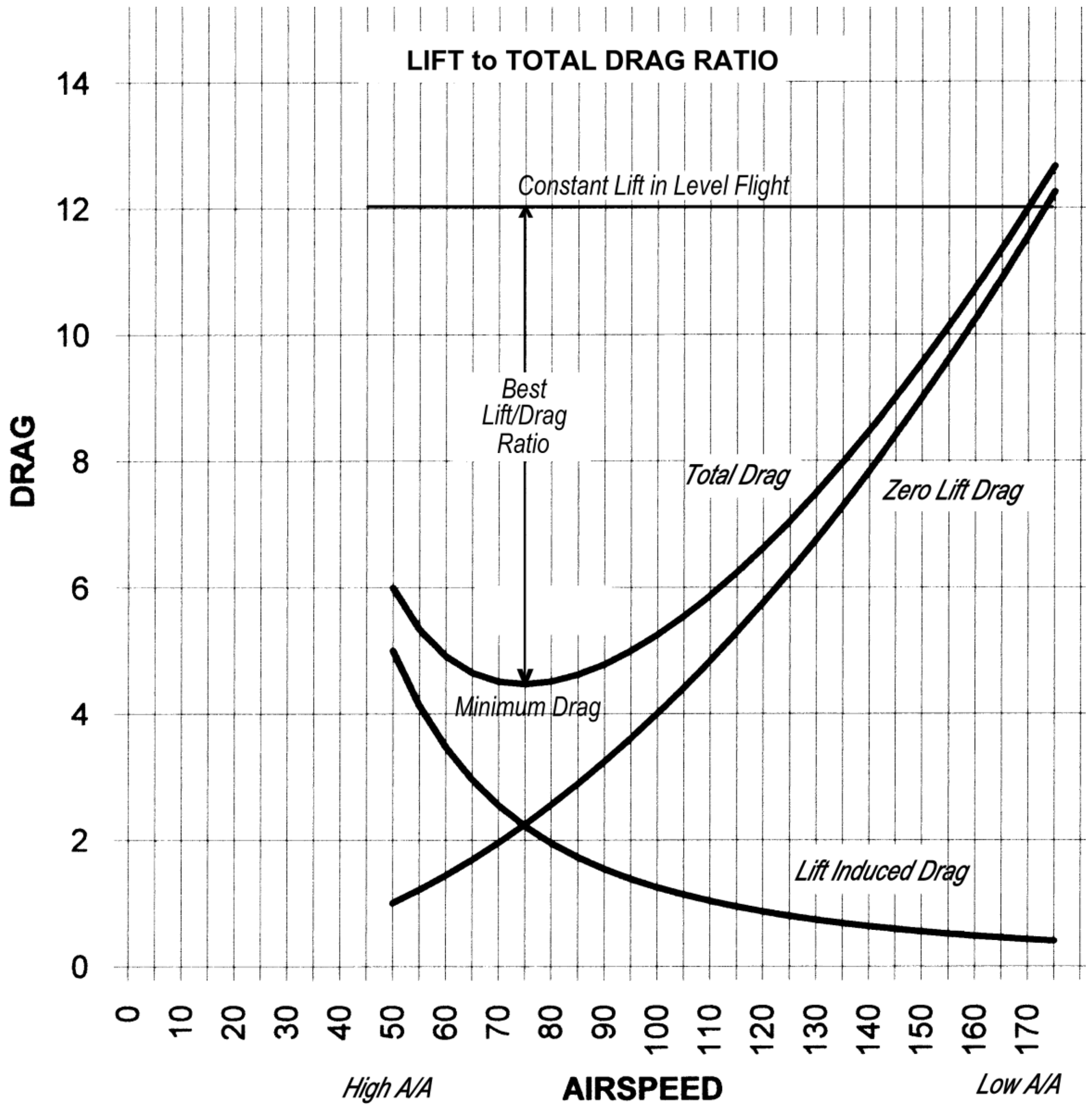


Figure Eight – Airspeed for Best Lift to Total Drag Ratio.

Note: this is NOT the 'lift to drift' ratio, as that pertains only to the wing, but Lift to Total Drag ratio which pertains to the whole aeroplane and includes all of the other components of the aeroplane that do not contribute to the lift but do add to the drag (like the fuselage, wheels and tail etc.).

Unfortunately the two distinctly different L/D ratios have become confused. Many student texts state that the angle of attack for the best L/D ratio is about 4º, but that is just for the wing. Go back and take a look at the wing data in appendix A to the lecture on lift again. You will note the graph for L/D ratio peaks at 4º A/A and corresponds to a ratio of 22:1. This is interesting but not very useful to the aviator. In the 'real world' the best Lift to Total Drag ratio occurs between about 10º and 12º A/A and corresponds to ratios varying from about 10:1 to 14:1 for any particular aeroplane. (Much of this variation depends upon whether the propeller is delivering thrust or 'wind milling' and adding more drag). This is useful knowledge when we are gliding or recovering from a stall. (More on gliding and stalling in future lessons.) At annex C, I have explained where and how this 'L/D Ratio confusion' has come about, and the truth of the matter.

So what is going on at the wingtips? Well, in the process of generating a total reaction the wing causes a static pressure difference between the top and the bottom of the wing. The air at higher pressure at the bottom of the wing 'spills' around the wingtip to the low pressure region and imparts a helical or vortex motion to the airflow which causes the local downwash angle at the wingtip to increase and therefore increases the rearward angle of the total reaction slightly. This greater angle results in an increased rearward horizontal component of the total reaction, that is, greater induced drag. Effectively the vortex reduces the lift to drift ratio at the wingtip. Generating a vortex also absorbs energy from the airflow, which is another way of saying that it increases the drag at the wingtip. This is often called 'Vortex Drag'. Figure Nine shows this diagrammatically.

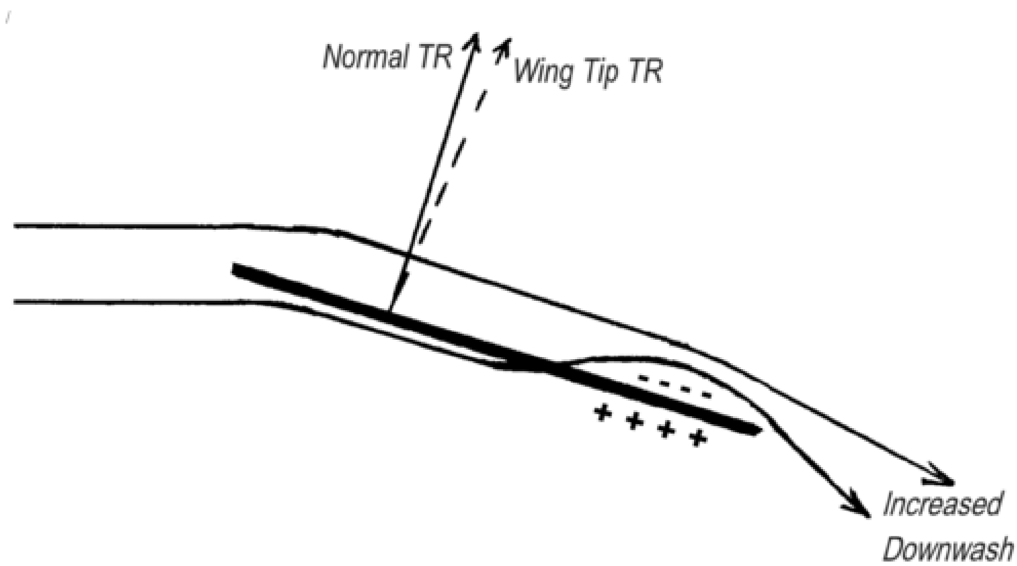


Figure Nine - Side Elevation of Wingtip Vortex.

The forgoing diagram (Figure Nine) shows a side elevation of the wing tip vortex and the following diagram (Figure Ten) is a plan view of the path of the airflow within the vortex and its influence on the rest of the airflow:

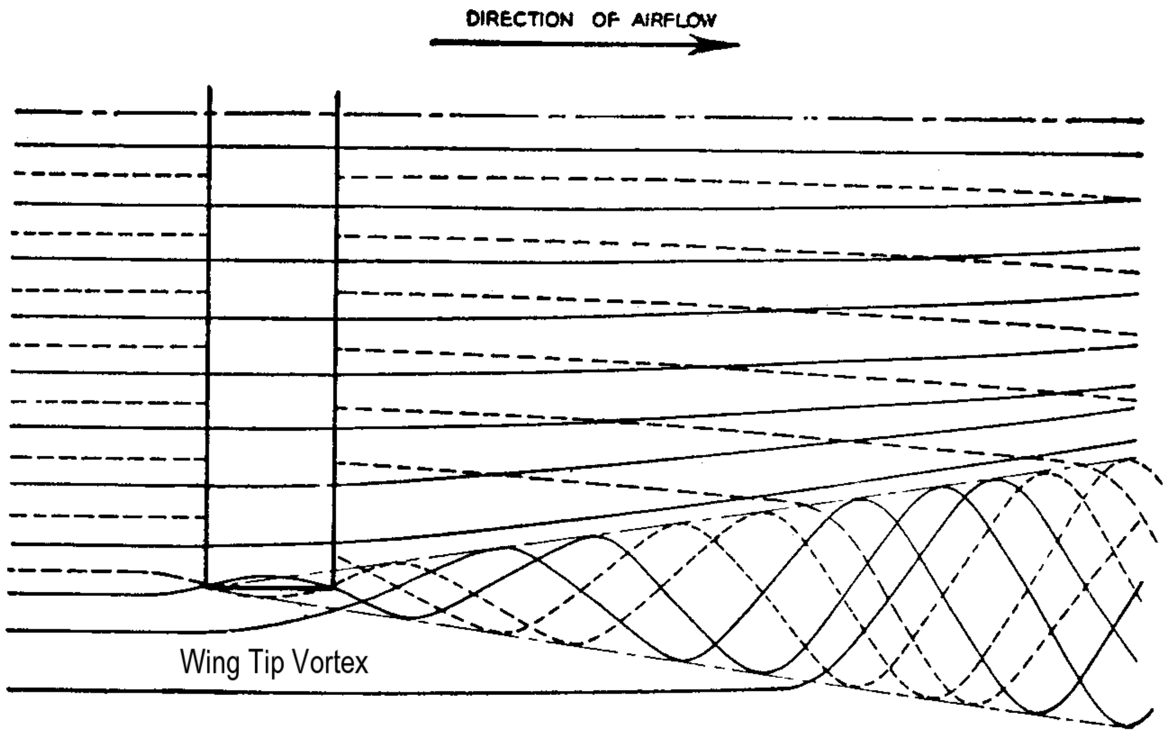


Figure Ten - Plan View of Wingtip Vortex.

Now various shapes and sizes of wingtips and winglets have been used on different types of aeroplanes in an attempt to stop this 'spillage' and whilst they work in theory, the advantage they gain is often offset by the extra weight of the device (and extra weight demands more lift, therefore more induced drag!) and the extra zero lift drag created. Because of this you won't often see them on light aeroplanes. I should emphasize that even when they work, these winglets only reduce the induced drag at the wingtips to the same value as the rest of the wing, they cannot reduce it more, for reasons I am sure you understand by now.

Another method commonly used on light aeroplanes to reduce the induced drag at the wingtip is to twist the wing slightly such that the angle of attack at the wingtip is a little less than at the wing root. This is called 'washout' and is reasonably effective for this purpose. It also delays the stall at the wingtips when flying at or near the critical angle of attack, thereby avoiding premature loss of lateral stability and control. (There will be a lot more on this in the lesson on 'Stalling' later.)

The planform of the wing, both the shape and the aspect ratio, can also have an effect on the wingtip vortexes. I have discussed both of these in more detail in Annex A.

The induced drag at the wing tip can also be varied by the movement of the ailerons. As the aviator moves the ailerons to cause the aeroplane to roll, one goes down (just like a flap) and increases the angle of attack which results in an increased angle of deflection of the local airflow and an increased total reaction on that part of the wing, whilst the other goes up having the reverse effect (Figure Eleven).

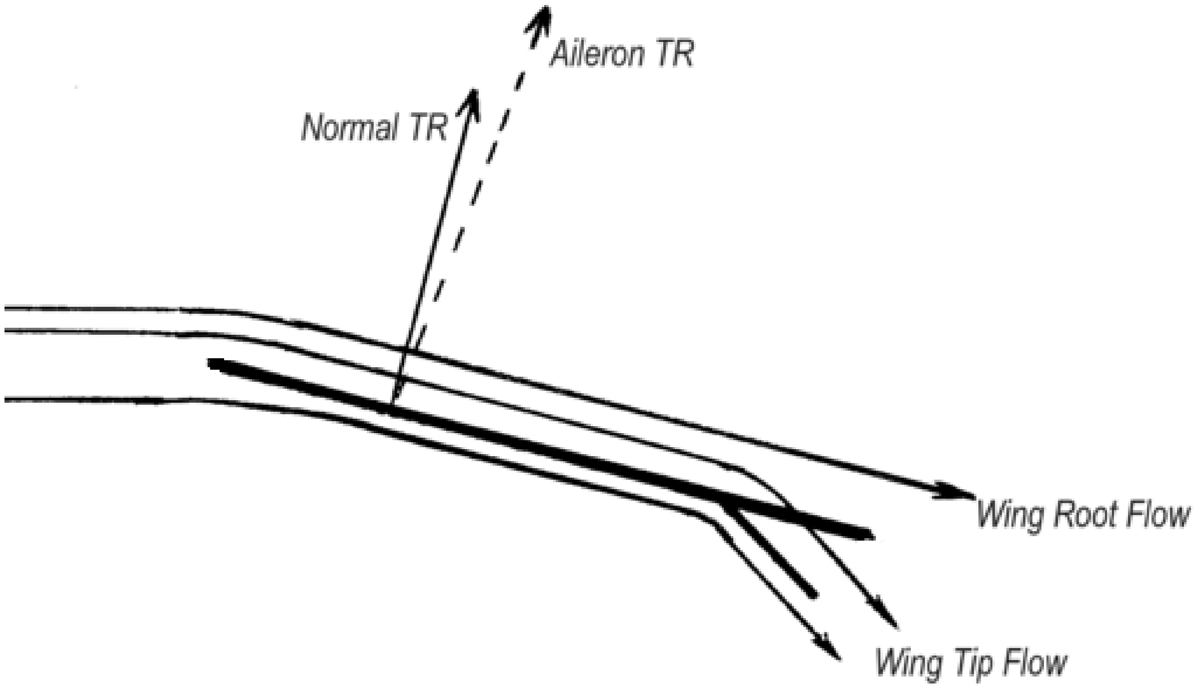


Figure Eleven – The Ailerons Effect on Induced Drag

Note the effect on the wingtip with the down going aileron, of increasing the length of, and the further 'angling back' of, the total reaction vector. It is the same as if we could just change the angle of attack of the wing in the region of the tips. (Indeed that is how the Wright brothers did it on their machines; it was called 'Wing Warping')

Either way, along with increased lift we get increased induced drag. So whilst the ailerons roll the aeroplane in one direction the induced drag imbalance causes the nose of the aeroplane to swing in the opposite direction! This is called 'adverse yaw'. (I will be explaining 'Yaw' in more detail in future lessons.) For example, if the aeroplane is rolling to the right the nose will tend to swing (yaw) to the left, and vice versa!

Many design 'fixes' have been explored over the years to reduce the adverse yaw by trying to reduce the induced drag caused by the down going aileron, but the most effective 'fix' utilizes a bit of lateral thinking and, instead of reducing the induced drag on one wing, increases it on the other, to balance the situation. This results in an overall slight increase in the total drag whenever the ailerons are used, but only a little and only for a very short time. The device that does this is called the ‘Frize’ aileron. The Frize aileron has the hinge point positioned so that the leading edge of the up going aileron protrudes into the airflow below the wing more and more as the aileron is deflected, thereby progressively increasing the zero lift drag on this aileron to balance the progressively increasing induced drag on the down going aileron. (Figure Twelve).

Figure Twelve - Frize Ailerons

A neat side effect of this offset hinge point is that it gives the down aileron a ‘slot’ thereby increasing its effectiveness. Most modern light aeroplanes are fitted with Frize ailerons, so you will probably not notice much adverse yaw when flying them, but if you decide to fly an older aeroplane like a Tiger Moth or a modern Sailplane with very long wings, be prepared to do ‘battle’ with it.

In Annex D to the lesson on ‘Lift’ I suggested to all of the junior flying instructors out there that the Newtonian principles, when applied to the explanation of the production of lift, enable student pilots to more easily understand how the wing works. This also applies to the production of Lift Induced Drag. In 54 years of flying I have yet to hear anyone adequately explain the variation of induced drag with A/A using the so called ‘Bernoulli principle’.

List of Annexes to the lesson on: Drag

Annex A. The Effect of Wing Planform on Drag

Annex B. The Zero Lift Drag Formula

Annex C. Lift to Drag Ratio

Annex A.

The Effect of Wing Planform on Drag

You may recall from the lesson on Lift that I said that "a high aspect ratio wing affects a greater volume of air as it moves through it, which means it can generate the same total reaction as a wing of lower aspect ratio but at a slightly reduced angle of attack, thereby reducing the drag component in relation to the lift component". Of course the drag component I was talking about was the 'Induced Drag' of the wing. (The 'Drift'). The diagram at Figure One depicts this effect:

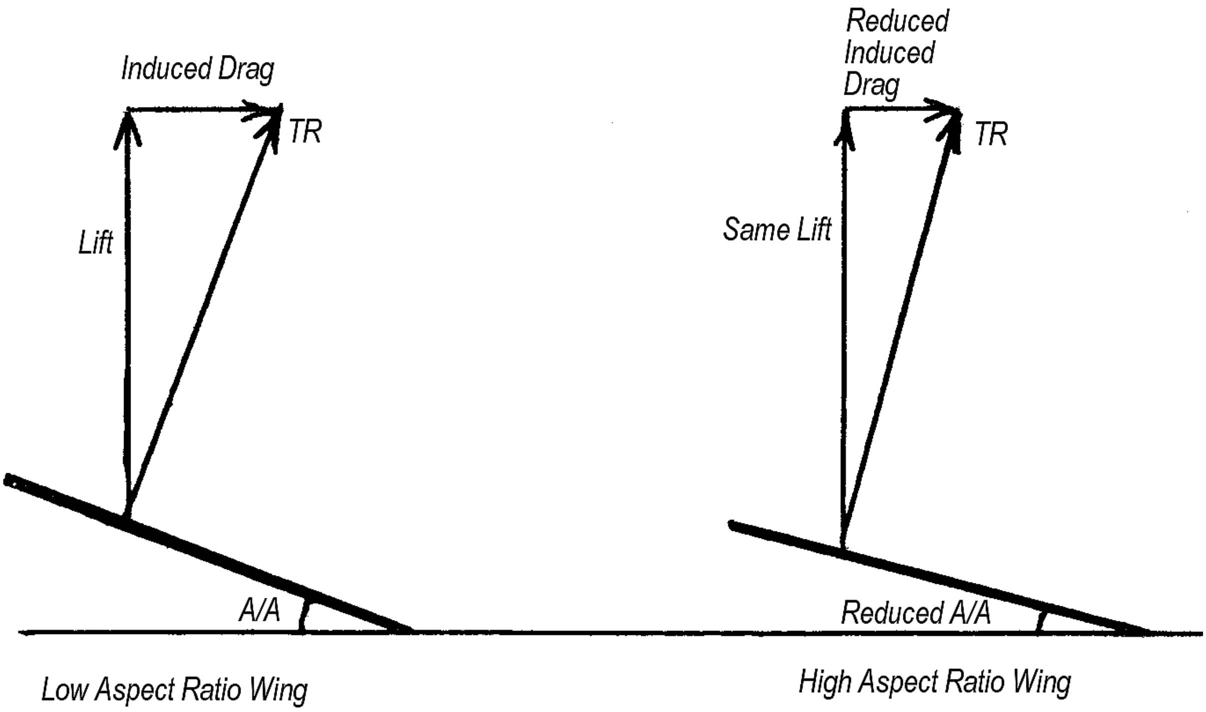
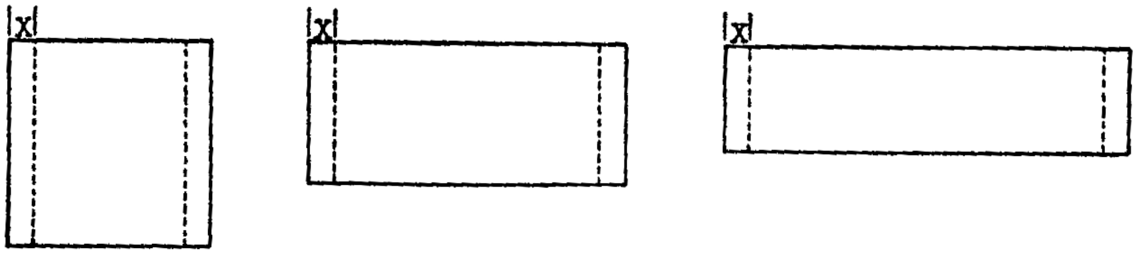


Figure One – The Effect of Aspect Ratio on Induced Drag

You can also see from the diagram at Figure One that the Lift to Drag (Drift) Ratio of the high aspect ratio wing is much better than that of the low aspect ratio wing, which, as I said in this lesson, is the measure of efficiency of the wing. There is a simple relationship between change of aspect ratio and change of Lift Induced Drag, and that is that the LID reduces in direct proportion to the increase in Aspect Ratio. For instance, if two wings of the same **area** have aspect ratios of **5** and **10**, then (when producing the same Lift) the LID of the higher aspect ratio wing will be half that of the low aspect ratio wing.

Since LID is 50% of the total drag at the minimum drag speed any reduction in LID will provide significant performance advantages, which is why modern sailplanes have very high aspect ratio wings.

A high aspect ratio wing also has less vortex drag than a low aspect ratio wing. In the following diagram (Figure two) you can see that even though the distance **(x)** in from the wing tip that the vortex affects the airflow over each wing is similar; this translates into less wing area that is affected as the aspect ratio increases. This means that less energy is absorbed from the airflow over the remainder of the wing and therefore less vortex drag is created



Area effected by tip vortices.

Figure Two – The Effect of Aspect Ratio on Tip Vortices

So when the two effects are combined it is obvious that high aspect ratio wings are aerodynamically more efficient than low aspect ratio wings. I say "aerodynamically more efficient" because structurally they are less efficient. That is, a high aspect ratio wing is far more demanding to manufacture strong enough to withstand all of the flight loads it will be subjected to. This means that heavier structures are needed with all of their associated weight penalties or more 'exotic' materials are needed with all of their cost disadvantages.

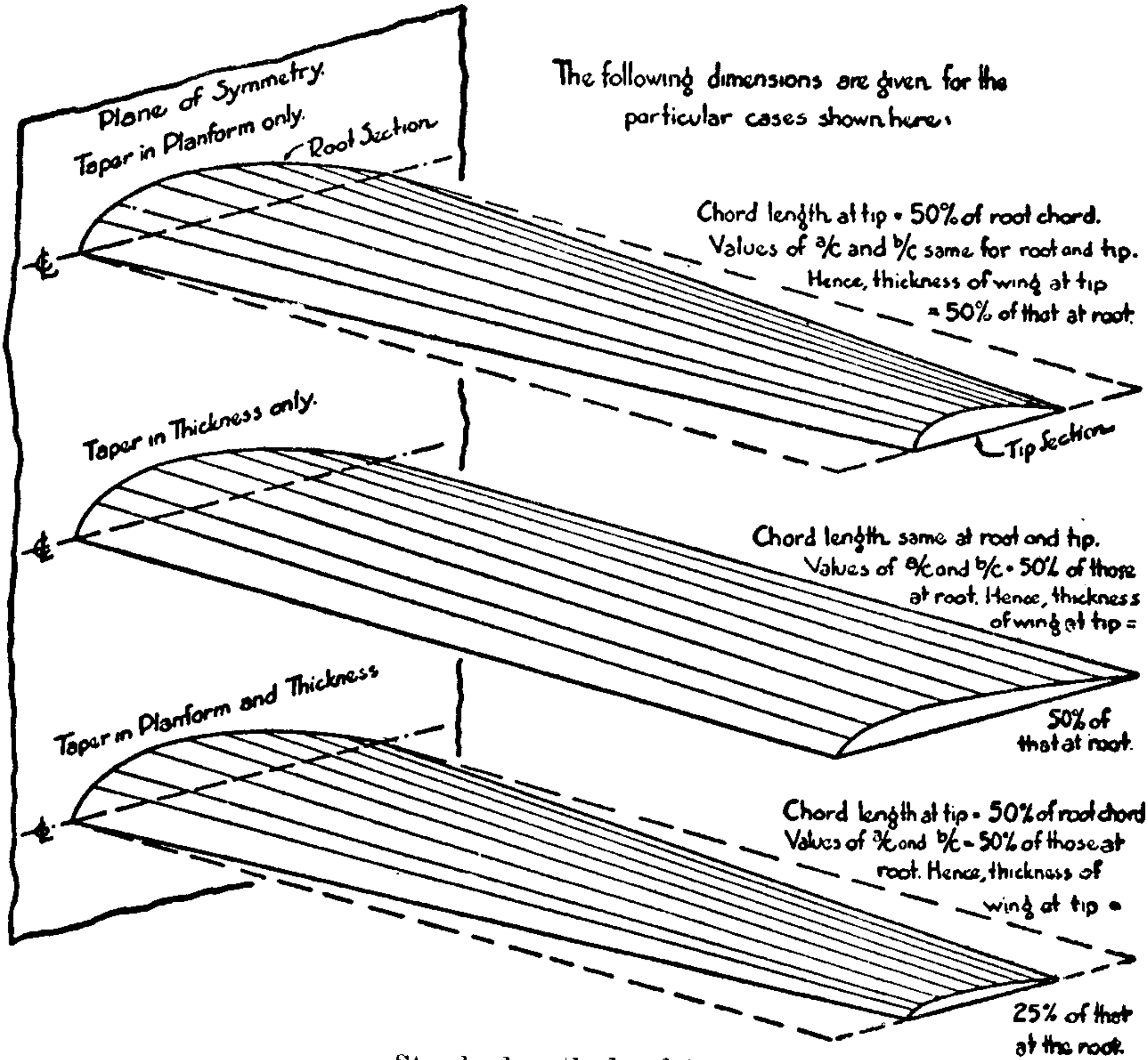
In an attempt to get the 'best of both worlds' aircraft designers have for many years experimented with different wing shapes and wing tip designs, and a wide variety of these shapes has been seen on aeroplanes over the years. There is no one perfect wing shape because for each type and purpose of aeroplane there are several wing shapes which suit and of course there are many different purposes for the aeroplanes we see. Often it comes down to a question of aesthetics.

As the wing shapes vary, the method of calculating the aspect ratio (AR) becomes more difficult. Two methods are employed. The first is to divide the wingspan by the 'Mean Aerodynamic Chord' (MAC). The method of determining the MAC is detailed in a forthcoming lesson. The second is to use the simple formula:

$$\mathbf{AR = Span^2 \div Wing\ Area}$$

Despite all of these potential differences in wing design one principle seems to dominate, which is that a tapered wing offers the best balance between aerodynamic efficiency and structural inefficiency.

Now a wing can be tapered in three possible ways: it can be tapered in chord length (planform) whilst maintaining the same airfoil section, it can be tapered in thickness only which means the thickness/chord ratio of the section changes, or it can be tapered both ways. The following diagram (Figure Three) shows the three different ways that a wing can be tapered:



Standard methods of tapering airfoils.

Figure Two – Tapered Wings

By tapering the wing as shown, particularly the third (bottom) example, the vortex drag can be significantly reduced with an acceptable increase in structural complexity. However if the wing is tapered too much, adverse handling characteristics can occur at high angles of attack (tip stalling), so a balance between efficiency and handling qualities is also required. The adverse effects of tip stalling will be covered in the lessons on ‘Stalling’ and ‘Spinning’.

Annex B

The 'Zero Lift' Drag Formula

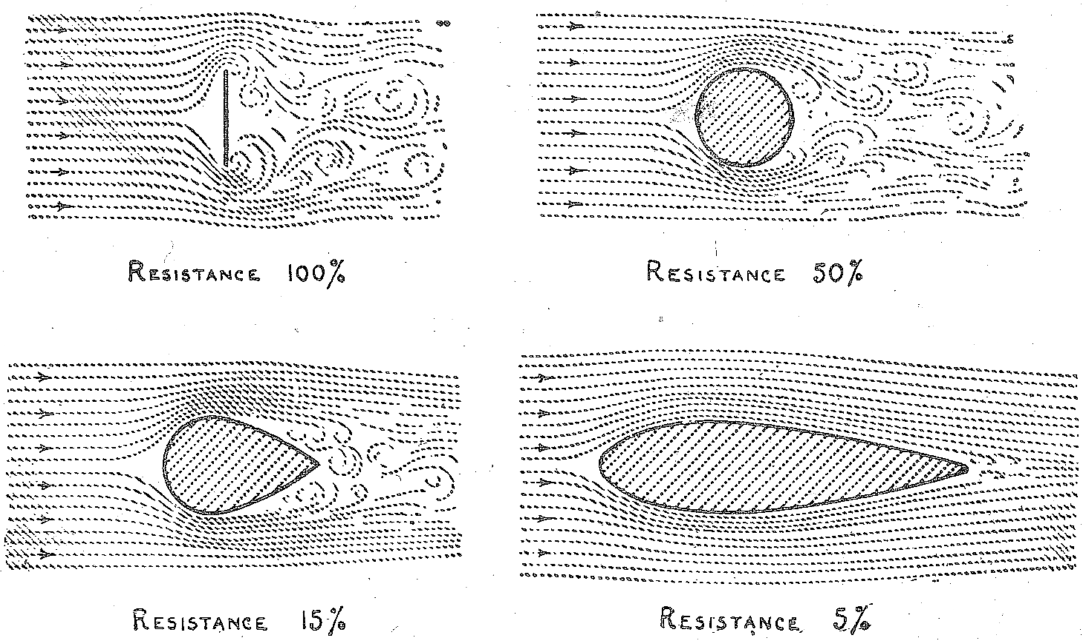
Whilst the derivation of the formula for determining the induced drag of a wing has been described in Annex B to the lesson on Lift, there still remains the question, "what is the Zero Lift Drag formula and how is it derived?"

Of the various components of Zero Lift Drag listed at the beginning of this lecture, by far the most dominant is 'Form Drag' which you will remember comes as a result of the general size and shape of the aeroplane. It should come as no surprise to you to learn that the formula for determining Form Drag is the same sort of fundamental formula as the formula for Induced Drag because the factors of density and velocity are the same; however, in the formula for Form Drag **'S'** is replaced by **'A'** because we are not dealing with the wing area (S) but the frontal area of the whole aeroplane (A). To start with, here is the formula for Form Drag:

$$\textbf{Form Drag} = C_D \tfrac{1}{2} \ell V^2 A$$

C_D in this formula is not determined by wind tunnel measurements on the same shape at different angles of attack but is determined from wind tunnel tests on objects of various shapes but with the same frontal area. Let me explain.

If we imagine that a flat plate held at 90° to a relative airflow has a C_D which we will call 100% then various 'streamlined' shapes of the same frontal area will have reduced drag coefficients depending upon their shape.



The Effect of "Streamlining"

You can see from the preceding diagram the significant reduction of drag which occurs if the correct streamlined shape is used; however, it is virtually impossible to create a database of drag coefficients for all possible shapes so a different method is often used. This is called the 'Equivalent Flat Plate Area' method. In this method the Form Drag of all the various shapes is expressed in terms of the equivalent frontal area of a flat plate at that airspeed. For example, from the foregoing diagram the shape with 15% of the resistance of the flat plate is said to have the 'equivalent flat plate area' equal to 15% of the area of the flat plate. Similarly the shape with 5% resistance has an equivalent area of only 5%.

Using this method, $\mathbf{C_D}$ in the formula remains constant (and is the $\mathbf{C_D}$ for a flat plate) and **A** becomes the variable and represents the equivalent flat plate area of the aeroplane. This method enables a designer to better estimate the potential Form Drag of the aeroplane. However, it must be emphasized that this method does not allow for many of the more subtle components that make up Zero Lift Drag (like interference drag). So ultimately when the shape of a particular aeroplane is finalized, wind tunnel tests (or test flights) must be carried out to establish the actual Zero Lift Drag characteristics of the aeroplane. (The difference in size between the real aeroplane and the wind tunnel model is resolved by using a 'compressed air' wind tunnel to maintain the Reynolds Number as previously described in Annex A to the lesson on Lift.)

Unfortunately the formula for Zero Lift Drag and the formula for Induced Drag are similar in appearance and cause considerable confusion amongst pilots, despite the difference in the method of determining some of the factors within the formula. Indeed in some text books the symbol 'S' is not even replaced by 'A', its meaning is just redefined elsewhere in the book, so it is no wonder that student pilots become a bit 'hazy' about the distinction. This confusion also flows over to the understanding of Lift to Drag Ratio, which is the subject of Annex C.

Annex C.

Lift to Drag Ratio

As mentioned in the main text of this lesson there has evolved, over a number of years, considerable confusion over the derivation and definition of the 'best' Lift to Drag ratio and its associated angle of attack. So what? Why is the Lift/Drag ratio so important?

Lift is the force we have to generate in order to fly, whilst drag is the price which must be paid to attain this lift. If you were to purchase a new car you would obviously like to get the best car at the cheapest price, right? It's the same with lift. Drag has to be offset by some form of thrust, which has to be provided by some type of energy source. Thrust comes from either engine power, or altitude loss (when gliding). There is much detailed discussion to come on each of these subjects but let's just say here that offsetting the drag in the least costly manner, that is, the most efficient manner, has considerable 'cost benefits'. The Lift to Drag ratio of the aeroplane is the way we express this efficiency, indeed, it is one of the most significant parameters in aerodynamics.

The following diagram (Figure One) is a simplified version of the graphs of the NACA 23015 wing characteristics contained in Annex A to the lecture on Lift (at a lower Reynolds Number):

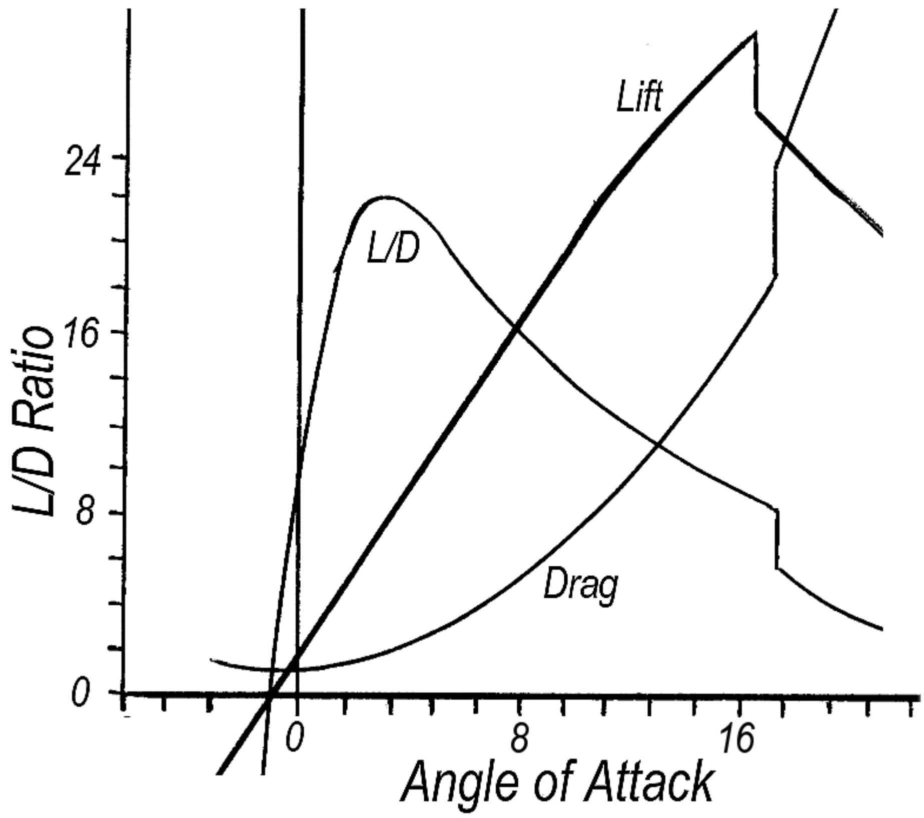


Figure One – Simplified Wing Section Characteristics Graphs

This diagram shows the increasing lift and drag plotted as a function of A/A, as two separate graphs and also a third graph which shows the ratio of the other two (the L/D ratio) plotted against the same angle of attack. You can see that for this wing section the L/D Ratio graph 'peaks' at about 22 **:**1 at about 4° A/A.

Note that the 'Drag' graph looks similar to the 'Zero Lift Drag' graph shown in the main text of this lesson. It could be, and often is, easily confused in the mind of a student pilot to be the same thing. It's not. First, it is the drag of the wing **only**, and comprises only a very small 'Zero Lift Drag' component (which is why the drag is not zero at zero A/A) and is mostly 'Induced Drag'. Second, it is plotted against A/A, not airspeed. That is, the induced drag is shown increasing toward the right of the chart, not decreasing as we have seen previously. (It is effectively the 'mirror image' of the previous induced drag graphs, hence the confusion.)

As I explained in the main text, early pioneers of flight called the Lift/Drag ratio of the wing the "Lift to Drift" ratio as they were dealing with the efficiency of the wing only. To the 'Drift' they added the 'Head Resistance' when dealing with the efficiency of the whole aeroplane. Somewhere along the line this very clear understanding of the effect of the two drag components became confused.

If we add the 'Head Resistance', sorry, the 'Zero Lift Drag' of the rest of the aeroplane to the forgoing drag graph it would move UP considerably and alter the L/D ratio graph significantly and making it more 'real' from a pilots perspective. Here it is at Figure Two:

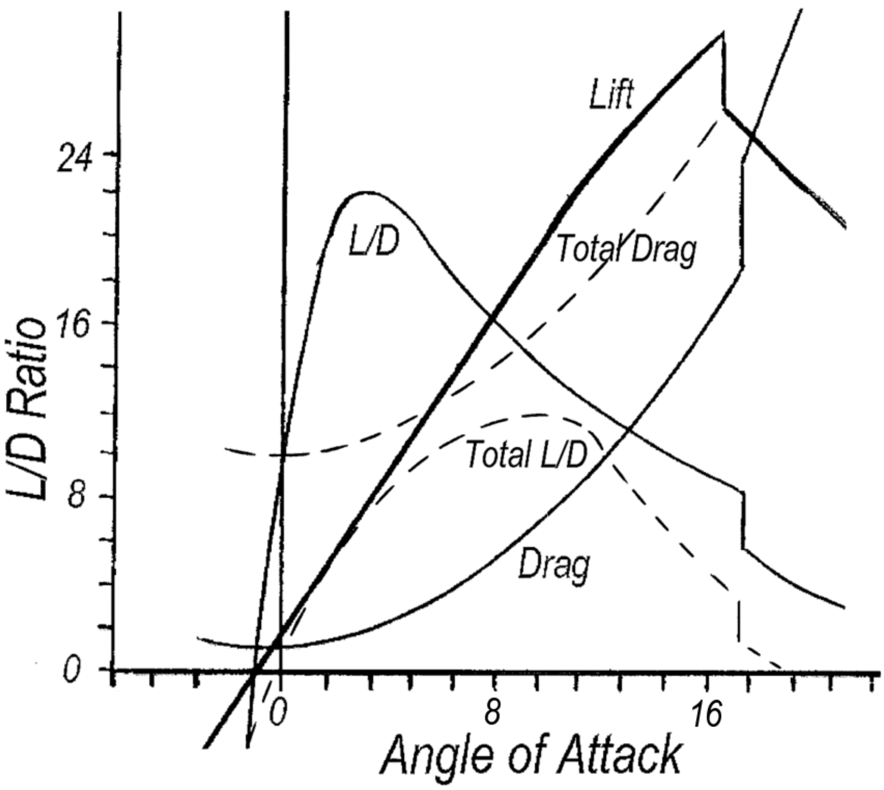


Figure Two – The 'Real' L/D Ratio Graph

The 'Total Drag' graph is indicated by a broken line as is the new 'Total L/D Ratio' graph. Notice that the Total L/D ratio graph has shifted significantly and now 'peaks' at about 10º A/A, which means that, for the aeroplane as a whole, the angle of attack at which the best lift to drag ratio occurs is about 10º. Also the actual L/D ratio is now down to a realistic 12**:**1. Obviously this 'peak' will be different for different aeroplanes depending upon how much 'Head Resistance' they have even though they may be using the same wing section.

If you are finding all of these graphs a little confusing, here is an alternate way to understand it based upon the flight manual figures of a typical GA aeroplane.

If the level flight stall speed (**Vs)** of the aeroplane is 55kts and the critical A/A of the wing is 18º then it follows that if we double the speed to 110kts the lift (at the critical A/A) would increase 4 times (because lift increases as the 'square' of the speed and $2^2 = 4$); so as the aircraft gains speed, in order to maintain level flight, the A/A would have to be progressively reduced to ¼ the critical A/A, which is 4.5º! The following is a simple formula which can be used for calculating the A/A at any airspeed if **Vs** and the critical A/A are known.

$$\textbf{New A/A = Critical A/A x (Vs/Airspeed)}^{2}$$

So if the aircraft flight manual recommends a glide speed of 75kts the new A/A at that speed will be:

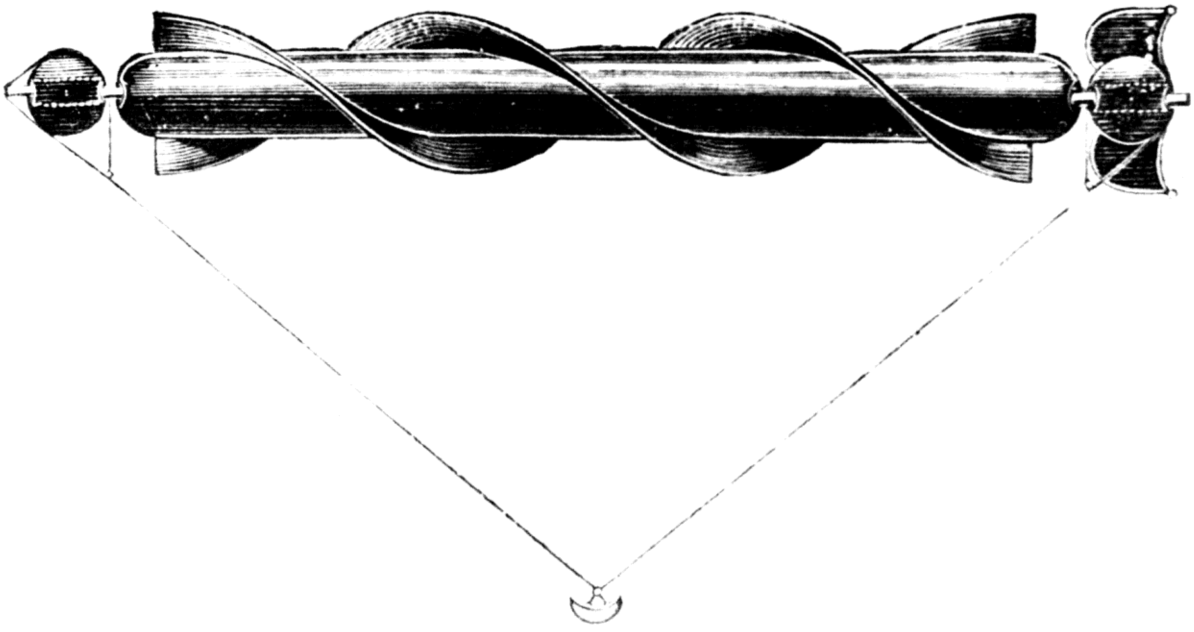
$$\begin{aligned}\textbf{Glide A/A} &= \mathbf{18 \times (55/75)^2} \\ &= \mathbf{18 \times (.733)^2} \\ &= \mathbf{18 \times .538} \\ &= \mathbf{9.7^o}\end{aligned}$$

As you will learn in the lesson on gliding, the 'best' glide range in still air is attained at the best L/D ratio for the aeroplane and you can see from the foregoing calculation that this occurs at about 10º A/A <u>not 4º</u>! Indeed if this aeroplane cruises at 120kts then its A/A, using the forgoing formula, would be about 4º, and it should come as no surprise to learn that the designer sets the wings onto the fuselage at this angle (the angle of incidence) so that the wing is operating very close to <u>its</u> most efficient A/A at the aeroplane's cruising speed.

The fact that this misunderstanding of the speed versus glide A/A relationship of an aeroplane has evolved and persisted for so long, and has become enshrined in student, private and commercial pilot text books and exams, amazes me. I regularly see flight instructors quite happily teaching their students that the foregoing aeroplane has its 'best L/D ratio' at 4º A/A and glides best at 75kts without giving any thought to what they are saying, and I see licence exams asking for the best L/D ratio A/A and expecting the answer "4º ". If you have to answer such a question in an exam say "4º", but <u>know that it is wrong!</u>

Lesson Four

THRUST



This "Navigable Balloon" as patented by Jean Lassie in 1856 was proposed as the solution to the problem of propulsion through the air. It was to be 900 feet long and 90 feet in diameter! Three hundred men were to be carried within the cylinder; 150 to walk as in a treadmill turning the screw, thereby forcing the machine through the air, whilst the remaining 150 men were a relief crew. The weight suspended below is movable fore and aft to trim the ship. It was stated that the speed could be either fast or slow depending upon the pitch of the screw and the fitness of the men.

There are currently three *practical* ways to create thrust for the purposes of driving an aeroplane through the air. The first is the rocket, the second is the air breathing direct thrust jet engine and the third is the piston or gas turbine engine driven propeller.

In this lesson we will confine ourselves to discussing the propeller, its development, design, operation and limitations, because it is the device used exclusively on light training aeroplanes to convert piston engine power into thrust. Unfortunately, of the three ways to create thrust, the theory of propellers is the most complex, but since the propeller is the device you will be flying with for a while you can't avoid learning about it.

We will consider three types of propeller, the 'fixed pitch', the 'variable pitch' and the 'constant speed'. We will start with the fixed pitch propeller and I will begin with a simplified description and then progressively add the various 'layers' of complexity to ease you into the subject as gently as I can.

The fixed pitch propeller was the only type of propeller in use for about the first 20 years of aeroplane development. It was originally conceived as a device which simply 'screwed' its way through the air in the same way that a wood screw screws its way through wood. (Just like the 'Navigable Balloon' pictured at the beginning of this lesson.) Indeed a common name still given to the propeller is 'Airscrew'. The early propellers used on dirigible airships and flying model aeroplanes in the late 1800's (Figure One) were nothing more than angled paddle blades similar to the early screws of ships, but whilst ships screws were reasonably efficient in water that efficiency did not translate to airscrews. (This has something to do with 'Reynolds Number', because water is a lot denser than air.)

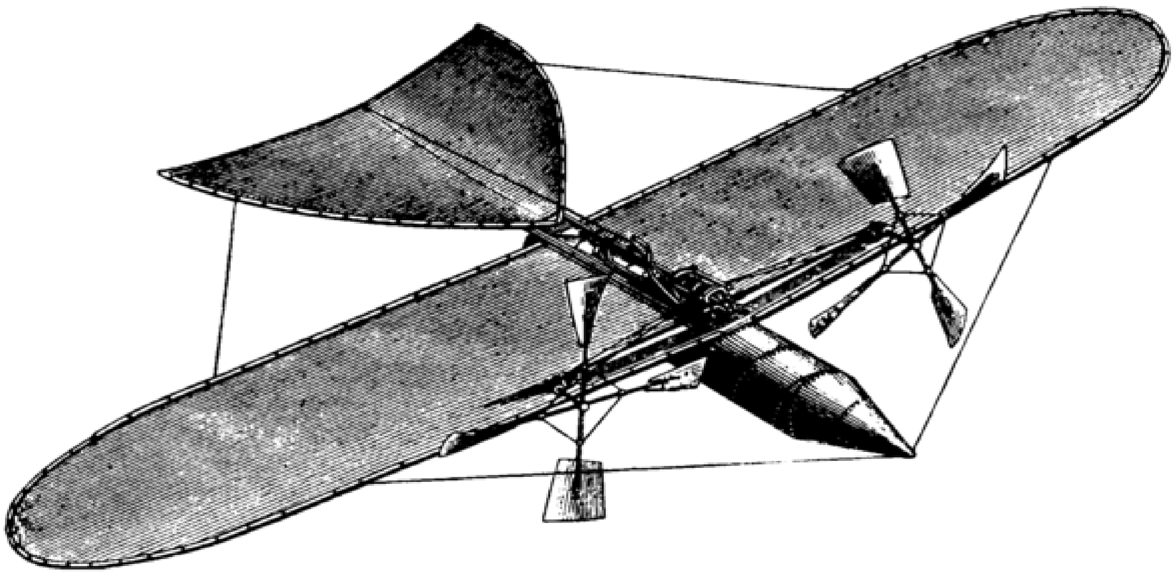


Figure One – Early Model Aeroplane

The Wright brothers were the first aeronautical experimenters to realize that the blades of a propeller were small rotating wings with all of the same lift and drag characteristics of larger wings. When they came to the manufacture of the propellers for their first powered aeroplane they contracted marine screw manufacturers to build them, but these manufacturers, unfamiliar with the brothers' requirements, ignored their specifications and made them ship screws, which of course they were forced to reject. So they made them themselves. Have I mentioned that they were two extremely gifted guys?

First let's consider a section of a fixed pitch propeller blade; and let me say at the outset that it has become customary to use the section which is 75% of the total blade length out from the hub when measuring the angles of, or considering the characteristics of propellers. So we will stay with that convention. The following (Figure Two) illustrates this 75% point on each blade.

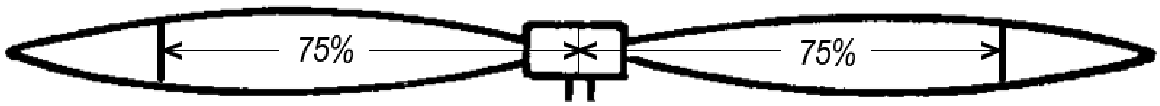


Figure Two – The 75% Point

Imagine our simplified propeller being rotated by the engine whilst the aeroplane is stationary (on the ground obviously, with the park brake on and the chocks in place):

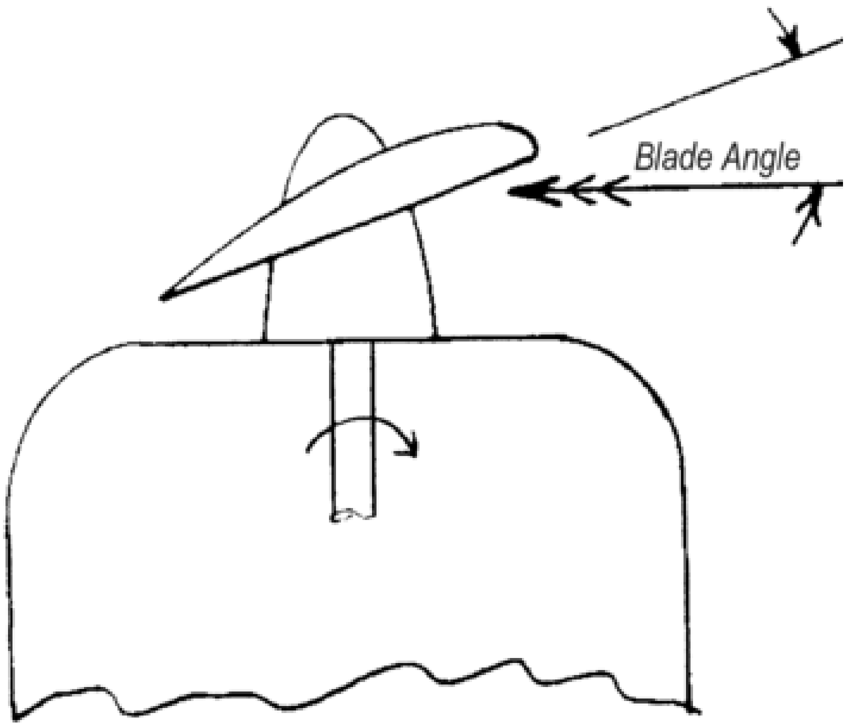


Figure Three – The 75% Propeller Blade Section

The foregoing diagram (Figure Three) shows the 75% section of a propeller blade set at a certain blade angle. The blade angle is defined as the angle in degrees between the chord line of the blade section and the plane of rotation. This blade angle is also referred to as the 'geometric pitch' of the blade, which is a hangover from the 'screw' concept of propellers; that is, the pitch of a woodscrew is the distance it moves into the wood with each full rotation, so the geometric pitch of an airscrew is the theoretical distance it moves through the air with each revolution. Geometric pitch is expressed in terms of this theoretical distance, usually in inches, or in relative terms such as 'coarse pitch' or 'fine pitch'. We also define the type of propeller with reference to 'pitch', such as 'Fixed Pitch' or 'Variable Pitch'.

As the propeller is rotated by the engine drive shaft its movement causes a relative airflow so the blade angle becomes its angle of attack and it develops a total reaction at about 90° to the blade. We then divide this total reaction (TR) into the components of lift and drag just as we have done before, so the lift becomes the 'thrust' because it is along the axis of engine rotation which in general is aligned with the longitudinal axis of the aeroplane and which will primarily be used to balance the drag of the aeroplane. The drag of the propeller opposes the engine rotation and is also referred to as 'propeller torque', but for now I am going to keep it simple and use the term we have all become familiar with – drag. The angle at which the blade is set is the angle for the best lift/drag ratio for all those reasons covered in the lesson on 'Drag', which as we have already learned, is about 4° (for the wing/prop only). The following diagram (Figure Four) illustrates these forces.

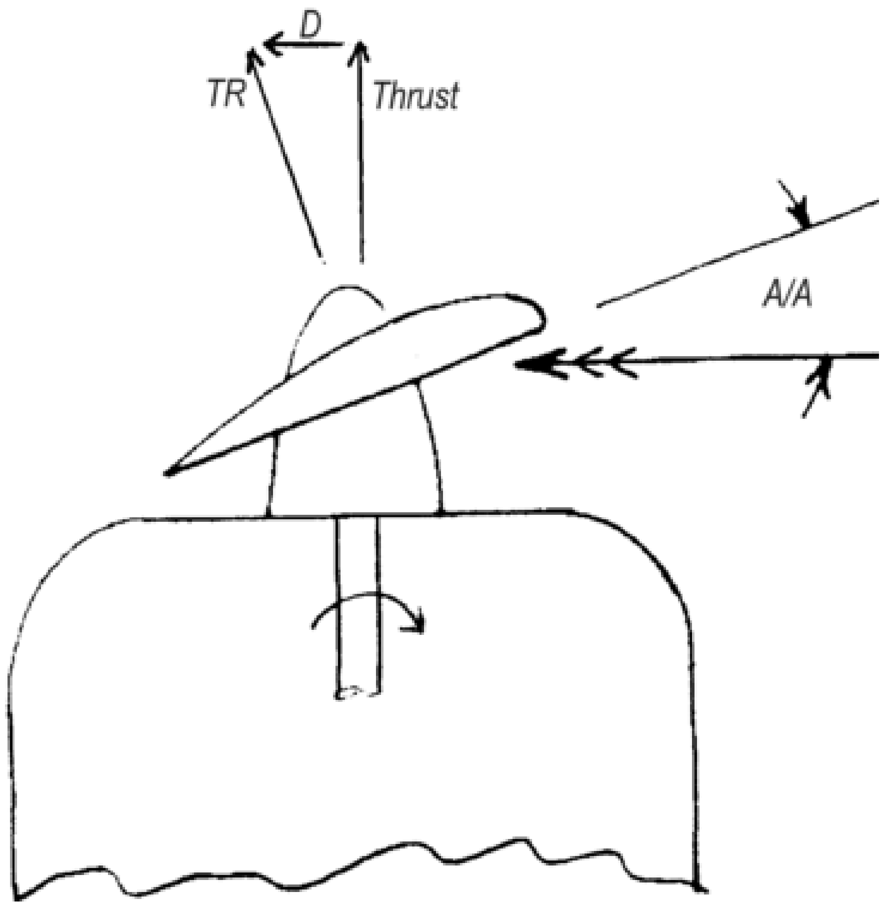


Figure Four – Forces acting on 'simple' Propeller

No surprises so far. Now unlike a wing the blades of a propeller rotate about the propeller hub, so each part of each blade, as we move out from the hub toward the tip, is moving at a different speed and therefore experiencing a different relative airspeed, being slowest at the hub and fastest at the tips (Figure Five).

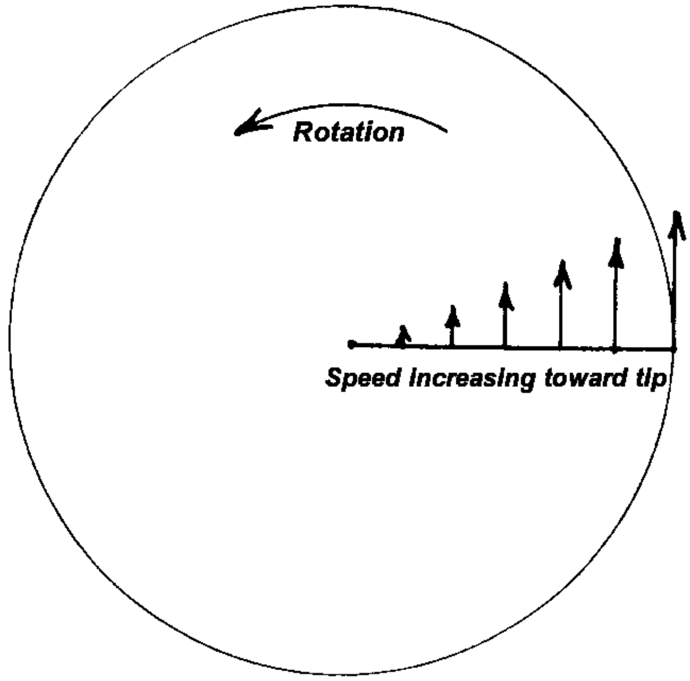


Figure Five – Increasing airspeed from Root to Tip

The speed of the blade increases proportionally as we move out from the hub toward the tip. If we say that the speed at the 25% point is 1, then the speed at the 50% point will be 2, at the 75% point 3, and at the tip 4. And, since the total reaction increases with the square of the airspeed, if the entire blade had the same angle of attack, the total reaction would increase exponentially, that is: 1, 4, 9, 16, and the distribution of this reaction along the blade would be as shown in the following diagram (Figure Six).

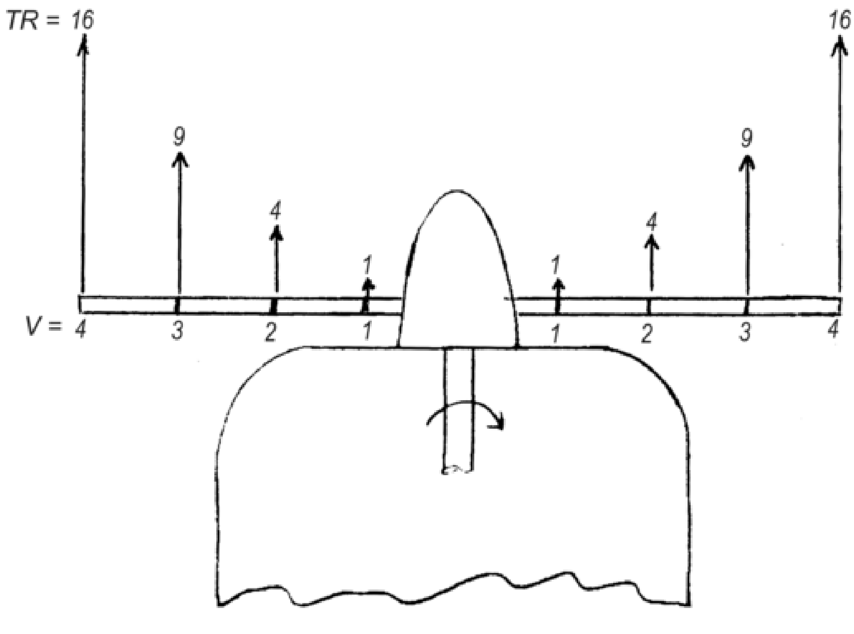


Figure Six – Exponential Increase in TR from Root to Tip

As you can see, most of the reaction is at the propeller tips and it diminishes significantly toward the hub so the inner sections are not contributing their 'share'. In order to distribute the force more evenly along the length of the blade, the blade is 'twisted' in such a way that the angle of attack increases toward the hub and decreases toward the tip. The amount of twist imparted to the blade is just enough that the angle of attack at any point compensates for the differing airspeeds (sound familiar?). The following diagram (Figure Seven) shows the angle of attack at each of the four positions on a blade. (Note that the best L/D angle of attack is at the 75% point.)

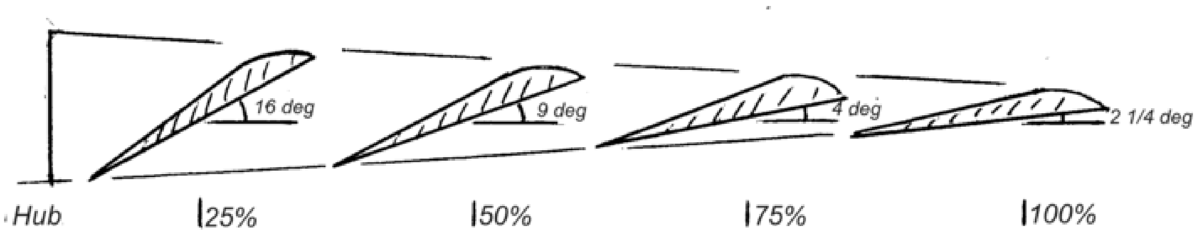


Figure Seven – Reducing Blade Angle from Root to Tip

The changing angle of attack along the blades now distributes the total reaction evenly along the blades as illustrated by the following diagram (Figure Eight).

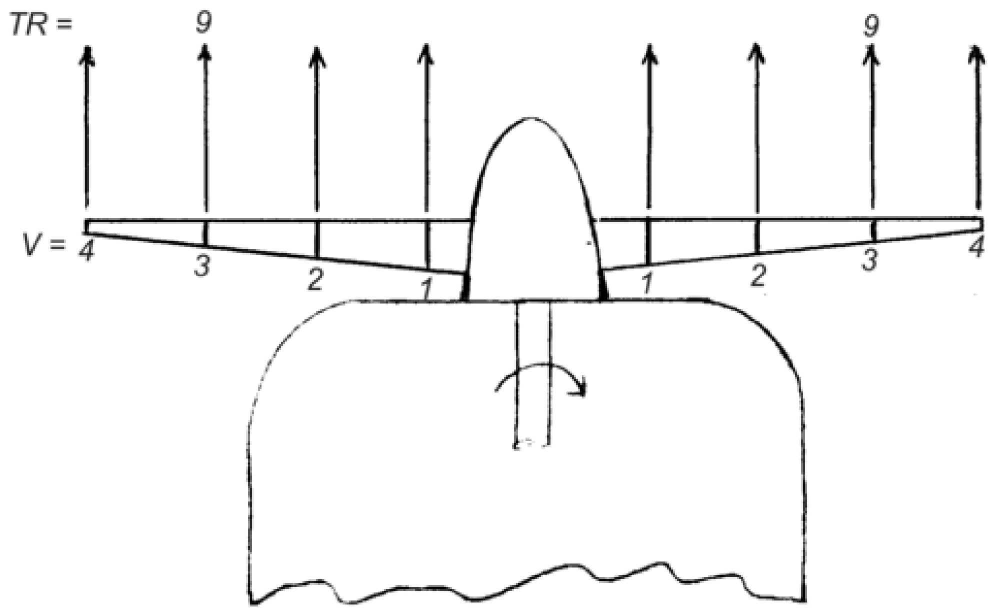


Figure Eight – Evenly Distributed TR along Blade

Once again it was the Wright brothers who first designed the properly 'twisted' aeroplane propeller as shown in the following photograph of one of their propellers (Figure Nine).

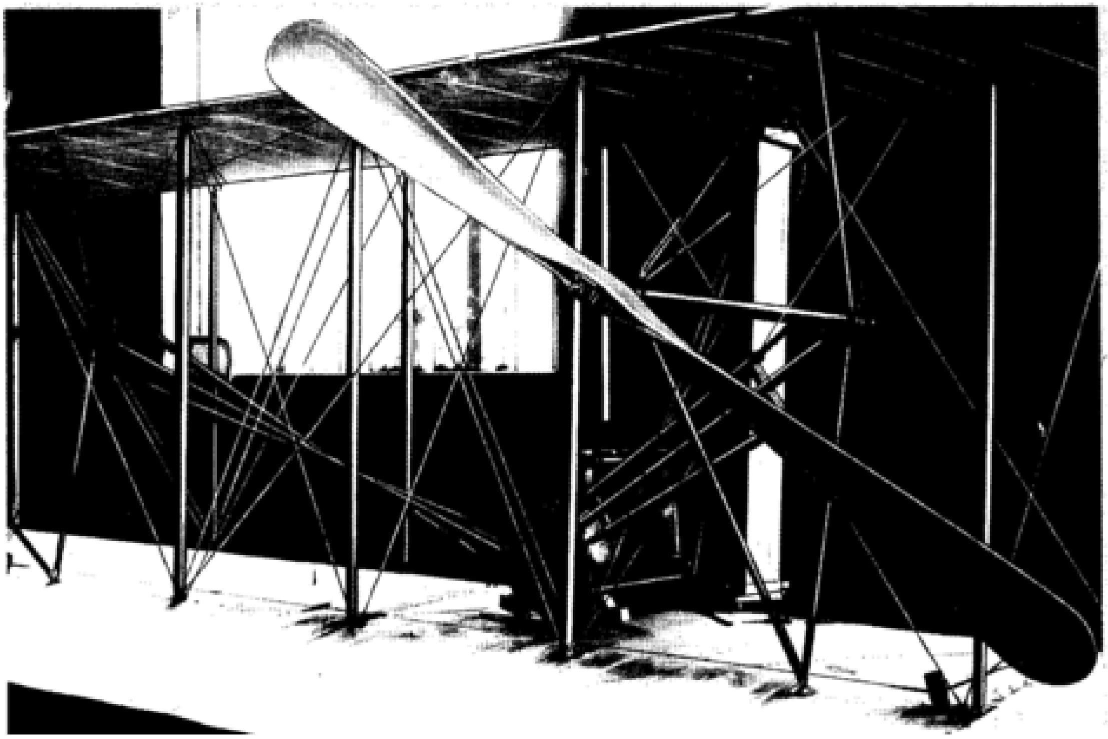


Figure Nine – Wright Brothers Propeller

Note also that the angle of attack at the 25% point has reached the critical angle. Any further increase in angle toward the hub will only increase the drag, so the twisting stops at this point. Indeed the inner 25% of a propeller blade is considered a 'non contributor' to the overall thrust of the propeller and is often partially covered with a streamlined faring called a 'spinner' which helps eliminate the drag of rotation of this inner part and the drag of the hub too. The spinner also helps direct the airflow into the engine cooling duct and makes the aeroplane look 'racy'! (Figure Ten.)

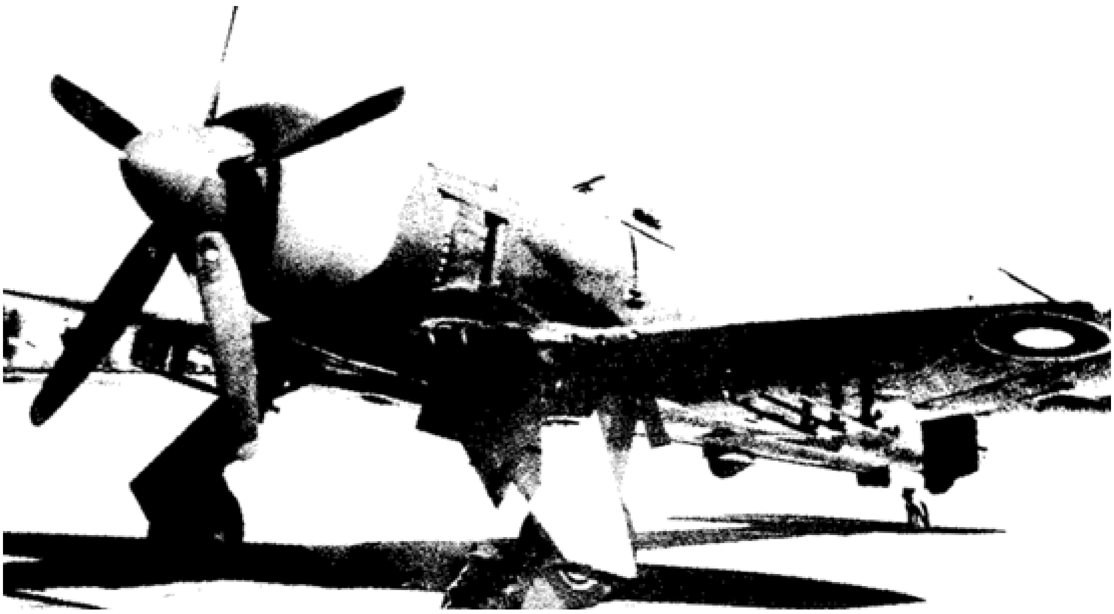


Figure Ten – 'Spinner' enclosing Propeller Hub

Note that I have been using the term 'total reaction' (TR) in the foregoing explanation of twist, not 'thrust'. Since the thrust (T) is only the component of the total reaction in line with the drive shaft it still diminishes toward the hub because of the angle the total reaction makes to the plane of rotation as we get closer to the hub. Study Figure Eleven and you will see what I mean.

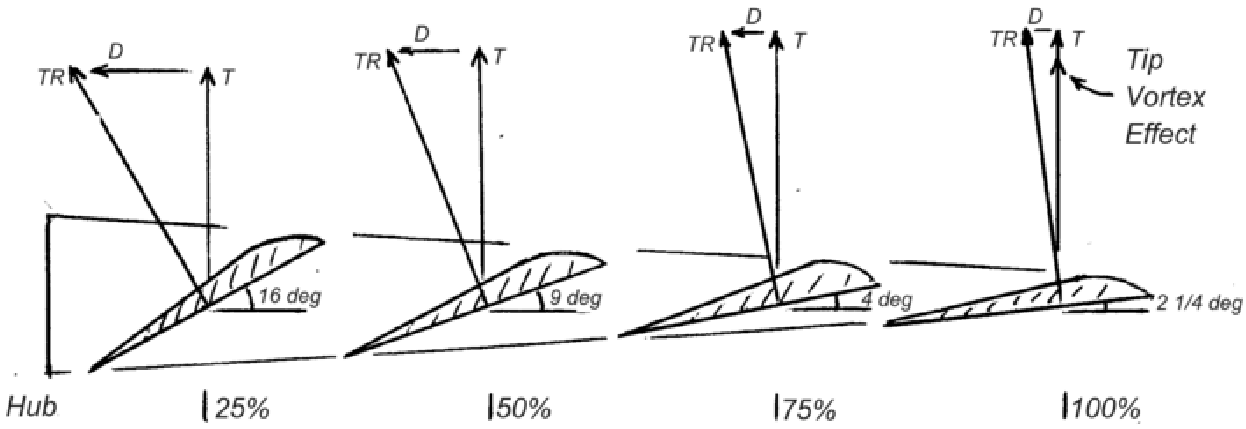


Figure Eleven – Diminishing Thrust with Increasing A/A

You will notice that even though the total reaction is the same at each point along the blade the thrust component decreases as the angle of attack increases toward the hub. Also the induced drag is increasing as the angle of attack increases too! This increasing drag tends to retard the speed of rotation and requires more 'torque' from the engine to overcome. The tips of the blades suffer the same vortex problems as a larger wing so the thrust is diminished a little out there too. So the thrust distribution along the blade looks like the illustration at Figure Twelve.

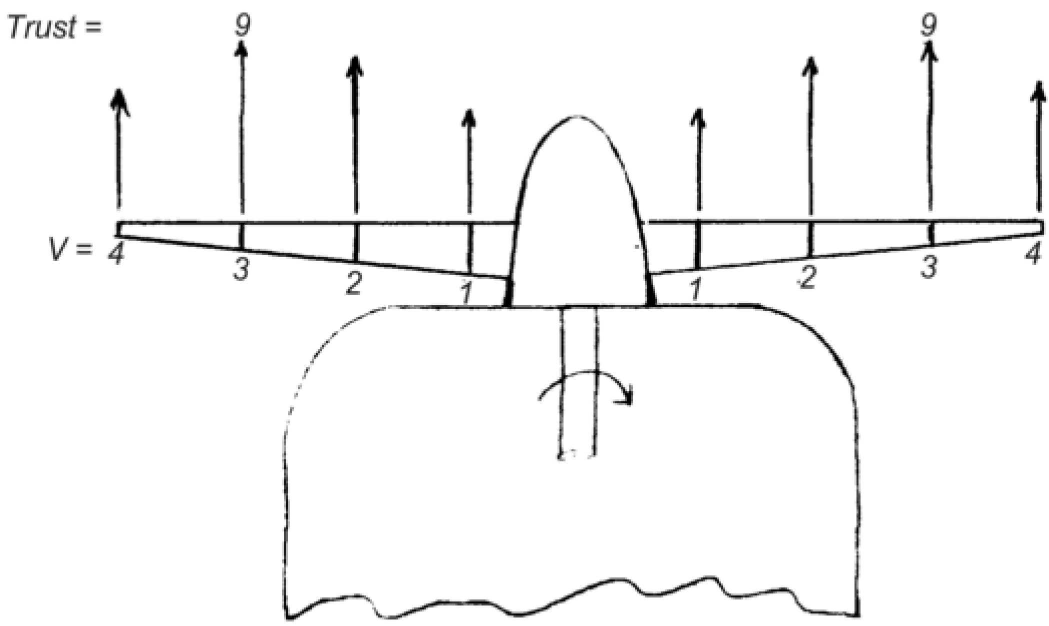


Figure Twelve – Thrust Distribution along Blade

Just in case you have forgotten, let me remind you that so far the aeroplane is still stationary with the chocks in place. But once the aeroplane starts to move forward 'things' start to change and the effect of the relative airflow due to the forward motion of the aeroplane has a significant effect on everything I have said so far and our 'simple' propeller becomes a 'not so simple' propeller. Let me explain.

Suppose the engine is turning the propeller at an RPM that gives the 75% point a speed of 600 feet per second. And the aeroplane is moving forward at a speed of 200 feet per second (118 knots TAS). This will result in the relative airflow coming at the propeller blade at an angle of 18º (Figure Thirteen).

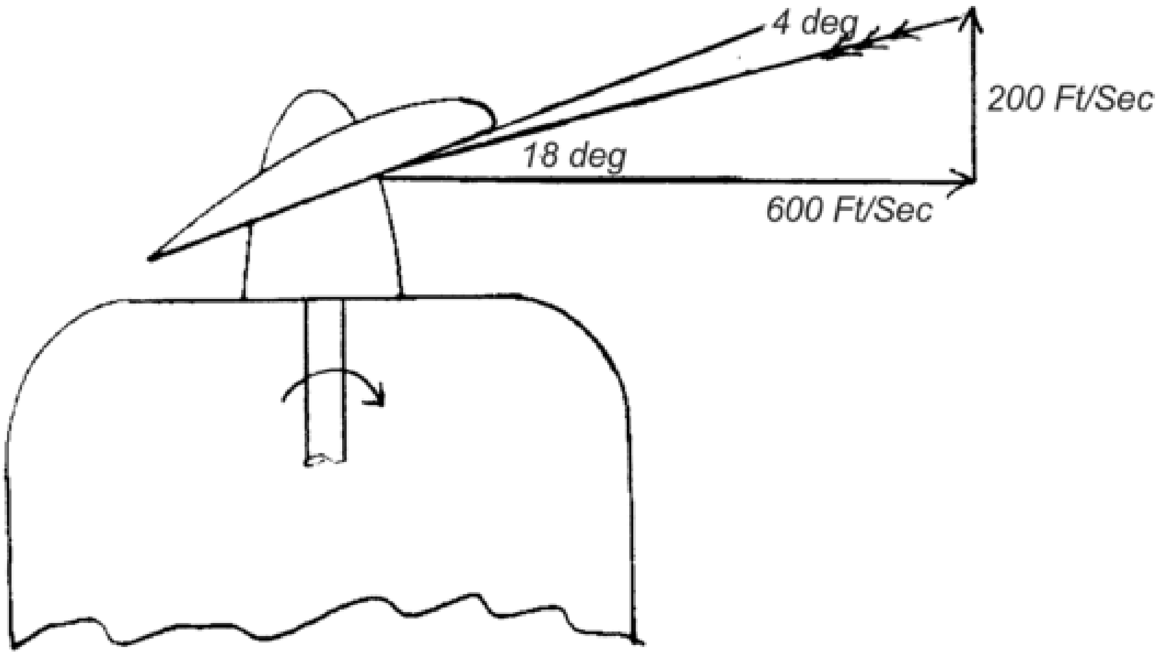


Figure Thirteen – Effect of Forward Motion on Blade Angle

This would mean that in order to maintain the 4º angle of attack the blade would actually have to be set on the hub such that the 75% point was at an angle of 22º! So no longer is the blade angle the same as its angle of attack. Since lift by definition is the component of the total reaction at 90º to the relative airflow whilst thrust is the component in line with the axis of rotation, no longer is the lift the same as the thrust! Also since drag by definition is the force at 90º to the lift (parallel to the relative airflow) it can no longer be synonymous with the force resisting rotation; that is, 'propeller torque' (PT), which is the force at 90º to the thrust. You can also see from the following diagram (Figure Fourteen) that the ratio of Thrust to Propeller Torque is no longer the same as the L/D ratio so from this point on, we will be talking in terms of 'Thrust' and 'Propeller Torque'.

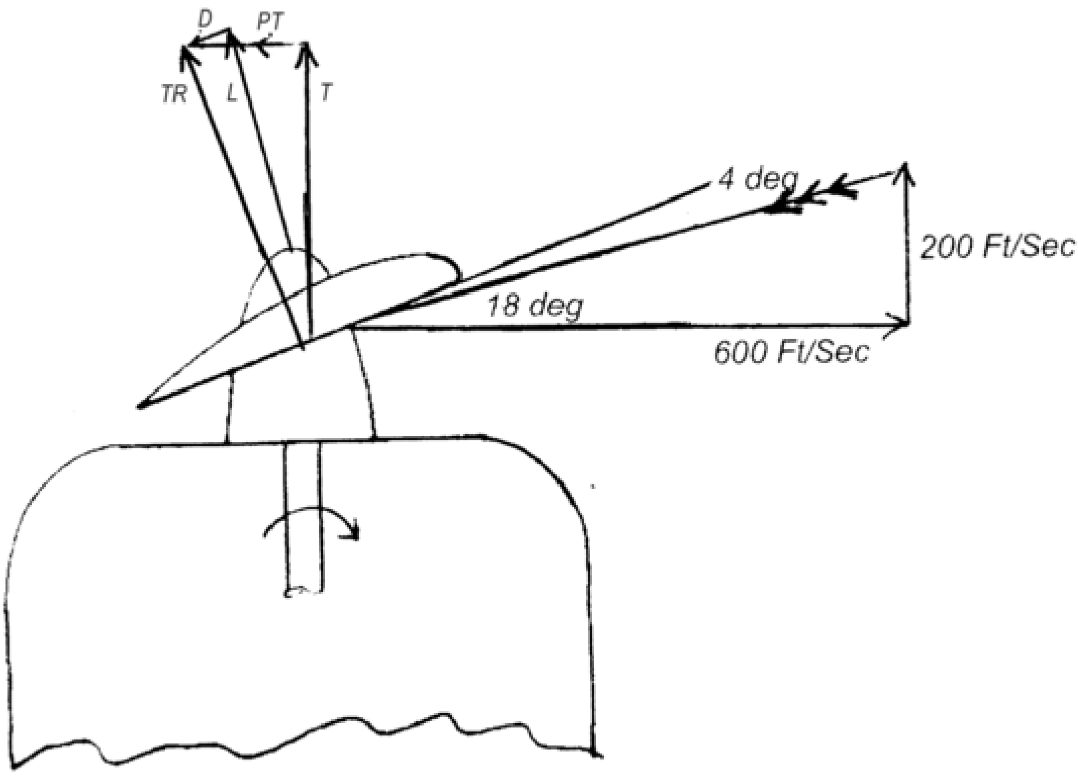


Figure Fourteen – Lift/Drag versus Thrust/Prop Torque

I must also ‘back up’ a little bit here to explain that even when the aeroplane is stationary this ‘forward motion’ effect is present. If you stood behind a stationary aeroplane whilst its engine was running you would feel the slipstream, so even when stationary the propeller is pushing a lot of air back and that air has to come from somewhere, right? It flows into the propeller ‘disk’ from the front causing what is called ‘induced airflow’. This induced airflow is the equivalent of the aeroplane moving forward at low speed when the engine is idling and the equivalent of moving at high speed when the engine is developing its full power. So induced airflow is not just present when the aeroplane is stationary but is present as a component of the forward speed of the aeroplane whatever speed it is doing with power applied. Indeed the induced airflow velocity at full power is equal to about 30% of the slipstream velocity.

In my initial ‘simplified propeller’ explanation I equated blade angle with angle of attack and lift with thrust, but you can now see that because of induced airflow they can never be equivalent, even when the aeroplane is stationary. So there goes our ‘simplified’ propeller ‘out the window’!

Induced airflow is not present if the aeroplane is diving with the engine throttled (closed) and the propeller is ‘windmilling’. (A detailed explanation of ‘wind milling’ is contained in Annex A.)

So what is the situation at the other stations along the propeller blade when the aeroplane is moving? Check out the following diagram (Figure Fifteen).

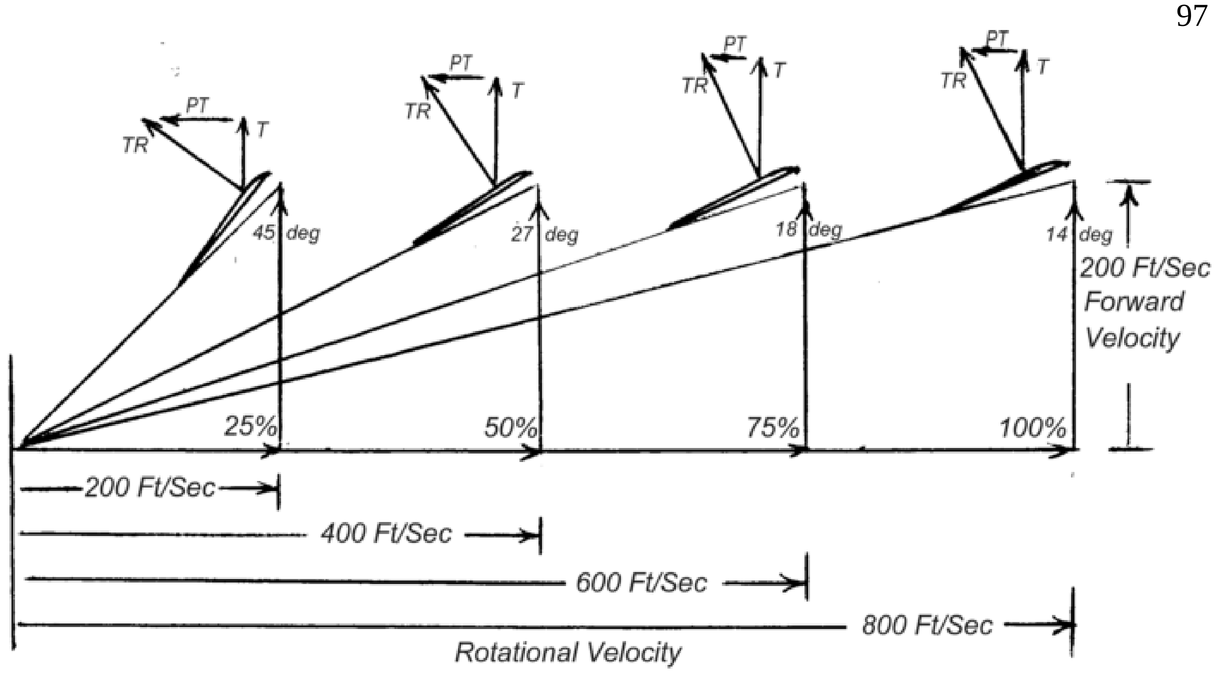


Figure Fifteen – Thrust & Prop Torque at each Blade 'Station'.

You can see that the angles become quite extreme as we move toward the hub and even though the angle at the 25% point is theoretically correct, the propeller at that point is generating more propeller torque than thrust! Indeed at all points along the blade the total reaction 'leans' further back and thereby reduces the overall thrust of the propeller.

It is the designer's job to determine the blade angle which will most suit the aeroplane, depending upon its designed take off speed, operating speed, the power of the engine, the operating altitude and a host of other considerations. I have said 'operating speed' rather than cruise speed because the aeroplane may be intended for racing where maximum speed is required or it may be a glider tug where it is required to pull another aeroplane 'up hill' at slow speed. In the former case the blade angle would be greater that in the latter. (Coarse Pitch Vs Fine Pitch.) This means that a fixed pitch propeller can only have its blades operating at the most efficient angle of attack (Thrust/Torque) at one speed.

So what happens to the thrust of a propeller that is designed to be most efficient at cruising speed, when it is very slow, say during take-off? Well, even though the RPM will be less than the maximum because of the very high propeller torque (caused by the very high blade angles) the thrust will also be very high (because of the same high blade angles). As the aeroplane accelerates the angle of attack of the blades will reduce, allowing the RPM to increase: the thrust will initially increase but at about 'lift off' speed, will start to decrease and will continue to decrease until, at a speed somewhere above cruising speed the blades will reach zero 'lift' angle of attack and the thrust will be zero. (The aeroplane will have to be diving to achieve this.)

The following three graphs show what happens to blade A/A, RPM and Thrust as the aeroplane accelerates from stationary (Figure sixteen).

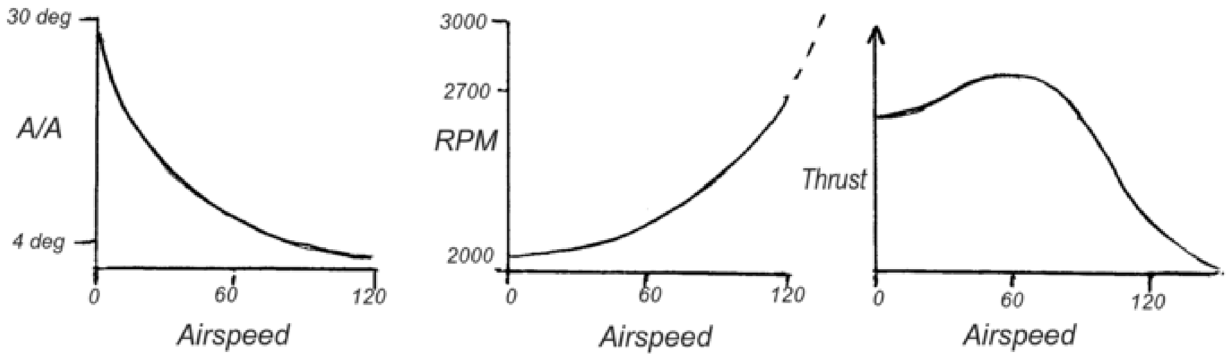


Figure Sixteen – A/A, RPM & Thrust during acceleration.

For those of you who don't mind some simple mathematics you will find at Annex A an expanded explanation of the effect of air speed on a fixed pitch propeller including an explanation of why the thrust graph has that strange 'hump' in it.

Flying an aeroplane with a fixed pitch propeller is like driving a car stuck in one gear. If it is stuck in first gear it will accelerate away from a standing start quite rapidly but reach maximum RPM at quite a low speed, and then be limited to this speed. This is the equivalent of a fine pitch propeller. If it is stuck in top gear it will be hard to get moving without stalling the engine or doing a lot of 'clutch slipping' but after a long and slow acceleration it will finally reach the car's top speed. This is the equivalent of a very coarse pitch propeller. Wouldn't it be nice if we could select a different propeller pitch for each speed, in the same way that we can select gears of a successively higher ratio as we accelerate a motor car?

During the 1930's, as aero engines became more powerful and the potential top speeds of aeroplanes increased, it was necessary to develop a propeller which gave the pilot control of the pitch so that he could 'change gear' as required. This was called the 'variable pitch propeller'. The variable pitch propeller initially came with two 'gears'; fine pitch for take-off and climb and coarse pitch for cruise and top speed. It was achieved quite simply by having the blades rotate within the hub. The amount of twist did not have to change, just the overall basic blade angle. This was controlled by a lever in the cockpit (not unlike a car 'stick shift') via a system of mechanical links. The pitch control was usually marked "coarse pitch" and "fine pitch" at the appropriate positions of the lever. This simple design change gave aero engines the capability of operating much more efficiently. Indeed, the take-off performance of the famous WW2 fighter, the Hawker Hurricane had its take-off roll halved by the replacement of its fixed pitch wooden propeller, optimized for high speed, with a two position variable pitch propeller. The following three graphs at Figure Seventeen show what happens to blade A/A, RPM and Thrust as the aeroplane accelerates from stationary using a two position, variable pitch propeller, in this case 'changing gear' at about 80 knots.

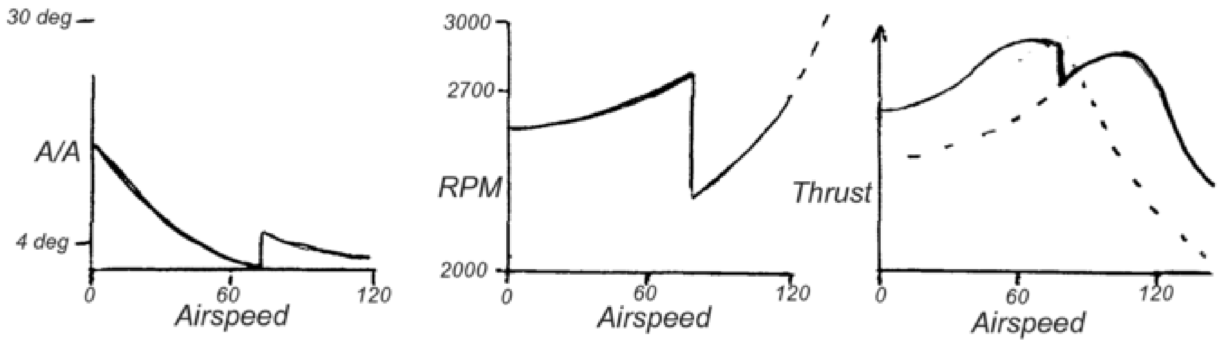


Figure Seventeen – Two position Variable Pitch Propeller

Later a third and sometimes a forth 'gear' were added. On larger engines, in order to assist the pilot in moving the blades, a hydraulic actuating system was used. Some engines used the engine oil pressure to do this, whilst more powerful engines had an independent oil pressure system fitted. Oil pressure was fed into a cylinder in the propeller hub, often called the 'dome' and moved a piston which was connected to the blades by a gear or a cam to translate the pistons fore and aft movement into a rotary movement which rotated the blades against a centrifugal force provided by 'counter weights' on each blade. The following diagram (Figure Eighteen) shows a typical hydraulically actuated variable pitch propeller hub.

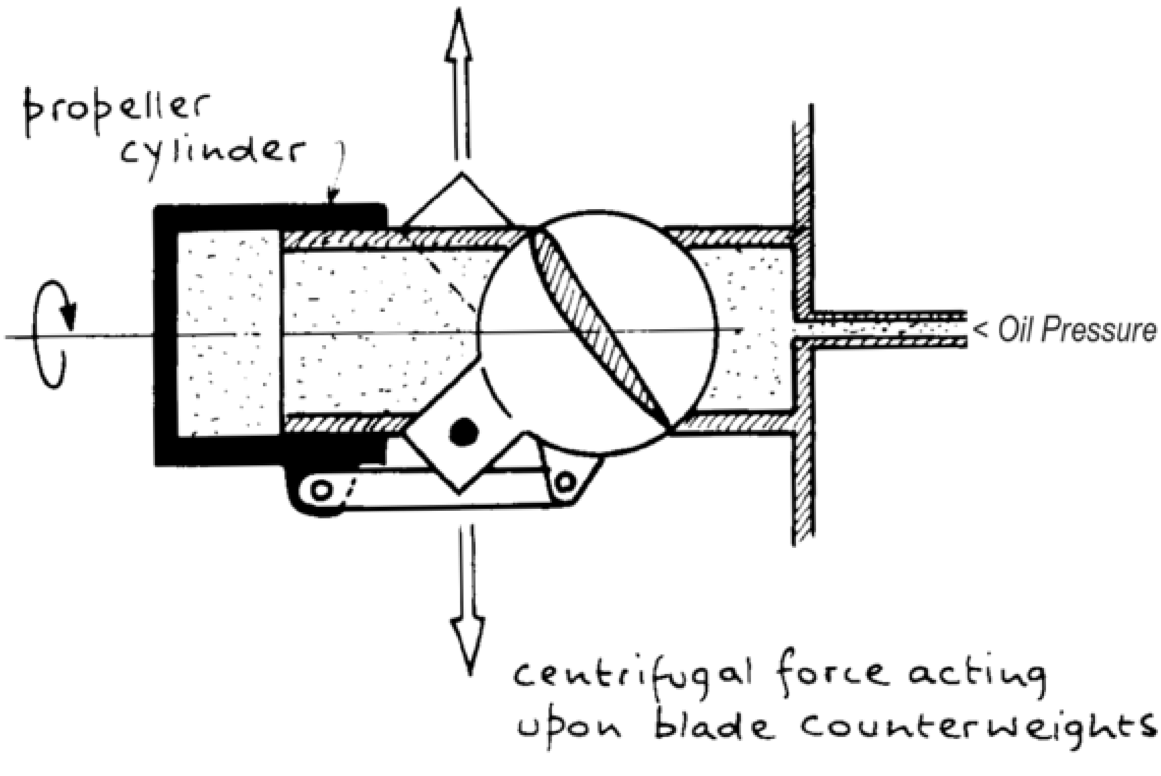


Figure Eighteen – Hydraulic Variable Pitch Propeller Hub

It did not take long before some bright engineer realized that the blade angles did not have to be limited to two or three positions but could be moved progressively through all of the possible angles hydraulically and the oil pressure required to do this could be regulated by a simple 'governor' system similar to that which had been used on steam engines for over a hundred years! (The 'centrifugal governor' was invented by James Watt in 1788.) The following diagram (Figure Nineteen) shows a typical governor system fitted to the hydraulic propeller.

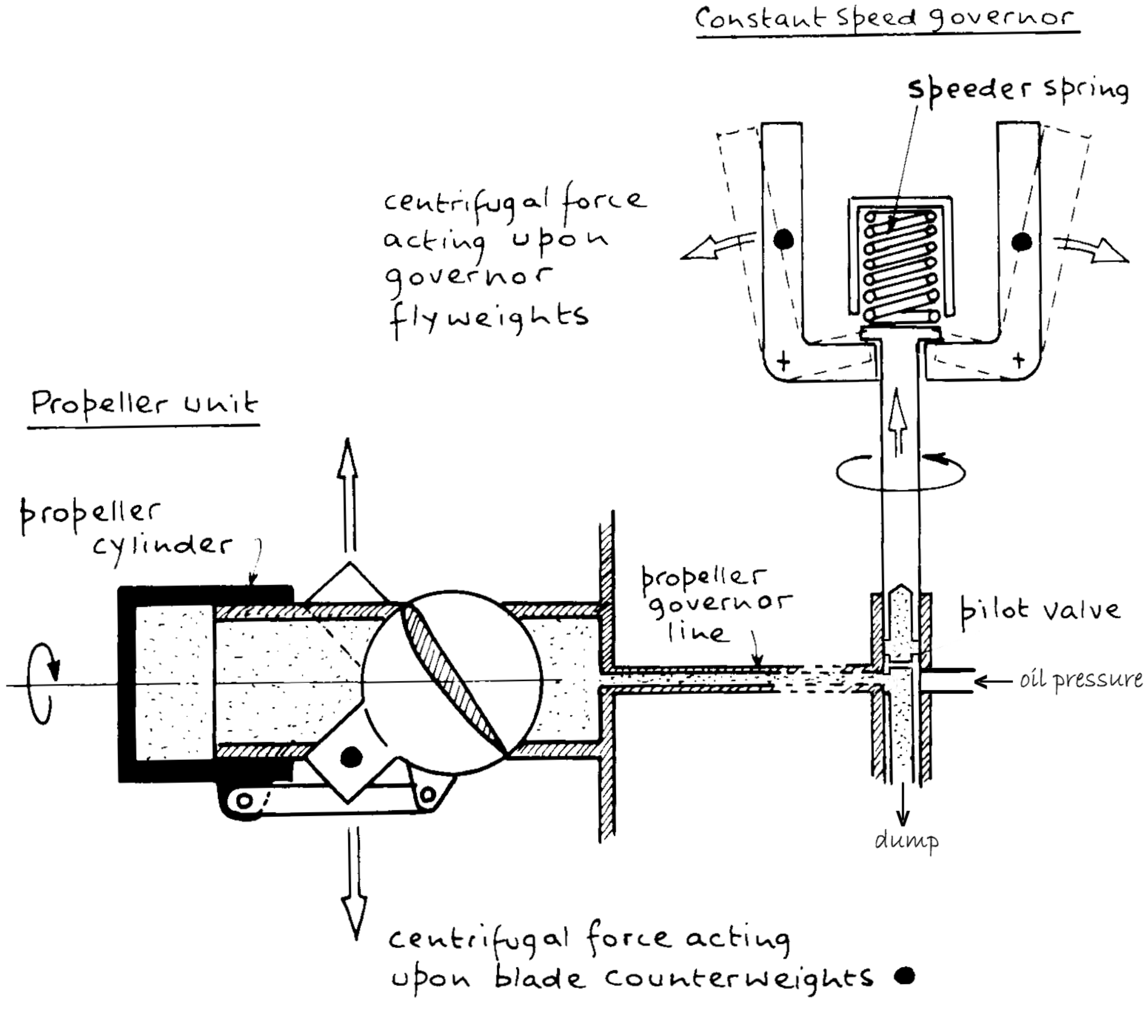


Figure Nineteen – Hydraulic Variable Pitch Mechanism with Governor.

The operation of this combined unit is quite simple. The governor weights are spun by the engine and tend to 'fly' out against the compression of a spring, called a 'speeder spring'. The weights control a 'pilot valve' which in turn controls the oil pressure flowing to and from the propeller hub cylinder (dome).

With a fixed pitch propeller, changes in the RPM are caused by either a change of engine power setting or a change in airspeed or both. The governor's 'job' in this new hydraulic mechanism is to control this potential RPM change as follows:

If the propeller RPM tends to increase, the governor rotation speeds up, throwing the weights further from their centre of rotation, lifting the pilot valve against the action of the speeder spring and allowing oil pressure to 'bleed' from the propeller cylinder via the 'dump' line. The counterweights rotate the blades to a higher blade angle (coarser pitch) which increases the prop torque and stops the tendency to increase RPM, (this is the action depicted in the diagram at Figure Nineteen). Conversely, if the RPM tends to decrease the governor rotation slows, the speeder spring pushes the pilot valve down and allows oil pressure into the 'dome', which drives the blades against the action of the counterweights to a lower blade angle (finer pitch), reducing the prop torque and thereby stopping the tendency of the RPM to decrease.

The modern propeller governor is so sensitive to potential RPM changes that it reacts to correct these potential changes before the aviator even notices a change in RPM on the engine tachometer. All he/she sees is a stable RPM regardless of the airspeed or power setting, (provided the engine power is set within the governor range). So unless the aviator changes the compression of the speeder spring the RPM will be automatically maintained by this mechanism.

The cockpit control, be it a lever or a knob, simply controls the compression of the speeder spring. If the control is moved to increase the spring compression the spring will push the pilot valve down introducing more oil pressure into the propeller cylinder, reducing the pitch of the blades and causing the RPM to increase. The rotation of the governor flyweights will increase and lift the pilot valve back to its neutral position against the increased speeder spring pressure and the RPM will stabilize at this new setting, as previously described. Thus the RPM setting depends upon the amount of compression of the speeder spring and since the governor reacts so quickly to these changes of speeder spring pressure the aviator can simply use the engine tachometer to set the desired RPM.

In order to prevent the aviator selecting RPM settings which would over-speed the propeller or cause the blades to stall, the governor has maximum and minimum RPM limits 'built in' and the propeller has fine and coarse pitch 'stops' built into the hub too.

By 1940 this type of propeller was fitted to all powerful piston engine aeroplanes and is still in use today. To continue the 'gearbox' analogy, this new type of propeller is equivalent to the automatic gear box on a modern motor car but better, because the car gearbox has a set number of ratios (3, 4 or 5 these days) whilst the propeller has an infinite number of 'ratios', that is, blade angles.

Because of its ability to maintain a constant RPM this new propeller was called a 'Constant Speed Propeller'. This was a new name for a new way of looking at how the pitch of the propeller was controlled. No longer did the aviator set a pitch, he/she simply set the compression of a little spring in the hydraulic governor to a certain RPM (by reference to the engine tachometer) and the governor automatically maintained this RPM. The control in the cockpit is now called the 'Prop Governor Control' or the 'RPM Control': however many pilots (including instructors!) still refer to it as the Pitch Control and still call high RPM settings 'Fine Pitch' and low RPM settings 'Coarse Pitch' (indeed some aeroplanes still have their propeller governor control labeled this way!). This is not correct and is very confusing for student pilots because in certain flight conditions such as high speed and high RPM settings the blades can in fact have a very coarse pitch. This is yet another example of incorrect and confusing information being spread as a result of ignorance.

When using a constant speed propeller the tachometer can no longer be used as an indicator of throttle setting as it can with a fixed pitch propeller. All aeroplanes fitted with constant speed propellers will also have a gauge in the cockpit which indicates 'Manifold Air Pressure' (MAP), which is an indication of the pressure of the fuel/air mixture entering the intake manifold of the engine. This gauge is used to set the throttle position and the combination of the RPM and MAP settings determines the power output of the engine.

The constant speed propeller has enabled aero engines to develop full power at all airspeeds and has enabled the aircraft fitted with them to attain their full performance potential without compromise. The following three graphs (Figure Twenty) show what happens to blade A/A, RPM and Thrust as the aeroplane accelerates from stationary using a constant speed propeller. Note that even though the RPM and Angle of Attack are constant the Thrust will decrease with speed because the increasing blade angle causes the total reaction to 'lean' further back as previously described.

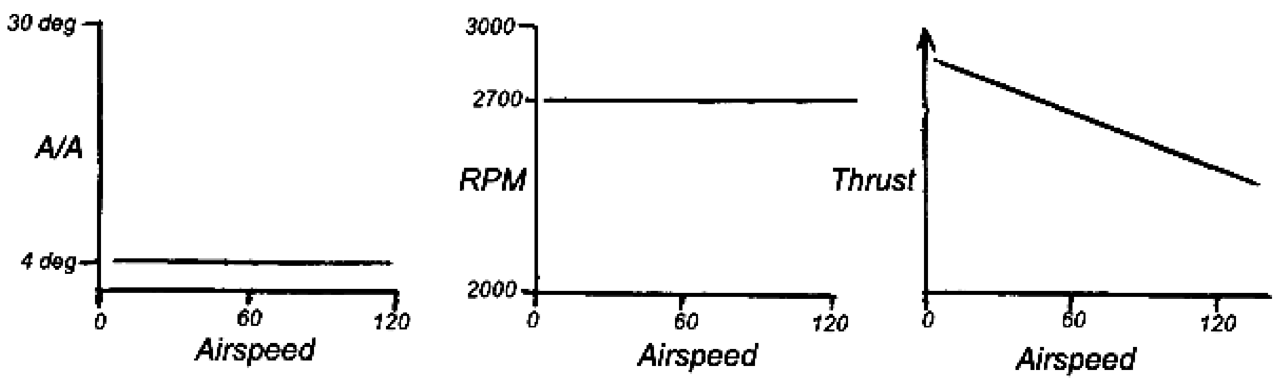


Figure Twenty – A/A, RPM & Thrust of a Constant Speed Propeller

Nowadays engines with a power output as low as 150 HP are often fitted with hydraulic constant speed propellers. Fixed pitch propellers are still found on engines of less power simply because the weight, complexity and cost of the constant speed propeller are not warranted on the smaller engines. Many 'ultra-light' aeroplanes have reverted to the use of manual variable pitch propellers as a compromise between efficiency, weight and cost, whilst some have only 'ground adjustable' variable pitch propellers for the same reason.

I previously mentioned that the mechanical movement of the pitch angle of variable pitch propellers was made hydraulic to assist the pilot in moving the blades. This was necessary because the blades of all propellers, by virtue of their rotation within the hub, are subject to a number of forces in addition to lift and drag. The rigidity of a fixed pitch propeller absorbs these extra forces but because the blades of a variable pitch/constant speed propeller can rotate within the hub, control of the effect of these forces has to be incorporated within the design of the propellers pitch control mechanism. What are these forces?

The first force is the 'centrifugal force' which tends to pull the blades from the hub! Well-engineered bearings are necessary to prevent this happening but still allow them to rotate freely within the hub. The second force is called the "Aerodynamic Twisting Moment". This twisting moment is caused because the aerodynamic centre of the blade is well forward of the blades axis of rotation within the hub. The following diagram illustrates (Figure Twenty One).

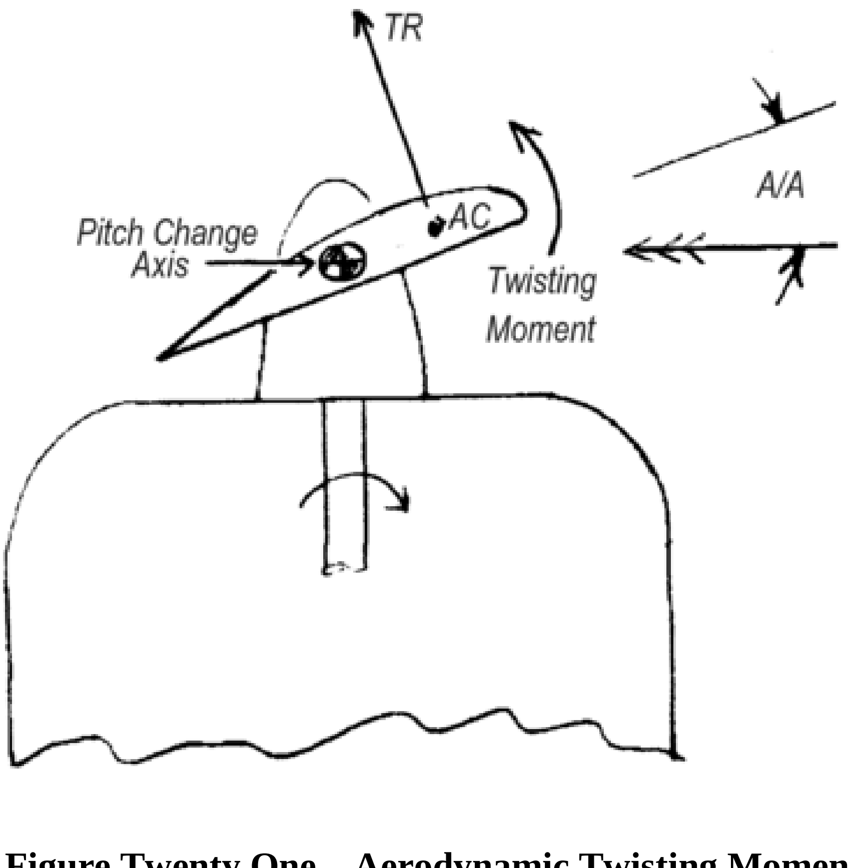


Figure Twenty One – Aerodynamic Twisting Moment

The normal aerodynamic 'pitching moment' which we have discussed in the lesson on Lift, is over powered by the aerodynamic twisting moment and tends to drive the blades to excessive coarse pitch.

The third force is called the 'Centrifugal Twisting Moment'. This twisting moment is caused by tangential components of the centrifugal force on the blades. It becomes greater as the pitch angle increases. The following diagram illustrates (Figure Twenty Two)

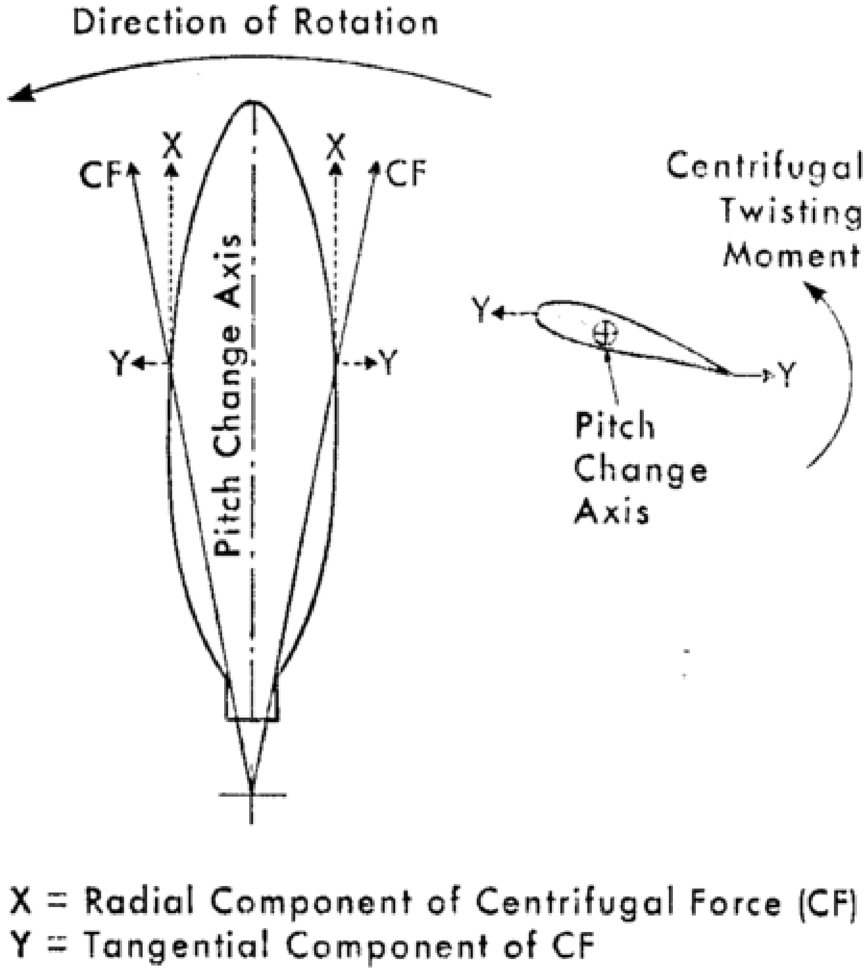


Figure Twenty Two – Centrifugal Twisting Moment

The torque of the centrifugal twisting moment can be up to 20 times greater than the torque of the aerodynamic twisting moment and if unchecked would dominate and drive the blades to excessive fine pitch.

Many constant speed propeller hubs work in the reverse sense to that which I explained earlier, in that they allow the centrifugal twisting moment to tend to reduce the pitch angle and use hydraulic pressure to either resist this tendency to maintain pitch or overcome it to increase pitch. This system works well until there is a loss of oil pressure, then the propeller blades will rotate to fine pitch and start to windmill with the power on! This will require the aviator to quickly 'throttle' the engine or a serious engine over speed will result. (See Annex A) Before the invention of 'feathering' propellers this was called a 'runaway propeller' and could be quite dangerous. (I will talk about feathering propellers in just a moment).

The propeller hub illustrated earlier in Figure Nineteen had special 'counterweights' fitted to the inner part of the blade (the 'non-contributing' part) in such a way that the centrifugal twisting moment on them was greater than and opposite to, that on the blade. The following diagram illustrates (Figure Twenty Three).

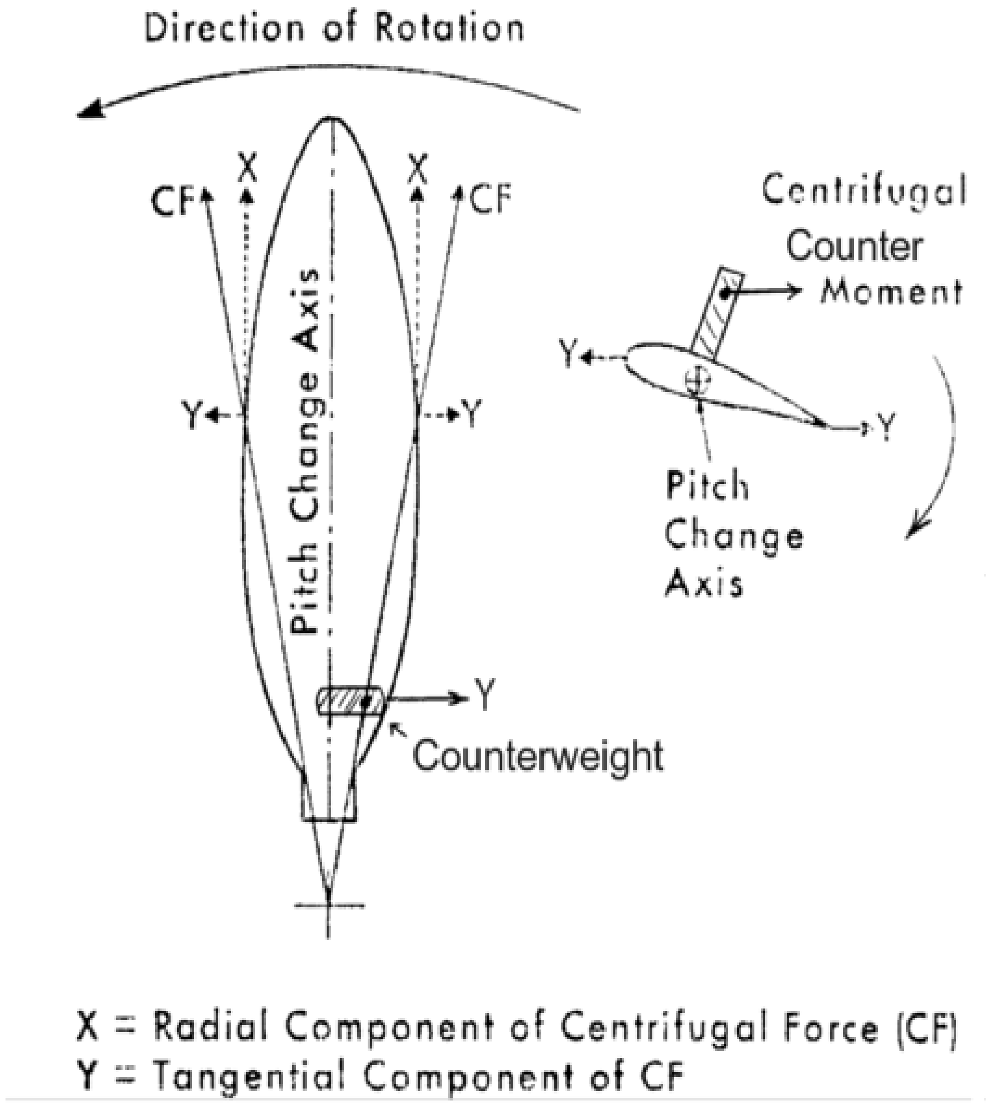


Figure Twenty Three – Counter weights and Centrifugal Counter Moment

With this system an oil pressure loss will allow the blades to twist to the coarse pitch stop, thereby preventing an engine over speed and allowing the flight to continue (assuming an independent propeller oil system failure but continuing engine oil pressure). A later development of this system enabled the aviator to override the coarse pitch stop in the hub and allow the blades to continue twisting to 90º of pitch! This is called 'feathering' the propeller and is extremely useful in the event of an engine failure on a multi engine aeroplane. In this event the remaining engine(s) have the 'responsibility' of keeping the aeroplane airborne at a controllable speed so the last thing 'they' need is the extra drag of a windmilling propeller to overcome! Feathering the propeller stops its rotation and presents the blades at zero lift angle of attack to the airflow thereby reducing the drag as much as possible (Figure Twenty Four).

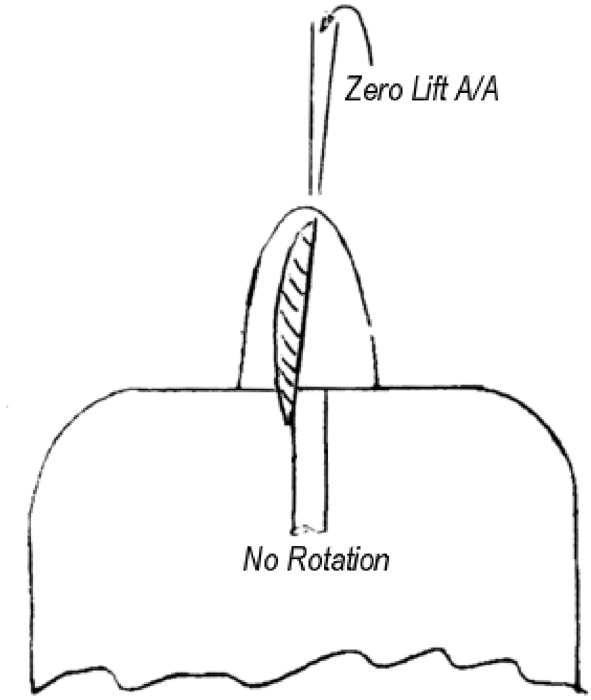


Figure Twenty Four – Feathered Propeller

Prior to the 1940's many multi engine aeroplanes were built without feathering propellers (because they hadn't been invented yet) and without counterweighted blades. Many crashes and many deaths occurred due to 'runaway propellers' that couldn't be feathered. Nowadays a multi engine aeroplane cannot be certified unless it is fitted with propellers capable of being feathered. Certain multi engine 'vintage' aeroplanes, such as the De Havilland 'Dragon' and 'Rapide', which only have fixed pitch propellers, have been given special approval to fly, but if they suffer an engine failure, it is said that the other engine simply takes the aeroplane to the scene of the crash!

Non-counterweighted constant speed propellers are still fitted to many modern light single engine aeroplanes. These propellers use engine oil pressure in the 'dome' (boosted by a small booster pump within the governor) so I guess the idea is that if the oil pressure fails the engine is about to fail too, so the tendency for the propeller to run away will be offset by a lack of power! However, aerobatic aeroplanes which have constant speed propellers, have counterweighted blades because of the possibility of experiencing transient oil pressure fluctuations during aerobatic manoeuvres. (Most aerobatic aeroplanes also have 'inverted' oil systems, to guarantee continuity of supply.) Modern counterweighted propellers have the counterweight cast as an integral part of the blade, right at the hub, and the counterweight is usually hidden by the spinner so it is hard to tell the difference without close inspection.

The introduction of light 'Gas Turbine' engines has brought with it a more complex version of the constant speed propeller described herein, whereby feathering and reverse thrust capability are also incorporated, even on single engine aeroplanes. These more complex mechanisms will not be discussed in this lesson, but they are based on what has been described here.

During World War Two, because of the demand for ever improving aircraft performance, more and more powerful engines were being fitted to combat aircraft. It was found that this extra power could be absorbed by increasing the number of blades and the chord width of each blade. But not by increasing propeller diameter as this would cause the propeller tip speed to approach the speed of sound (Mach 1.0) thereby reducing its efficiency. (This places a serious limit on the diameter and RPM that can be used on any propeller, see annex A for more details). By the end of the war the later marks of Spitfire were fitted with engines twice as powerful as the Mark 1 and 'turned' five bladed constant speed propellers.

A propeller also causes an assortment of unwanted forces on the whole aeroplane too. I refer you to annex B for a description of these forces and their effects on aeroplane handling.

The propeller was the first successful means of moving an aeroplane through the air, but with increasing demand for speed its ability to translate engine power into thrust ran up against the inherent limitations of its own design and the effect it was having on the aviator's ability to control the aeroplane. A new power source was needed and of course necessity being the 'mother' of invention, a new source came along just in time, the 'Turbo Jet'.

After having done 'battle' with the effects of propellers driven by engines of up to 450 horse power as a student pilot, I was introduced to the turbo jet in 1963. When I first experienced the straight, no side effects thrust and additional power of the turbo jet all I could think was "baby, where have you been all my life?"

But that's another story.

List of Annexes to the lesson on: Thrust

Annex A. The effect of air speed on a fixed pitch propeller

Annex B. The effect of the Aerodynamics and Dynamics of the Propeller on Aeroplane Control

Annex A

The effect of airspeed on a fixed pitch propeller

A common general aviation engine is the 320 cubic inch 4 cylinder horizontally opposed 160 HP aero engine. It normally drives a 72 inch diameter propeller with a 66 inch pitch. The engine is 'red lined' at 2700 RPM and will cruise comfortably at 2500 RPM.

First, what do I mean by a 66 'inch' pitch? Rather than express the pitch in degrees - because as we have seen, the blade angle varies along the length of the blade - propeller manufacturers express the (geometric) pitch as if it were a 'wood screw': that is, the pitch is expressed as the theoretical distance the propeller will move forward for every revolution. On this engine a 60 inch pitch would be a fine pitch propeller and a 70 inch pitch would be a coarse pitch propeller.

The speed of the propeller tips at the engines 'red line' RPM can be simply calculated as follows:

Tip speed (in ft/sec) = Revolutions per Second x Diameter in Feet x Pi

Tip speed (in ft/sec) = (2700RPM ÷ 60Seconds) x (72 inches ÷ 12) x (22/7)

= 45 (Revs per second) x 6 (feet diameter) x 3.143 (pi)

= 848.6 ft/sec

848.6 ft/sec is about 8/10 the speed of sound at sea level or Mach 0.8. Any faster and the tips will start to suffer transonic effects which would make the propeller about as efficient as a car spinning its wheels on ice! That is why most low power aero engines which drive the propeller directly are designed to deliver full power at these low RPM values. Some more powerful engines which work more efficiently at higher RPM translate this power to the propeller by a fixed ratio reduction gearbox.

As the following diagram (Figure One) shows, at the 75% point on the propeller blade (using similar mathematics) the speed at 'red line' RPM is 636 ft/sec and at cruise RPM 589 ft/sec. A typical aeroplane using such an engine would have a cruise speed of 120 knots, which is 202 ft/sec. So the pitch at the 75% point would be $20^{o}+4^{o}=24^{o}$ because the airflow is approaching the propeller blades at an angle of 20^{o}. (I am going to ignore 'induced airflow' for the moment.)

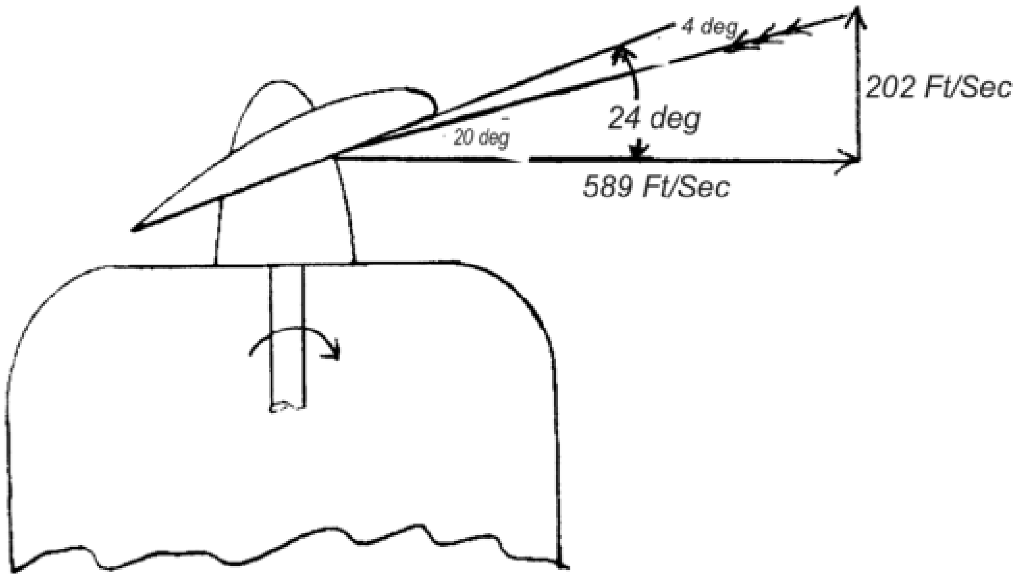


Figure One – 120 knots at Cruise RPM

Prior to take off, if the aviator opened the engine throttle fully before releasing the brakes, the engine would not develop full power because without forward speed the entire propeller is at such a high angle of attack (24º at 75%) that the resulting propeller torque would limit the RPM to about 2100 which is 77% of maximum. But despite this reduced RPM the thrust will be quite high. (I am assuming that the aeroplane is taking off from an airfield at zero feet 'density altitude', which means that TAS = IAS.)

As the aeroplane gathers speed the angle of attack of the blades will decrease, reducing the propeller torque and allowing the RPM to increase. Thrust will initially increase slightly too.

By the time the aeroplane reaches 'lift off' speed (about 60 knots or 101 ft/sec) the RPM will have increased to about 2250 (83% of maximum) and the angle of attack of the blade at the 75% point will be 24º-11º=13º (11º is the angle the airflow is now approaching the propeller blades) and the thrust will be at a maximum.

Once the aeroplane reaches a climb speed of 85 knots the RPM will have increased further to about 2350 (87% of maximum) and the angle of attack at the 75% point will be 24º-14º=10º but the thrust will now be decreasing. Indeed throughout any further acceleration the thrust from the propeller will reduce further because the effect of the angle of attack reduction on the thrust is greater than the effect of the increased RPM. Ultimately the aeroplane will reach cruising speed and the angle of attack will be 24º-20º= 4º, as previously calculated, and the thrust available will be only slightly greater than the drag. The aviator at this point would normally 'throttle' the engine slightly to maintain cruise speed.

However, if the throttle is left 'wide open' and the airspeed allowed to increase further the RPM will continue to increase and the angle of attack of the blades and the thrust will reduce further. If the aeroplane is then dived slightly a speed will be reached where the propeller blades will be at zero lift angle of attack and the thrust and the propeller torque will be zero. This speed could, of course, only be attained by diving the aeroplane and would require the aviator to retard the throttle control to prevent engine RPM from increasing beyond its limit. Beyond this speed the propeller will develop a negative angle of attack and start to 'wind mill' and cause increasing drag on the aeroplane, (I am not talking about the drag resisting rotation here but the 'negative thrust' caused by the windmilling propeller.) The following diagram shows this 'windmilling' effect (Figure two).

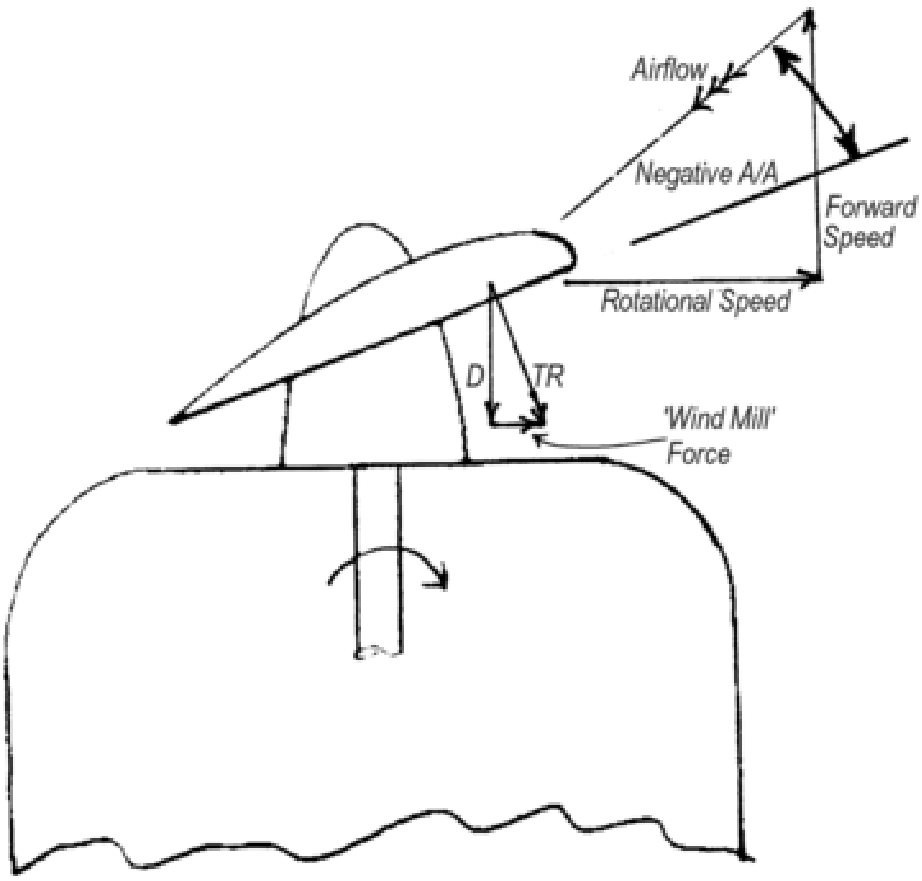


Figure Two – Forces on a 'Windmilling' Propeller

You can see from the diagram that in addition to 'D', the 'negative thrust', the propeller is now driving the engine, in much the same way as the wheels drive the engine of a car rolling down a hill, in gear, when the driver 'lifts his foot off' and lets the engine act as a brake. (Anyone who has 'clutch started' a car with a flat battery will know exactly what I mean by 'the wheels driving the engine'.) As the aeroplane dives steeper and steeper and gets faster and faster, it will be necessary to retard the throttle more and more to prevent the engine RPM 'over speeding'.

Quite often the never exceed speed (Vne) of an aeroplane fitted with a fixed pitch propeller is predicated upon the speed that will cause the propeller to 'windmill' at the engines 'red line' RPM with the engine throttle completely closed.

A question that should have popped into your head by now is: "how can the propeller operate at 24º angle of attack when stationary and not be stalled?" Good question. Go back and look at annex A to the lesson on Lift. You will notice that the 'lift' graph doesn't stop increasing in value till 22º at high 'Reynolds number'. To reiterate, Reynolds Number defines the 'stickiness' of the air. Remember the Coanda effect? Well, the ability of the air to stick to a curved surface and not break away depends upon its density and viscosity, the size of the curved surface it is following (the 'scale effect') and the speed of the airflow. The primary factor affecting the propeller blade is the speed of the airflow. Put simply, the faster the airflow the more it sticks to the curve of the blade. In a future lecture we will discuss the stall characteristics of wings at low subsonic speeds and low Reynolds numbers, but even at 2100 RPM the 75% point on the propeller blade is doing Mach 0.6, so it is operating at a very high Reynolds number and therefore the airflow doesn't break away as readily and the wing (blade) can operate at a much higher angle of attack without stalling.

That still leaves 2º to be accounted for, doesn't it? Well, if we now stop ignoring the induced airflow effect we will find that it accounts for the missing 2 degrees because the propeller 'thinks' it is moving forward even faster, so the induced airflow will reduce its angle of attack by a further 2º.

This means that a large percentage of the 'stationary' propeller is operating at a very high angle of attack and delivering a very high thrust. However, despite the high Reynolds number and the induced airflow, the inner part of the propeller is stalled at very low forward speed. It then un-stalls and starts contributing to the thrust during the initial acceleration, which is why the thrust initially increases as these parts of the blades 'come on line' during the take-off roll. The thrust reaches a peak at about lift off speed and then decreases as the aeroplane accelerates further. (This is why there is a "Hump" in the 'Thrust' graph of a fixed pitch propeller.)

One final word on induced airflow: if whilst still on the ground you were to stop with the aircrafts tail pointing into a moderate breeze and the engine idling, you would feel the vibration caused as more of the propeller blade is stalled because the tailwind has cancelled out much of the induced airflow effect.

An extreme example of the 'problem' of fixed pitch propellers was the Supermarine S6B racing seaplane which was the outright winner of the Schneider Trophy in 1931 and then set a new world airspeed record of 407mph (346 knots.) It was powered by a 2600 horse power engine driving a 12 foot diameter two blade fixed pitch wooden propeller! (It only had a 30ft wingspan!) The geometric pitch of this propeller was so great that its initial take off run was made with the blades fully stalled and most of the power being absorbed by the massive propeller torque being generated. (Proving that there is still significant lift being developed from a stalled 'wing'.) The propeller was optimized for its design speed of 350 knots so it took a long time to reach this speed and even when it did the propeller was operating very inefficiently, as you can imagine.

The Supermarine S6B

The S6B's successor, the famous 'Spitfire' fighter, entered service with a 1050 horse power engine also driving a two blade fixed pitch wooden propeller. Its take off and acceleration also suffered as a result. The Spitfire propeller was soon upgraded to metal variable pitch and finally constant speed multi blade designs which significantly improved the efficiency and also allowed for a continual increase in the power output of the Spitfire's engine.

1936. Prototype Spitfire: 1050HP, Two blade fixed pitch wooden propeller.

1945. Mk22 Spitfire: 1850HP, Five blade constant speed metal propeller.

Annex B

The effect of the Aerodynamics and Dynamics of the Propeller on Aeroplane Control

In addition to thrust, there are four ‘side effects’ produced by a propeller which affect the handling of an aeroplane. Two are aerodynamic and two are, as the title suggests, dynamic. By dynamic I mean those physical forces which accompany any mass which is rotating rapidly. (40 to 50 times per second.) I have categorized the forces under these two general headings as follows:

Aerodynamic:

1. Slipstream Effect.
2. Asymmetric Blade Effect.

Dynamic:

1. Torque Reaction.
2. Gyroscopic Effect.

First let’s look at the aerodynamic effects, and the first of that category is the slipstream.

A rotating propeller will impart a rotation to the slipstream in the same direction. This rotation produces a helical airflow which in turn produces an asymmetric flow over the fin and rudder, that is, the helical airflow impinges on the vertical tail surface above the fuselage at a slight angle but not on the one below because there isn’t one below! (The aeroplane when viewed from the side is asymmetric).

The angle that the airflow impinges on the fin and rudder is an ‘angle of attack’ and will produce an aerodynamic force to one side (a sideways ‘lift’). This aerodynamic force will cause the aeroplane to yaw and will necessitate a rudder input from the pilot to correct it. The following diagram (Figure One) shows this helical slipstream over the aeroplanes fin and rudder and the resulting ‘sideways lift’ force.

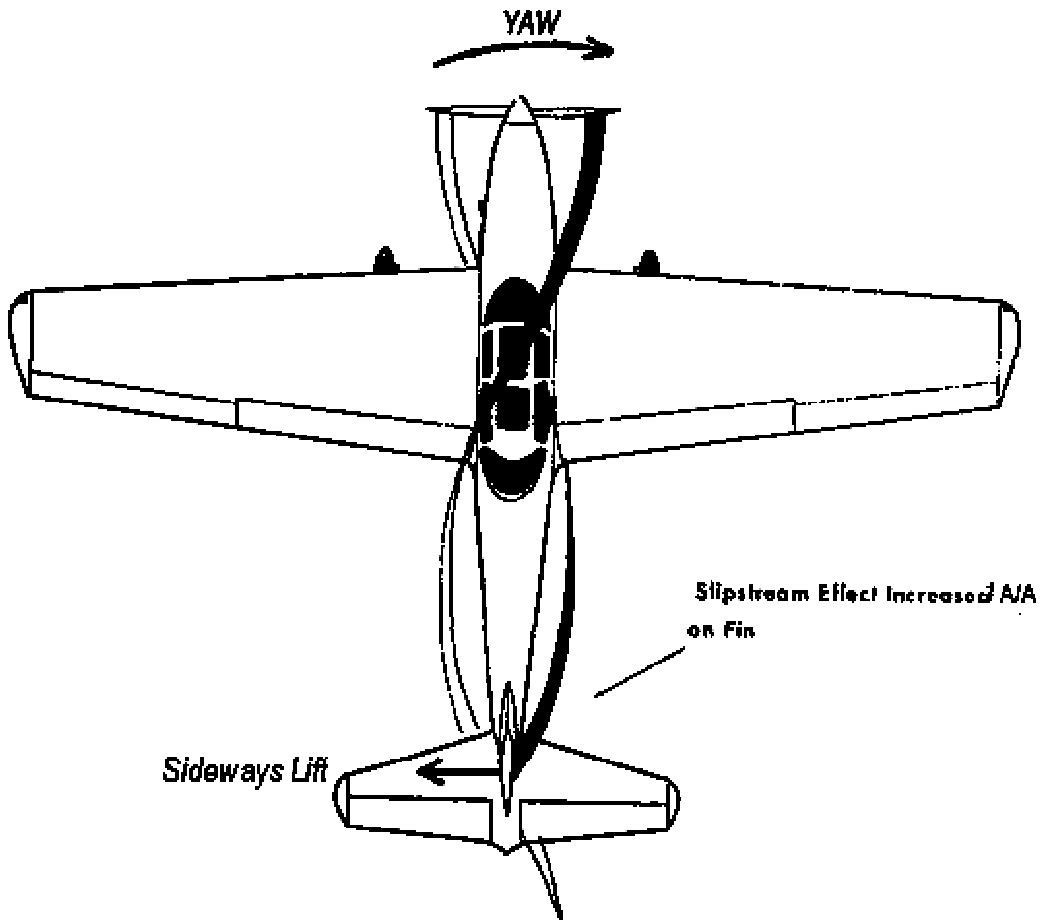


Figure One – Helical Slipstream

The helix produced by the propeller will depend upon the rotational speed of the propeller and the forward speed of the aeroplane. At high power and low speed, such as at take-off, the helix will be ‘tight’; whilst at cruising speed with the engine throttled slightly the helix will be ‘relaxed’. In the first case the angle of attack on the fin will be greater than in the second ‘relaxed’ case, so the aeroplane will have a greater tendency to ‘swing’ (yaw) on take-off.

Which way it will swing will depend upon which way the engine rotates. Just to confuse everybody, British and American engines generally rotate in opposite directions to each other. When viewed from the cockpit an American engine rotates clockwise and a British engine, anti-clockwise! The aeroplane in the preceding diagram has a British engine.

From the early years of aeroplane development, designers have countered the slipstream effect by offsetting the fin so that it is flying at zero degrees angle of attack at cruise speed and power. This eliminated the slipstream effect at cruise speed but only slightly diminished it during take-off, so a rudder correction by the pilot was still required. As aero engines became more and more powerful the swing on take-off from this effect became almost uncontrollable. Many engines were fitted with two concentric counter rotating propellers to straighten the slipstream. It worked, but at a cost of greater weight and complexity.

Most modern light aeroplanes don't have offset fins; they have offset thrust lines which help counter the effect over a broader range of airspeeds. How does that work? Imagine an aeroplane that yaws to the left because of the slipstream effect and instead of offsetting the fin, the designer has 'angled' the engine a few degrees to the right. The thrust would now tend to cause a yaw to the right (just like moving the thrust line of an outboard motor on a boat in order to steer (yaw) it). If the power was suddenly increased, the helix from the slipstream would 'tighten' tending to cause more yaw but the added offset thrust would have an equal countering effect. The opposite would occur when the engine was throttled. In this way the slipstream effect can be automatically 'countered' over a greater range of airspeeds.

This offset thrust line works very well on smaller aeroplanes but unfortunately on the powerful piston engine aeroplanes of WW 2 it could not work as the engine would have to be angled off quite a bit and could you imagine a MK 16 Spitfire or P-51 Mustang flying around with a 5 degree bend in the middle?

Let us now look at the second aerodynamic effect, the Asymmetric Blade Effect. The asymmetric blade effect is present whenever the axis of rotation of the propeller is not aligned with the aeroplane's flight path (relative airflow). Once again high power and low speed exacerbate the effect and an excellent example is afforded by a 'tail dragger' aeroplane during the early stages of its take off roll, where the airflow is horizontal but the axis of propeller rotation can be 18º-20º different. First we need to illustrate a situation without asymmetric blade effect to help us understand the problem (Figure Two).

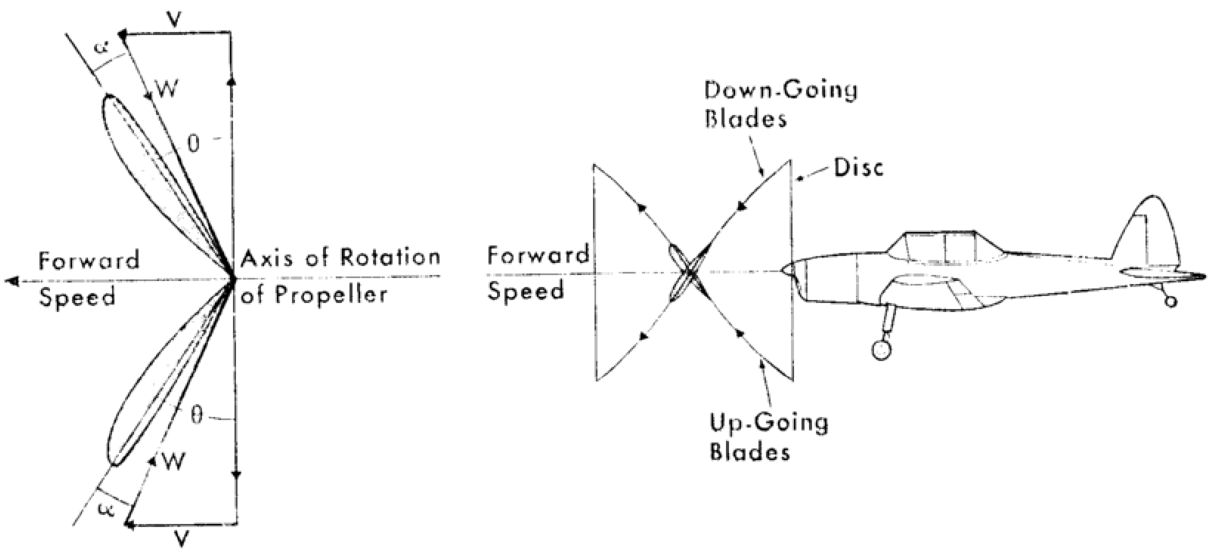


Figure Two – Propeller Blade A/A Symmetrical with Tail Up

The foregoing diagram shows the condition where the axis of rotation is in line with the flight path. In this case the angles of attack and relative airflows on both propeller blades are equal. Also the distance traveled in unit time by both the down-going and the up-going blades are equal and, therefore, the speeds of the blades are equal. The next diagram (Figure Three) shows how the angles of attack and resultant velocities are changed when the axis of rotation is inclined upwards.

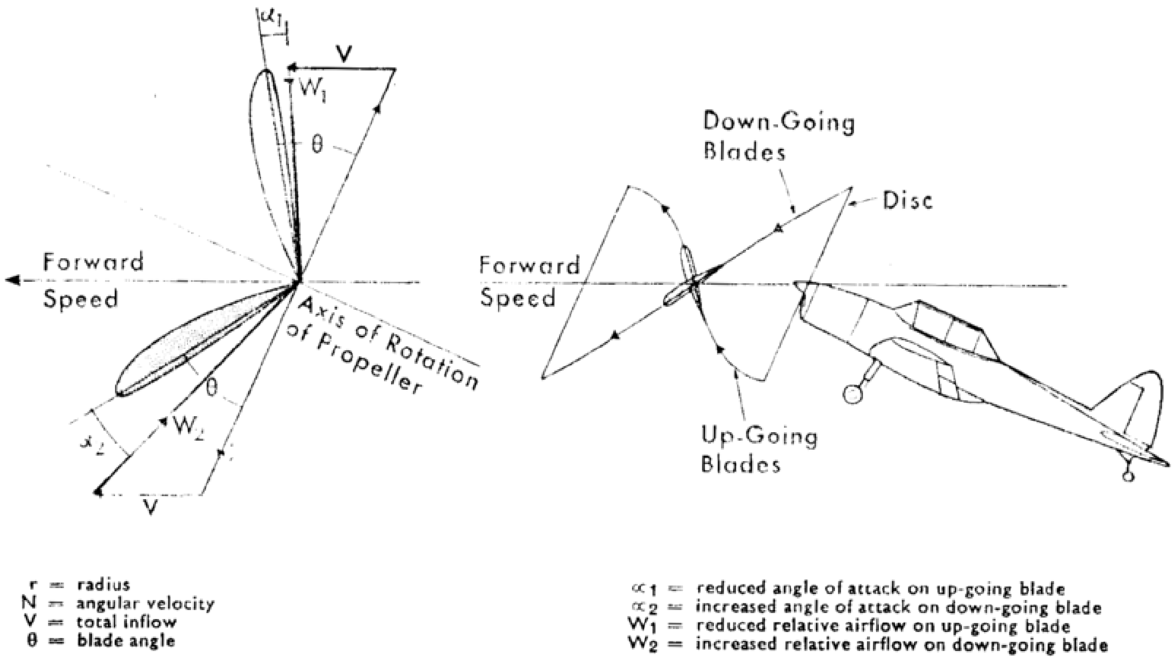


Figure Three – Propeller Blade A/A Asymmetrical with Tail Down

You can now see that the down-going blade has a higher angle of attack and is therefore producing more thrust than the up-going blade. Also, the distance traveled in unit time by the down going blade is greater than that for the up-going blade. This means that the down-going blade has a higher speed relative to the airflow than the up-going blade and will, therefore, produce even more thrust.

This asymmetric thrust will cause the nose of the aeroplane to yaw ‘away’ from the down-going blade. Which way it yaws will also depend upon which way the engine rotates, but the ‘bad news’ is that the yaw is in the same direction as that caused by the slipstream effect.

Asymmetric blade effect will also cause a degree of pitch if the aeroplane is skidding through the air. I will leave you to think about how that effect manifests itself on your aeroplane. (?!)

Now let’s move on to the Dynamic Effects, and the first in that category is Torque Reaction.

We are back to Newton's Third Law again, but in the rotational sense, so it can be paraphrased as: "To every rotational force, there is an equal and opposite rotational force." This is called a 'Torque Reaction' and it means that, as the propeller rotates one way, the torque reaction is trying to rotate the engine and the aeroplane the other way! Since the aeroplane has a much greater mass than the propeller, it doesn't rotate as fast. (Fortunately)

When in the air this torque reaction will manifest itself as a tendency for the aeroplane to roll. This roll is not very pronounced in a light aeroplane and what there is can easily be corrected with the flight controls. On the ground, during the take-off run the torque reaction causes one wheel to be 'loaded' more than the other and this will cause greater rolling friction on that wheel (particularly on a soft surface) which in turn will cause yaw! Once again the direction of rotation of the propeller will determine the direction of this yaw, and once again the 'bad news' is that it is in the same direction as the slipstream effect and the asymmetric blade effect.

Finally we come to Gyroscopic Effect. For those of you who are not familiar with gyroscopes let me briefly digress into a short explanation. A gyroscope is a spinning wheel (like a bicycle wheel) and it exhibits two interesting characteristics. The first is called 'rigidity in space'. What this means is that the axis of rotation of a gyroscope will always point to a point on the other side of the universe for as long as it keeps spinning, independent of the rotation of the earth (or the Galaxy). This is a useful characteristic and is used to stabilize compasses, attitude indicators, turn indicators, autopilots and inertial navigation systems and helps to stop you falling off a bicycle, but it is not the characteristic which interests us here.

The second gyroscopic characteristic, the one we are interested in, is called 'Precession'. Precession is a strange phenomenon in that it moves the effect of a force applied at one point on the spinning wheel to a point 90° further around in the direction of rotation! The following diagram (Figure Four) is an illustration of 'Gyroscopic Precession'.

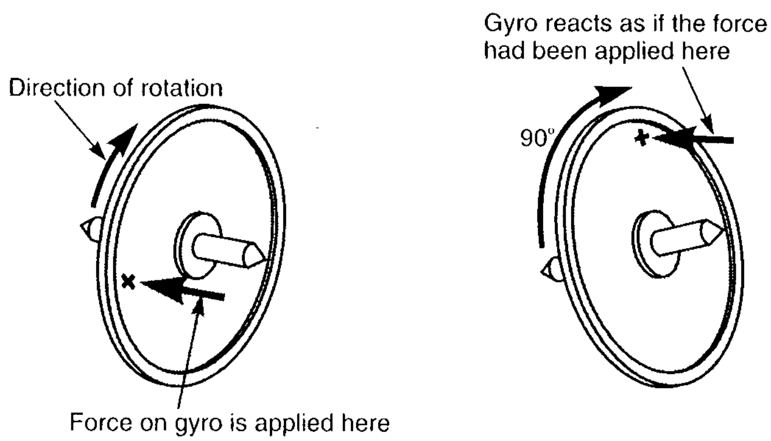


Figure Four – Gyroscopic Precession

When riding a bicycle you lean into a corner to turn, right? When you lean you are effectively applying a force to the top of the front wheel and this is being precessed through 90º to the front of the wheel and turns the front wheel into the corner. "Look mum, no hands!"

So how does this affect an aeroplane? A propeller also acts as a gyroscope and any movement of its axis of rotation is precessed through 90º. So a pitch becomes a yaw and a yaw becomes a pitch! The precession forces are not huge; in fact they are hardly noticeable on a light aeroplane during normal flight manoeuvres - except on take-off, particularly in a 'tail dragger'.

During the take-off roll in a 'tail dragger' there comes a point when the tail has to be lifted to a more level attitude. During this change of attitude we are effectively pushing on the top of our gyroscope and the force is precessed into a yawing force, *and*, you guessed it, it is in the same direction as all of the other effects! (Figure Five).

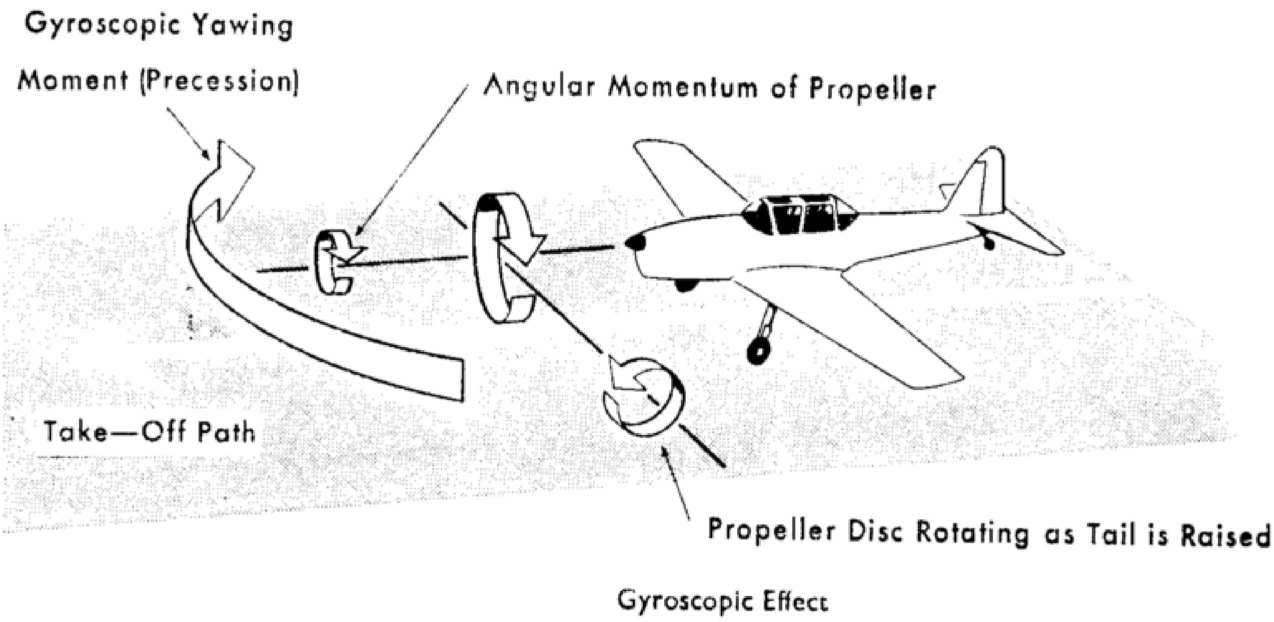


Figure Five – Yaw due to Gyroscopic Precession of Propeller

As I said, the gyroscopic effect is hardly noticeable in modern light aeroplanes, particularly a tricycle undercarriage aeroplane; however, spare a thought for those WW 1 pilots flying aeroplanes fitted with rotary engines, where the whole engine whirled around with the propeller, which caused huge gyroscopic effects when taking off and manoeuvring.

So the final situation is that all four propeller 'effects' are 'ganging up on us' when we try to take off in our tail dragger aeroplane! They are all contributing to 'swing' on take-off as illustrated in Figure Six.

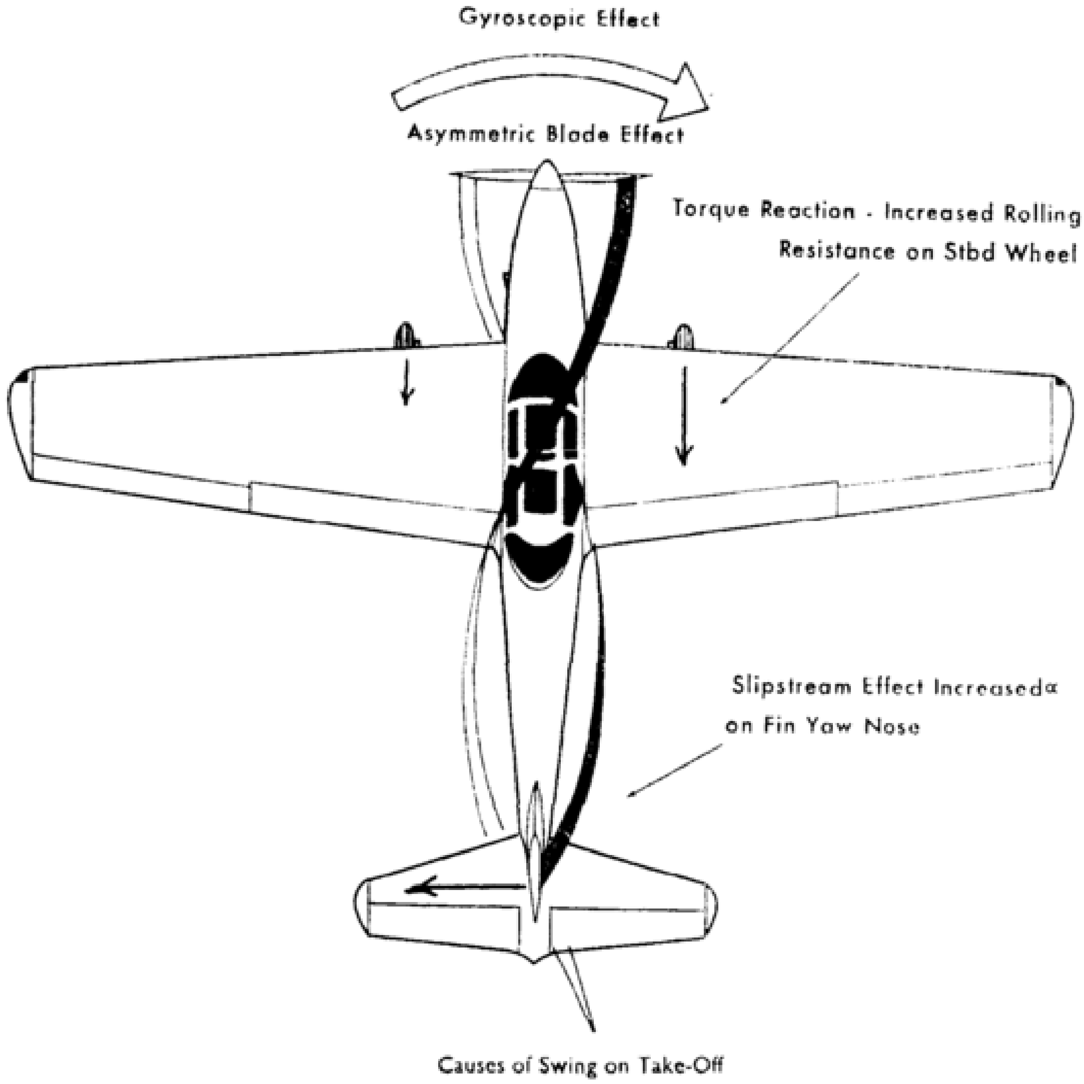


Figure Six – The four compounding forces causing 'swing' on take off

The aeroplane illustrated in the foregoing diagrams is a 145 HP De Havilland Chipmunk. Now imagine that it is a 1400 HP World War Two fighter and you will realize that the jet engine had to be invented, if for no other reason than to prevent further crashes on take-off!

Lesson Five

POWER

You will note that throughout the text of the lessons so far I have used the term 'Thrust' whenever talking about the output of the engine/propeller. In order to maintain flying speed the thrust must balance the drag, so the total drag curve, (detailed in the lesson on Drag), can also be considered to be a 'thrust required' curve. Now, most people when talking about the performance of their car, boat or aeroplane talk about how 'powerful' it is, but the term 'power' means a bit more than we first realize. The correct concept of power is a measure of how much 'work' is done in a certain time and work is a concept which involves applying a force to move a mass over a distance. So we have force, distance and time all mixed into the concept of 'power'.

To be more specific, if we apply a force of one pound to something and, as a result, it moves a distance of one foot, we have done one 'foot-pound' of **work**. If this movement takes a time of one second, then we have exerted a **power** of one foot-pound per second. The simple formula for this is:

Power = Force x Distance ÷ Time.

So twice the force applied or twice the distance moved, in the same time, is twice the power.

From the early days of engine development (both steam and internal combustion), the power output of an engine was expressed in terms that non engineering people could relate to. The term most commonly used was 'Horse Power' (hp). One 'Horse Power' was defined as 550 foot-pounds per second. I can imagine that 'they' could have used any other 'beast of burden' as the reference animal. How about 1000 ft-lb/sec as one "Ox Power', or 5000 ft-lb/sec as one "Elephant Power"? (Good for powering 'Jumbo Jets'.) I guess the horse was the most common beast of burden in those days so a farmer could most easily relate 'Horse Power' to the power of his new 'Steam Tractor'.

Despite half the world operating on the metric system, 'Horse Power' is still the most common term used to express power by non-engineering people because we can relate to the units of force, distance and time used. In the metric system the units have been obscured by naming them after renowned inventors or scientists, so in the metric system the common unit of power is the 'Watt' (named after James Watt, the inventor of the first practical steam engine.) and a 'Watt' is defined as one 'Joule' per second and a 'Joule' is the work done when one 'Newton' of force moves a mass one centimeter. Now a thousand 'Watts' is a 'Kilowatt' (kw) and 746 'Watts' or .746 'Kilowatts' equals one 'Horse Power'.

So in simple terms we can say that one Horse Power is about ¾ Kilowatts or looked at the other way, one Kilowatt is about 1⅓ Horse Power, so a 160hp aero engine is also a 120kw engine.

Most pilots, when referring to the power output of aeroplane engines, whether they live in a metric country or not, use the term 'Horse Power', probably because the majority of aeroplane engines are manufactured in Britain or the USA, where 'Horse Power' rules. I intend to stick with this convention in this book.

The power output of the engine of an aeroplane in flight is the product of the thrust (force) required to move the aeroplane, the distance it moves and the time it takes to move that distance.

So the power required = Thrust required x Distance ÷ Time

And since 'Distance ÷ Time' is Speed

We have: Power required = Thrust required x Speed

And since Thrust required = Drag

Power required = Drag x Speed.

(The speed referred to here is of course the aircraft's **True** Airspeed.)

Simple huh? Now, since we can use the Total Drag graph of the aeroplane to determine the drag at any particular speed, multiplying the drag and the speed values together at any particular speed will determine the power required to fly at that speed. For example: an aeroplane flying at 169ft/sec (100kts) and experiencing 200lb of drag requires:

200 x 169 = 33,800 ft-lb/sec of power

And: 33,800 ÷ 550 = 61.45 Horse Power.

For the non-mathematicians there is another way to visualize this process. Since the speed scale is the horizontal scale on the total drag graph and the drag scale is the vertical scale, the values on these two scales define rectangular areas on the graph and these rectangular areas represent the power required at each speed. The greater the area, the greater the power required.

Take a look at the following total drag graph at Figure One, on which I have chosen three speeds to illustrate what I am talking about. Speed (3) is cruise speed, speed (1) is the minimum drag speed and the other, speed (2), is an intermediary speed. However it doesn't take much imagination to see that there is a particular rectangular area which corresponds to each and every speed on this graph, and that each area represents the power required to fly at that speed.

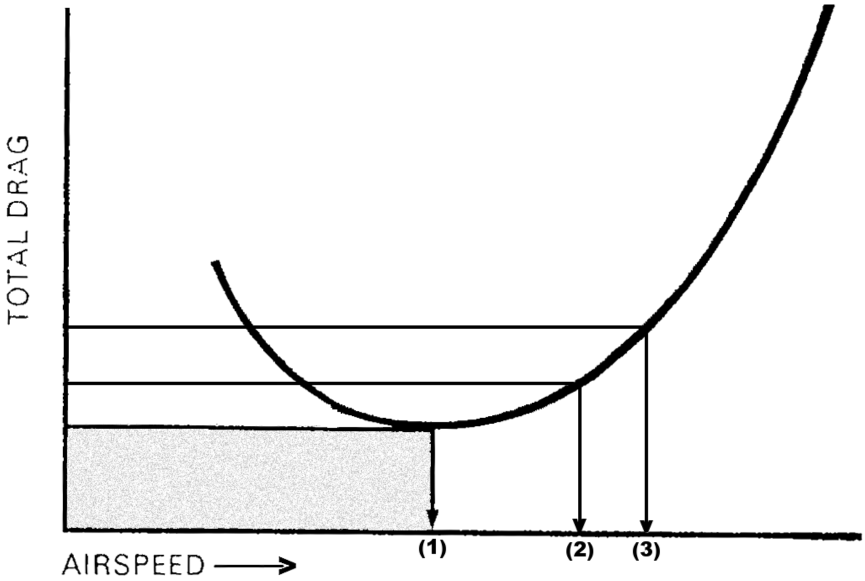


Figure One – Power Areas

You can see that the rectangular areas corresponding to the faster speeds are greater than that corresponding to the slowest speed of the three (the shaded area). The relative area of these rectangles represents the relative power required to fly at each of these three speeds. As you would expect, less power is required to fly as the speed reduces. However, when we slow to the 'backside' of the drag curve something happens which is counter-intuitive. Even though the drag starts to increase the power required continues to decrease…..for a while. Check out the following diagram (Figure Two).

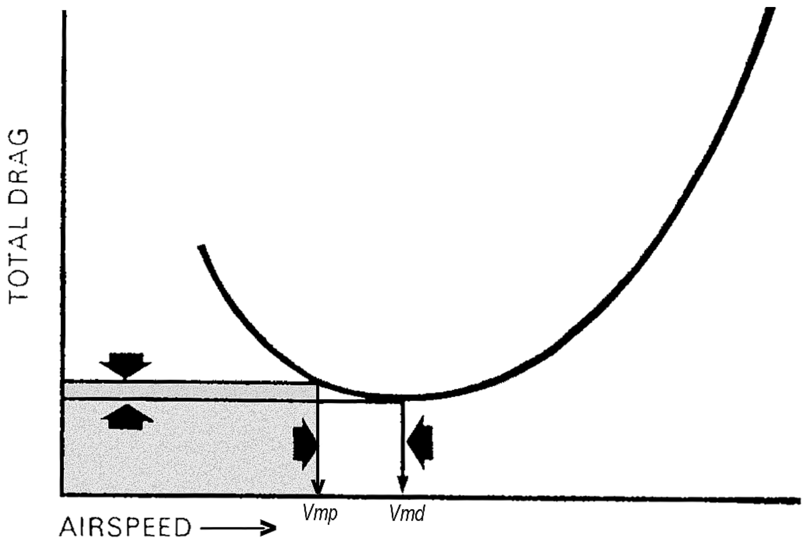


Figure Two – Power Areas on the Backside of the Drag Curve

This diagram illustrates the rectangular areas of power required at minimum drag speed and a lesser speed. You can see that the area of the rectangle formed by the slower speed and the greater drag (the shaded area) has a smaller area because even though the drag has increased the speed has decreased a lot **more,** so the area defined by them is **less**. It follows that there must be a speed a little less than the minimum drag speed which corresponds to an area which represents the minimum power required. This speed is called the 'Minimum Power Speed' (Vmp).

What this all means is that the minimum power speed (Vmp) is **slower** than the minimum drag speed (Vmd)! But fly any slower than that, and the area and the power required increases again. This is a most important point which I will return to in future lessons….. so remember it.

Also, flying at minimum power speed achieves the lowest rate of fuel consumption. A point I will return to when considering 'endurance' in Annex A to this lesson, and again in the lesson on Gliding.

Plotting another graph of the areas defined by each point on the total drag graph is how 'Power Required' graphs are determined. That is, the Power Required curve is a graphic plot of the 'areas' calculated by multiplying the drag by the speed at each point on the total drag curve. Here is the 'Power Required' curve (Figure Three) plotted as a broken line onto the Total Drag graph that we saw in the lesson on Drag, and from which it is derived. Note the similarity of the shape of the two curves. This similarity is the cause of much confusion amongst pilots:

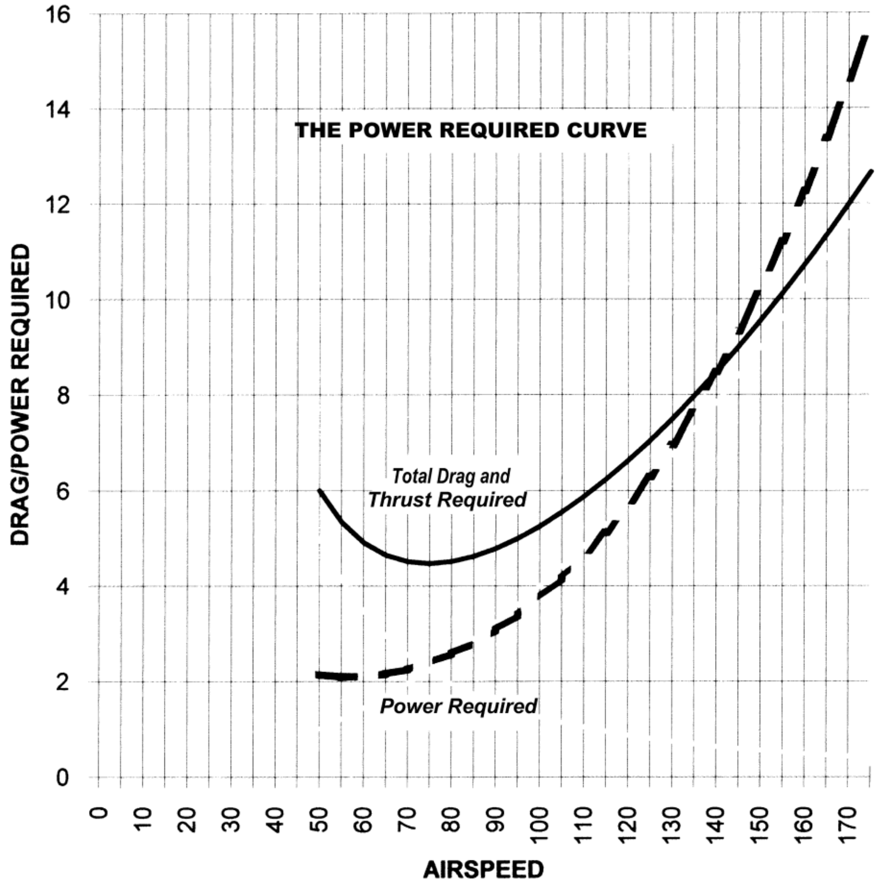


Figure Three – Power Required Curve

To help you avoid confusing the two curves, examine the following diagram at Figure Four. It shows more clearly the derivation of the 'power required versus true airspeed curve' from the total drag curve. I recommend that you 'book mark' this diagram so that you can refer back to it often:

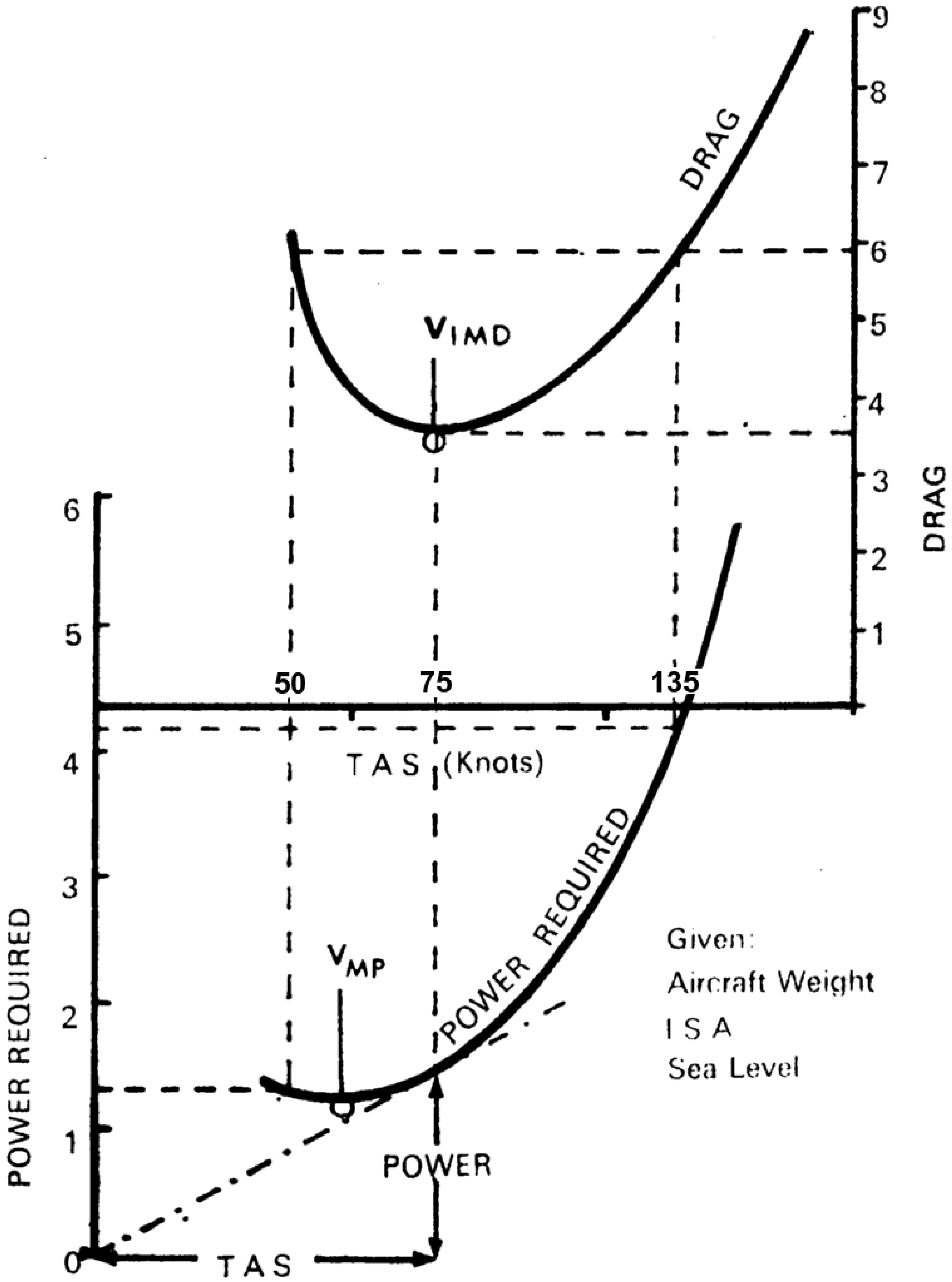


Figure Four – Power Required Curve versus Total Drag Curve

Take some time to study this diagram; you will once again note that the Minimum Power Speed (Vmp) is less than the Minimum Drag Speed (Vmd). Also note that whilst the minimum drag speed is determined by drawing a horizontal line from the bottom of the total drag curve, the power required to fly at this speed is determined by drawing a line from the 'zero zero' origin to touch the power required curve at a tangent. (I will return to the use of 'tangent' lines in a future lesson.)

Okay, that is enough about the thrust and power **required**; let's now turn to the thrust and power **available** from the engine and propeller. In the following diagram (Figure Five) I have taken the thrust graph for a fixed pitch propeller from the previous lesson on Thrust and superimposed it upon the Total Drag/Thrust Required graph.

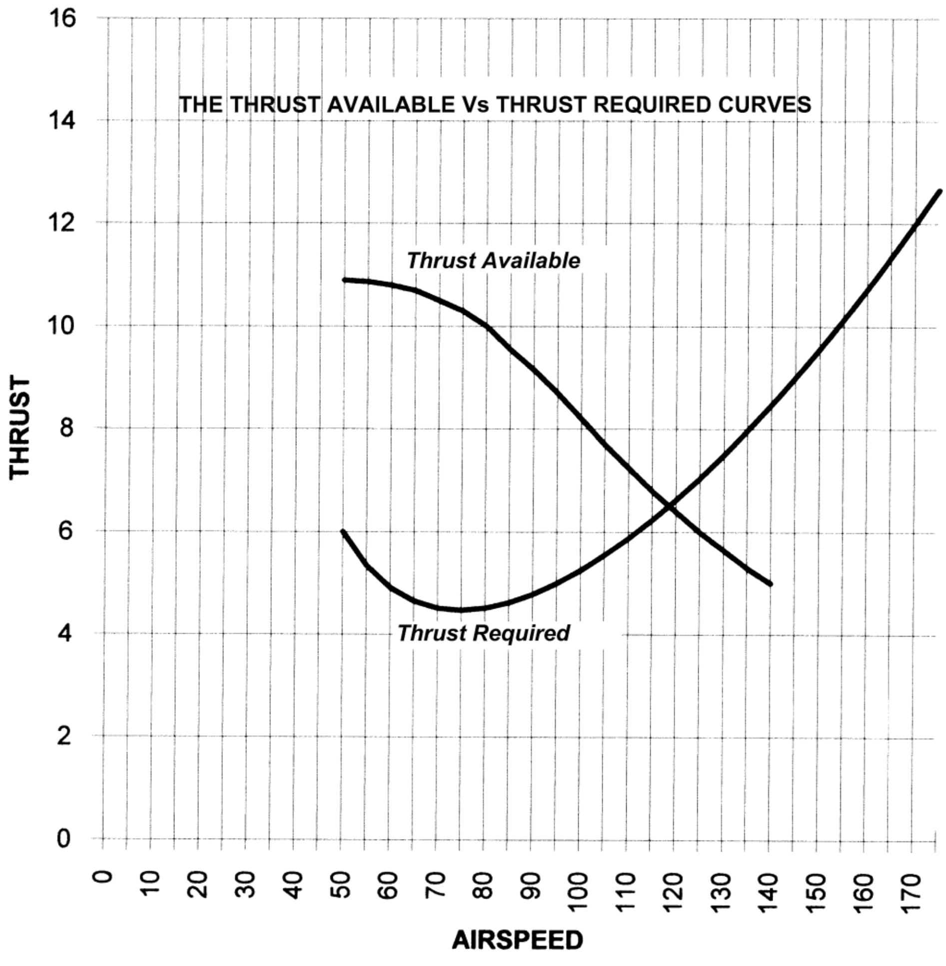


Figure Five – Thrust Available versus Thrust Required

Note that as the aeroplane goes faster the drag (thrust required) increases and the thrust available decreases until the two curves cross. At this point the thrust available just equals the thrust required and defines the maximum speed at which the engine/propeller can propel the aeroplane in level flight. As you can see, beyond this speed the thrust required is greater than the thrust available, so to attain any greater speed an 'assist' from gravity would be required, that is, the aeroplane would have to be pointed 'downhill'. (More on this in a future lesson.)

When we wish to talk about the power available for flight we have to go beyond the manufacturer's 'advertised' figure for the engine and consider the combination of the engine and the propeller. This figure will be somewhat less than advertised due to the efficiency (or inefficiency) of the propeller's ability to convert engine power into thrust, (i.e. fixed pitch versus constant speed). A similar situation exists with a motor car. The car manufacturer will proclaim a certain power output for the car's engine, but anyone who has seen a car on a dynamometer will realize that the final figure achieved where the wheels make contact with the road is considerably less. This is due to the friction of the drive train, the coefficient of friction of the tyres and other similar factors.

To convert the thrust available from an aeroplane's engine/propeller to power available, all we do is adopt the same procedure that we used when determining the power required, only this time we multiply the thrust available by the speed. Doing this reveals the following graph (Figure Six).

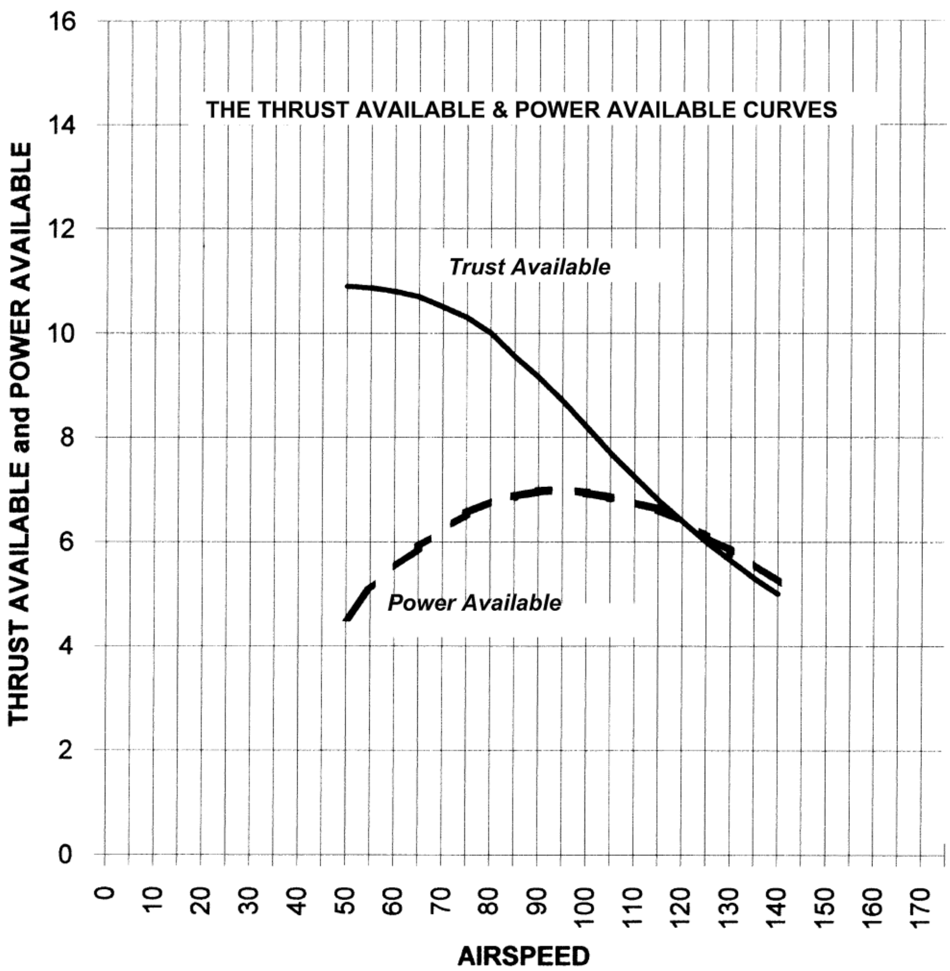


Figure Six – Thrust Available and Power Available

Note that this new ‘power available’ curve is sufficiently different to the ‘thrust available’ curve, that they cannot (should not) be confused.

Finally, if we now superimpose this new ‘power available curve’ onto the previously determined graph of power required we get the following (Figure Seven).

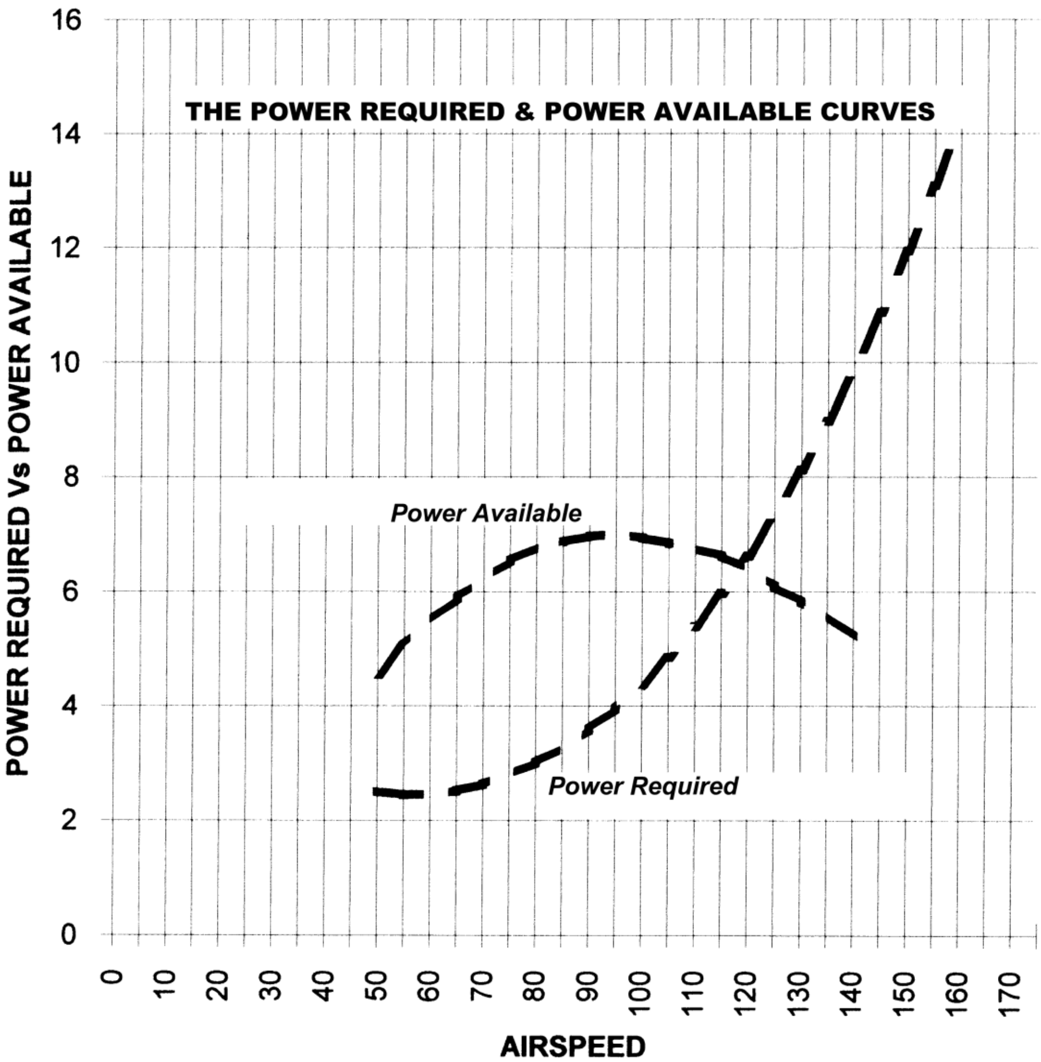


Figure Seven – Power Required versus Power Available Curves

It should not surprise you that the two curves also cross and that they do so at the same speed at which the thrust curves crossed. So regardless of whether we are considering the aeroplane’s performance from the point of view of thrust or the point of view of power, the limiting speed in level flight is the same.

Now throughout this lesson I have just referred to ‘airspeed’ because, in order to keep the discussion simple, I have assumed that the aeroplane is flying at a density altitude where the IAS and the TAS are the same, as it is the concept of the difference between thrust and power that I want to make clear. As the aeroplane climbs higher the two speeds split, that is, whilst the IAS is maintained the TAS increases, and the relationship between drag, which depends upon IAS, and power, which depends upon TAS, is altered, and this complicates things a bit.

Do you remember the discussion of 'Density Altitude' in Annex A to Lesson One? In that discussion I said that an aeroplane's performance is degraded as the density altitude increases. It is in fact degraded for two reasons. The first is the loss of power **available** from the engine as the density of the air it is ingesting becomes less and the second is the extra power **required** to accelerate to a higher **TAS** to achieve the correct **IAS** to take-off and climb. The simplest way to calculate the extra power required to fly at minimum drag speed at different density altitudes is to move the 'zero zero' origin point on the power graph at Figure Four to the right by an amount equal to the difference between the IAS and the TAS and then draw a new tangent line from this new origin point.

If you would like to test your understanding of the relationship of drag, power required and density altitude, imagine the aeroplane is flying at a density altitude where the 75kt IAS minimum drag speed is 100kt TAS. Now use the 'bookmarked' (Figure Four) drag and power graph and recalculate the power to fly at minimum drag speed. (Hint: same drag at higher TAS means more power required.) This little exercise will tell you if you have really 'got it'.

Before I conclude, there is one other term that I need to explain because it is going to appear in future lessons. The term is 'Energy'. Energy is defined as the 'capacity' for doing work, and as we have seen in this lesson, work multiplied by time is power, so the more energy an aeroplane contains, the more capacity for doing work it has and the more power it is capable of producing to overcome drag and gravity. An aeroplane has 'Kinetic Energy' by virtue of its motion, 'Potential Energy' by virtue of its height and 'Chemical Energy' stored in the fuel in its tanks. Chemical energy is converted to power via the aeroplane's engine, and the faster the engine can make this conversion the more 'powerful' is the engine. Potential energy is the energy used when gliding.

So what is the use of all of these definitions and graphs? In future lessons we will see their applicability to climbing, gliding and manoeuvring but for now, in Annex A to this lesson, I have introduced the basic principles of flying for range and endurance because they both depend upon how fast we burn our fuel and an engine burns fuel in direct proportion to its power output.

List of Annexes to the lesson on: Power

Annex A. Flying for Range and Endurance

Annex A

Flying for Range and Endurance

The subject of range and endurance can become quite complex so what I am about to say here is just an introduction to the subject so that you have a basis for further learning when you reach that stage of your training.

Since the rate of fuel consumption of an engine is proportional to the amount of power it is producing, and since the range and endurance of an aeroplane depend upon how quickly it is consuming the fuel it is carrying, we can use the drag and power curves detailed in the foregoing lessons on Drag and Power to determine the speed for the maximum range and the maximum endurance. How?

First let's consider range. What do we mean by 'range'? It means 'how far can we go on a given amount of fuel?' Imagine that you are flying along with 100% power set and that this power setting will use up all of your fuel in one hour. Also imagine that this power setting gives you a speed of 150 knots. So at the end of one hour you will be out of fuel and 150 miles from your start point.

Now imagine that you have set 50% power and this gives you 100 knots airspeed. Your fuel is now going to last two hours and at a speed of 100 knots for two hours you will fly 200 miles from your start point. Obviously we have achieved better range at the reduced power setting.

So at what speed do we fly to achieve a 'speed to power' relationship which gives us the best possible range from the available fuel? To put that question another way; what speed gives us the maximum speed to power ratio (speed/power)? Whatever that speed is, let's call it the 'Best range speed'. This question and its solution can now be expressed in the following logical steps:

1. Best range speed is the speed for maximum (speed/power).
2. Since power can be expressed as 'speed x drag', we have:
3. Best range speed is the speed for maximum (speed/speed x drag).
4. The two 'speeds' in the formula cancel each other out so:
5. Best range speed is the speed for maximum (1/drag).
6. Therefore the best range speed is the minimum drag speed!

So the **minimum drag speed** is the speed to fly to get the **maximum range** from a given amount of fuel.

The aeroplane's range is affected by other factors such as the IAS/TAS ratio (with increasing density altitude), engine performance considerations and the effect of 'wind' on the aeroplane's ground speed. Also flying at the minimum drag speed carries with it the risk of inadvertently slowing to the 'backside' of the drag curve (whilst turning or flying in turbulence) and needing a disproportionate increase in power to accelerate. So it is widely recommended that a light aeroplane be flown about 10 knots faster.

Now let's consider endurance. What do we mean by endurance? Simply put, it means how long we can stay in the air. Imagine you have arrived at your destination and the fog which was forecast to have cleared by now hasn't! You can't see to land yet so you decide to fly around until it clears. There is no point flying around at high power, burning fuel at a great rate because you don't know how long you will have to wait (and you are not going anywhere either). So you need to fly at a speed which demands the least power (minimum power speed) and so consumes the least fuel and therefore gives you the maximum time in the air. This is flying for maximum endurance. This speed is found simply from the power required curve shown previously in this lesson at Figure Four and is the point at the bottom of the curve marked 'Vmp'.

So the **minimum power speed** is the speed to fly to get the **maximum endurance** from a given amount of fuel.

Because the speed for maximum endurance (minimum power speed) is already less than the minimum drag speed, any flying inaccuracy at this speed could cause the aeroplane to 'slip' further 'behind' the curve necessitating an increase in power to accelerate and therefore using all the fuel that has just been saved! So a more practical speed about 10 knots faster is usually flown.

In both cases, range and endurance, the speed difference for a light aeroplane is small, maybe 10 to 12 knots, and since the optimum practical speed to fly for either is just a little greater than the theoretical 'best speed', as a general 'rule of thumb', if you don't have any better information, use the manufacturers optimum glide speed for endurance, plus 10 knots for range. (The relationship between power and optimum glide speed will be covered in greater detail in a later lesson.)

There are other factors which can influence endurance such as the aeroplane's changing weight as the fuel is burned, the density altitude and the engine mixture, throttle and RPM setting; all of which are beyond the scope of this introductory lesson. But I will say that if you are flying an aeroplane with a constant speed propeller and are faced with a number of combinations of Manifold pressure and RPM to achieve the power required, remember Charles Lindbergh's famous statement: "The slower it turns, the less it burns".

Lesson Six

STABILITY AND CONTROL

Prior to the year 1900, a popular concept was that when aeroplanes were finally developed they would be akin to ships in that they would stay upright because of an inherent stability and would only require a helmsman or pilot to steer them (that's right, the term 'pilot' is a nautical term). Giant aerial steam carriages were envisioned complete with promenade decks and steward service.

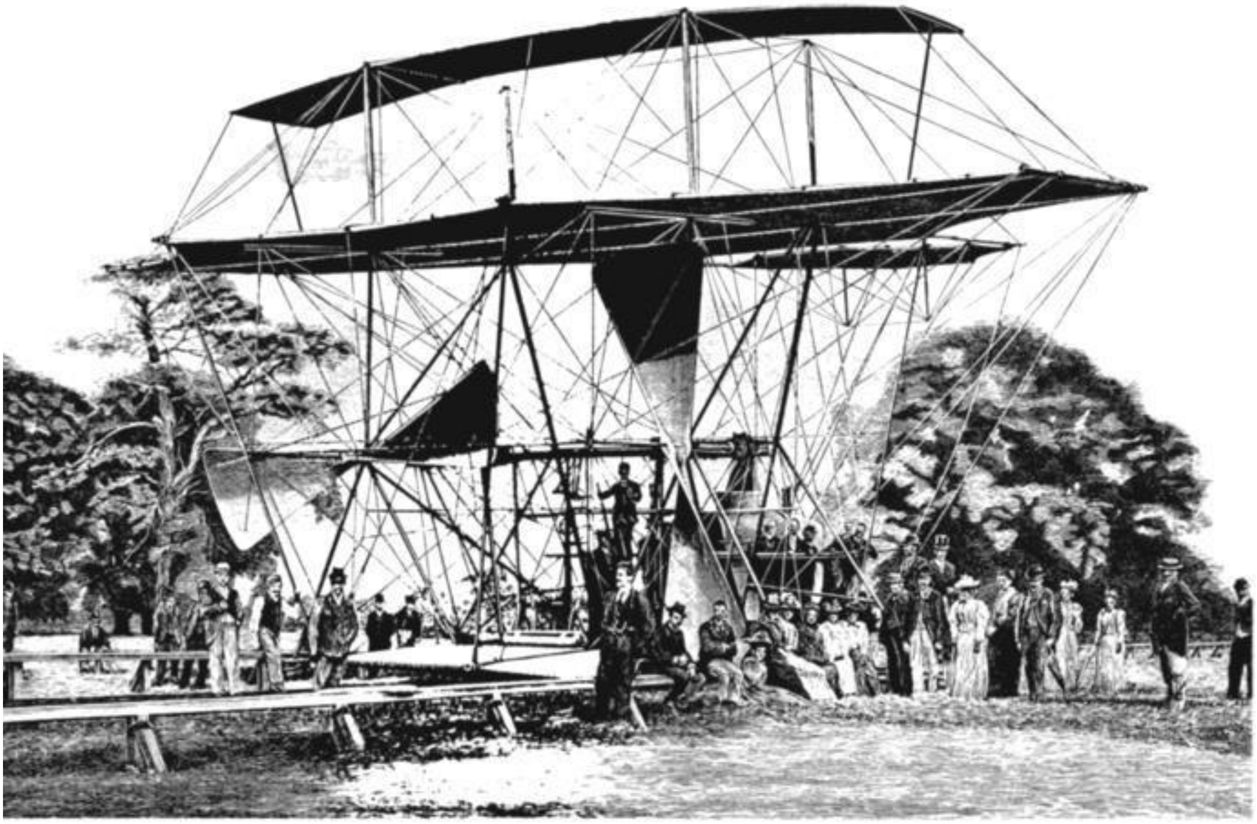


Figure One – Aerial Steam Carriage

Many successful free flight models based upon this principle were developed and flown. Samuel Pierpont Langley, the director of the Smithsonian Institute in Washington DC USA, made successful flights with very large steam powered models which he ultimately developed into a potentially man carrying craft he called the "Aerodrome". He had two unsuccessful attempts to launch his Aerodrome, both of which failed due to structural problems. If they had succeeded they would have preceded the Wright brothers' first flights by only nine days, but they were ultimately doomed to failure as the pilot had no adequate means of control. Despite this the Langley Aerodrome was displayed in the Smithsonian for the next 45 years and described as the world's first aircraft 'capable of man carrying flight'!

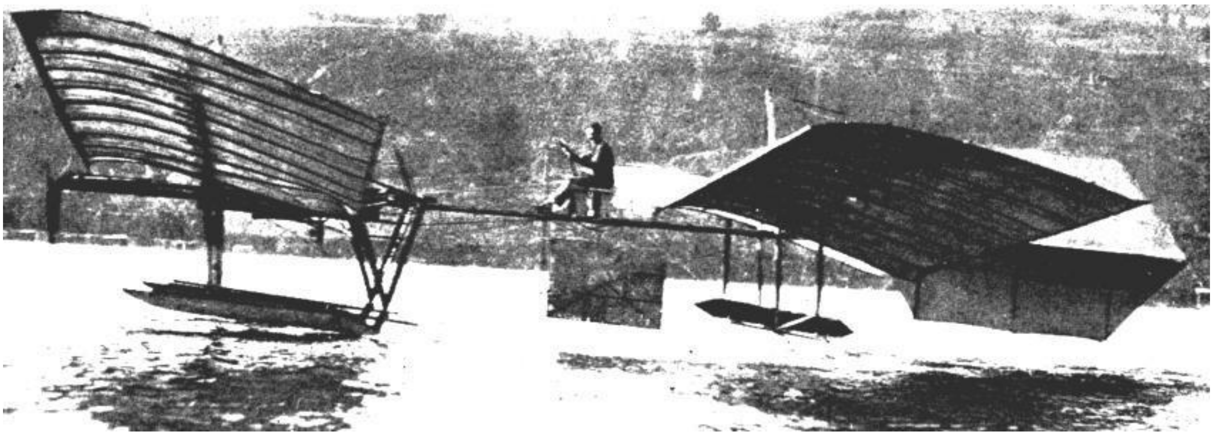


Figure Two - THE LANGLEY “AERODROME’, flying at last in 1915 (just!).

The Wright brothers were the only early aeroplane developers to understand that stability alone wasn’t the answer to successful powered flight. Precise and responsive control in the hands of a competent aviator was required. Perhaps it was because they were bicycle manufacturers and they were aware that whilst the gyroscopic effect of the wheels give the bicycle a basic stability, constant corrections need to be made by the rider to keep the machine under control. Observing the gulls soaring above the sand dunes of Kittyhawk must have reinforced this view, as the wings and tail of the birds were continually being adjusted to compensate for the effects of the ever changing airflow they encountered.

Long after the Wrights’ successful first flights in 1903 and the subsequent development and public demonstrations of their very impressive 1905 ‘Model B’, many early designers, particularly in France, refused to understand what they were seeing and continued to develop their aircraft as aerial boats. The unfortunate legacy of this is that we still use the name ‘rudder’ for one of the controls. It was reasoned that since ships were steered with a rudder an aeroplane could be too. This would be achieved by making the aeroplane very laterally stable and turning it with the rudder.

One classic example of this misunderstanding was the ‘Voisin Biplane’ of 1908 (see Figure Three below). It was a large box kite with multiple vertical curtains between the wings, a large rudder and no roll control! Later ‘racing’ models were fitted with separate movable little wings mounted between the main wings, which the French called ‘Stabilizing Planes’ or ‘ailerons’ (which means ‘little wing’). The rudder was used to steer the ship and the ailerons were used to help keep the wings level during the turn; the vertical curtains provided the ‘keel surface’ to enable the ship to turn. (Annex A includes descriptions of how these early aeroplanes were controlled; you should find them quite interesting.)

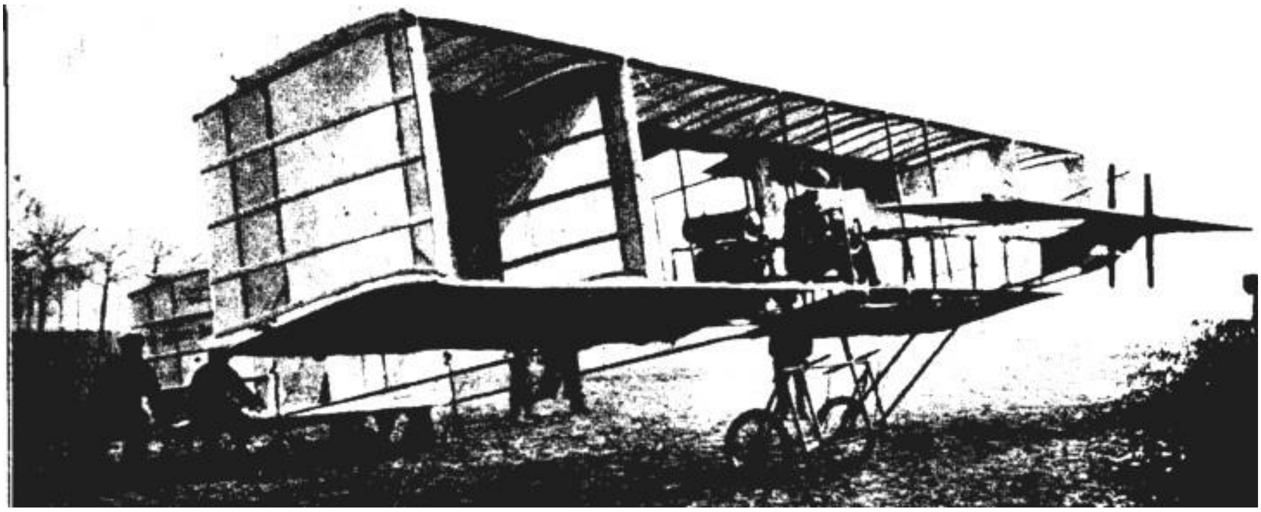


Figure Three - 1908 VOISIN

The Voisin did large flat skidding turns of hundreds of yards radius and this was considered by many French ‘experts’ to be the correct way to turn an aeroplane! Wilbur Wright’s spectacular flying demonstrations in France in 1908 were regarded by these ‘experts’ as trickery akin to a circus performance and not to be taken seriously! This attitude led to hundreds of crashes and dead French airmen over the next couple of years. As recently as 1977, I and thousands of other people at an air show I was running in Australia watched a ‘2 axis’ ultralight aeroplane, being controlled in a similar fashion, crash and kill its pilot. I couldn’t believe how little some people had learned in 70 years.

The first Wright glider in 1900 had ‘warpable’ wings for roll control, that is, the wings could be twisted to vary their angle of attack, but it had no fin for directional stability at all! By 1901 a fixed vertical fin was added (fixed like a modern water ski). The Wrights knew that in order to turn they would have to bank their craft in the direction they chose to turn, but their early trials revealed what we now know as ‘adverse yaw’ due to asymmetric induced drag created when warping the wings to roll into the turn. Consequently by 1902 they had made the vertical fin ‘adjustable’ (see Figure Four). The brothers could now move the fin to counter the asymmetric ‘warp drag’ and prevent this unwanted yaw. Unfortunately their adjustable fin looked just like a rudder so the name ‘rudder’ stuck and the world continues to call this control the rudder and continues to be confused about its correct use as a result. It is a pity they didn’t think of another catchy name for it right then and there and save a lot of misunderstanding, grief and lives. The Wright brothers (and now properly trained modern aviators) did not use the rudder to ‘steer the ship’, but it took a while for the control techniques developed by them to catch on, because entrenched concepts die hard. I will discuss what we should do and what happens in a turn in the lesson on Manoeuvring.

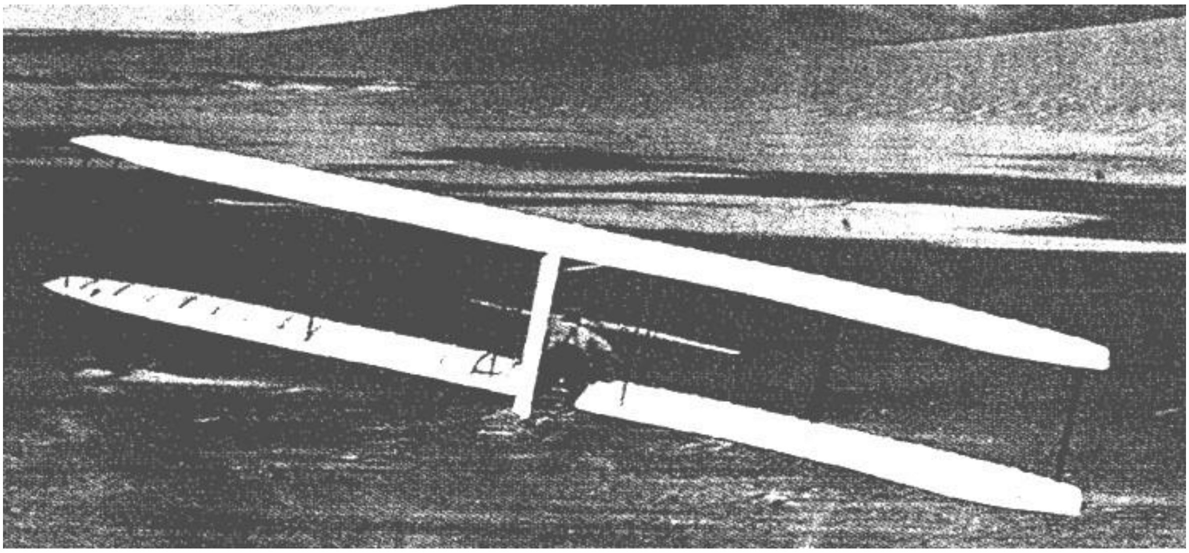


Figure Four - WRIGHT 1902 Glider

When I talk about the Wrights' "control techniques" I'm referring to how they integrated the use of each of the flight controls to manoeuvre the aeroplane. The actual control levers and the way they moved them to achieve this were quite different to what we are used to today. They worked the elevators and the rudder with fore and aft moving levers, and the wing warping with a cradle moved with their hips whilst lying prone on the lower wing! Indeed, an aviator trained on a modern aeroplane would not be able to fly a Wright biplane or many of the other early aeroplane types without extensive re-training. (See Annex A)

The ergonomic arrangement of the control levers and pedals that we know today was created by a Frenchman named Henri Farman in 1909 (See Annex A) and it too took a while to 'catch on'. But by the commencement of World War One in 1914, the Farman control configuration was the norm and used by aircraft manufacturers and aviators on both sides of the trenches and has remained so ever since. Ironically Henri's aeroplane was an adaptation of the Voisin biplane. Henri removed the interplane curtains, added what he called 'stabilizing flaps' (ailerons), employed the Wright flying technique and turned the Voisin into a successful and popular flying machine (now called a 'Farman' of course) and quieted the Wrights' critics.

Even so, the standard teaching of the flying schools up to and during WW1 was to enter a turn by applying rudder in the appropriate direction and then adjust the bank to keep the airflow central on the pilots face. The end result was a balanced turn but the entry technique still carried within it the misconception that the rudder was the primary turning control. (Nowadays the wind on the face has been replaced by the balance ball, but the misconception lingers on.)

Some time ago I set out to see if my aeroplane could be turned like a Voisin Biplane. From straight and level flight I progressively introduced left rudder whilst holding the 'wings level' with opposite aileron. I continued to increase the rudder deflection until I had almost run out of aileron. I kept just enough aileron deflection in reserve to control any bumps I might encounter. The aeroplane sluggishly skidded around a very large radius turn, the side of the fuselage replacing the Voisin's vertical curtains. It took almost 2 minutes to complete a turn through 180º at which point I gave up as I was developing a cramp in my left leg! I reflected on the fact that this was once how many airmen believed an aeroplane is turned. Tragically many pilots today still believe that a banked turn can be 'sped up' with the 'assistance' of excess rudder, as I will discuss in the lesson on Spinning.

OK, well all of this might be an interesting synopsis of the history of the development of aircraft control, but now it is time to get into the specifics of the stability and control of a modern aeroplane. Let me state at the outset that stability and control are the antithesis of one another: you cannot have an aeroplane that is both super stable and super agile. One has to be traded against the other. A modern aerobatic aeroplane has neutral stability and large control surfaces to make it very agile. A modern 'fly by wire' jet fighter is unstable and requires constant and rapid control inputs to keep it "pointing into the wind". These control inputs are made by a computer driven stability augmentation system, not by the fighter pilot. But when the pilot wants to manoeuvre....wow! The modern jet fighter is the most agile aeroplane ever created. Conversely the Boeing 747 and the Airbus 380 are 'people movers'; their job is to travel through the air from A to B smoothly, so they are very stable and not very maneuverable. Indeed flying these "Jumbo Jets" is about as close to piloting a ship as aeroplanes have gotten.....so far. (Giant aerial steam carriages complete with promenade decks and steward service.......not far from the truth!)

An aeroplane in flight is free to twist and 'pirouette' about three separate axes at 90 degrees to each other, the vertical, longitudinal and lateral axis (Figure Five). The movement about these three axes is called 'Yawing', 'Rolling' and 'Pitching' respectively (Figure Six). The aeroplane can be stable about these three axes and its movement can be controlled individually or simultaneously about these same three axes.

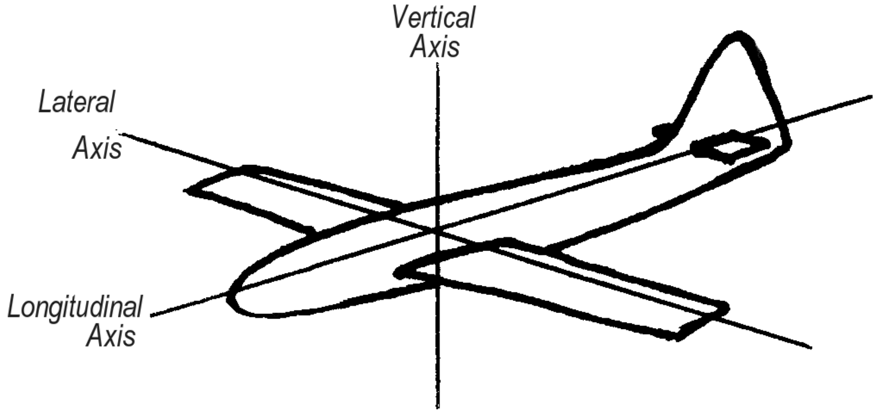


Figure Five – The Three Axis of Movement

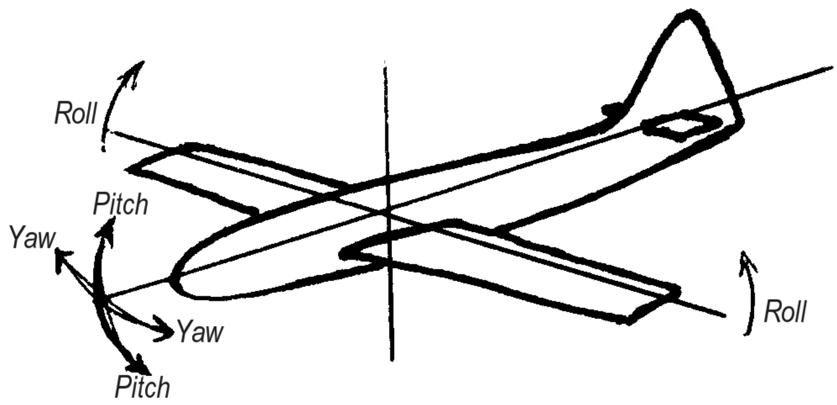


Figure Six – Pitching, Yawing and Rolling

In the two preceding diagrams I have assumed that the aeroplane is in cruising flight, that is that the longitudinal axis is aligned with the airflow and the vertical axis is at 90º to it. I will expand on this point a little later.

Now if the aeroplane is displaced about one or more of these axes, a measure of its stability is how quickly it will return to its former state once the disturbance has ceased. There are two different sorts of stability, 'static' stability and 'dynamic' stability. For an aeroplane to have static stability it must exhibit a tendency to return to its 'starting point' after it is disturbed by a transitory force (Newton's 1st law again). Let me give you an example from another field; sailing. A modern sail boat with a ballasted keel is constantly trying to return to an upright position despite the variable winds which are constantly trying to blow it over. A keelboat is statically stable, but if the keel snaps off all tendency to return to upright vanishes and the boat instantly becomes statically unstable and will just roll over! But there is a difference between an aeroplane and a keel boat and that is that the keel boat depends upon gravity for its stability, that is, its keel acts like a pendulum and tries to keep it upright with respect to the horizontal plane of the earth beneath it. Most things that we can think of that are stable have this gravity oriented pendulous type of stability. An aeroplane is different, it relies primarily on aerodynamic forces for its stability and since the aerodynamic forces come from its interaction with the air around it, it follows that an aeroplane is stable with respect to the air around it. What this means is that if the air around it is disturbed and turbulent a positively statically stable aeroplane will attempt to align itself with every changing air current, which can make for a wild ride.

I once blundered into an imbedded thunderstorm at night whilst flying a Caribou, which is a very stable transport aeroplane; we were flung around like a cork in a washing machine. I was barely able to keep the attitude of the aeroplane under control. Fortunately just as I was sure I was about to 'lose it' and the aeroplane was about to come 'unglued' we popped out the other side of the storm. I had been in similar storms previously in a fighter and had nowhere near the problems I had that night. So too much stability is not necessarily a good thing either!

Almost all aeroplanes are statically stable to some extent. I say almost, because as mentioned previously, modern jet fighters are designed to be statically unstable so that they can manoeuvre rapidly when required to do so and many aerobatic aeroplanes which are also designed for rapid maneuverability have neutral static stability, that is, they will stay in any new attitude that a disturbance puts them. The other 99.9% of aeroplanes have some degree of positive static stability and, as a result, are not as maneuverable.

The other sort of stability, dynamic stability, is a measure of how many oscillations a statically stable aeroplane will make as it attempts to return to its original attitude. These oscillations are the result of the aeroplane overshooting its starting point on its first return and then overshooting again the second time and maybe even a third time etc. For an aeroplane to be dynamically stable the amplitude of these oscillations should get progressively less and less till eventually it has settled in its original attitude (Figure Seven).

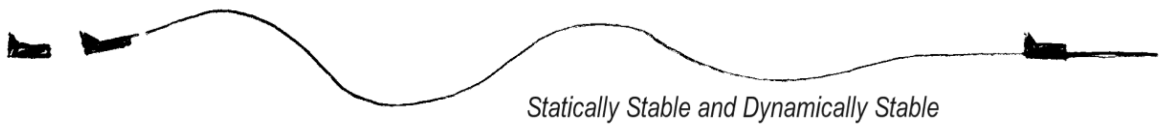


Figure Seven – Statically Stable and Dynamically Stable

If the oscillations continue at the same amplitude as the first one without ‘damping out’ the aeroplane is said to be dynamically neutral (Figure Eight).

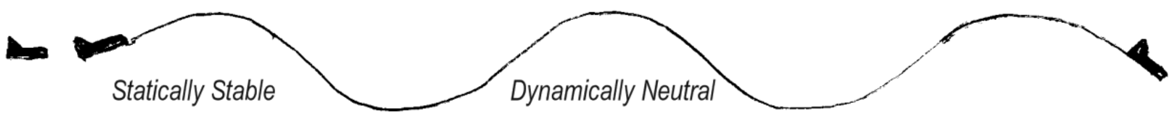


Figure Eight – Statically Stable and Dynamically Neutral

If the oscillations become progressively more divergent the aeroplane is said to be dynamically unstable! (Figure Nine.)

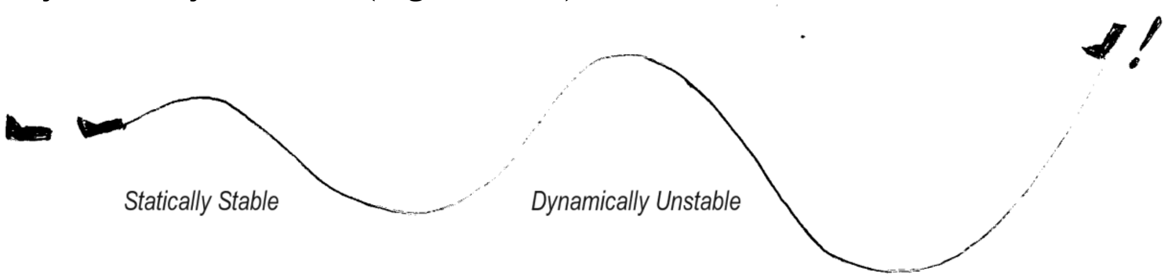


Figure Nine – Statically Stable and Dynamically Unstable

In all three cases the degree of dynamic stability is determined by the amplitude and frequency of the oscillations, (called ‘phugoids’) as it returns to (or passes through) its original attitude. Note that a dynamically stable aeroplane must first be statically stable. If an aeroplane is not statically stable in the first place it cannot have any type of dynamic stability; so discussions of dynamic stability do not apply to jet fighters or many aerobatic aeroplanes.

The aviator, by manipulating the controls, can also displace the aeroplane about one or more of its three axes either separately or simultaneously and at will. The rapidity of the response from the aircraft about each of these three axes will depend upon its static stability about each of these axes and how effective the control surfaces are. This is called ‘controllability’.

Let’s look first at stability and control about the vertical axis (which is sometimes also called the ‘Normal’ axis). The static stability about the vertical axis is called directional stability, the control is called the ‘Rudder’, and the action caused by the control is called ‘Yawing’, (not that we ever normally need to yaw the aeroplane with the rudder).

The degree of directional stability depends upon the area of the fin and rudder (and for this purpose we assume the rudder is fixed) and their combined distance from the aeroplane’s centre of gravity (moment arm). This is the same as the ‘flights’ on the end of a dart or an arrow, but unlike the arrow an aeroplane is often subjected to ‘destabilizing’ forces caused by the aeroplane itself, such as the rotary motion of the propeller slipstream, the adverse yaw caused by aileron deflection and even the subtle lag experienced in a turn (more on this in a later lesson), so the rudder’s primary purpose is to enable the aviator to overcome these destabilizing effects by ‘assisting’ the directional stability by ‘adjusting’ the rudder (and that is all).

During the early development of the aeroplane these destabilizing forces were quite pronounced as designers had yet to design the many compensating features that aeroplanes have today. Indeed those aviators flying aeroplanes fitted with rotary engines also had to contend with severe gyroscopic precession during turns, so the rudder had to be used quite aggressively to counter all of these unwanted effects. Unfortunately this only enhanced the incorrect view that the rudder “turns the ship”.

There are, still flying throughout the world today, thousands of ‘vintage’ aeroplanes which exhibit these characteristics, including the venerable old DeHavilland Tiger Moth. I single out this aeroplane because it is an aeroplane I am familiar with and which epitomizes my point. It is an aeroplane that requires positive but precise use of the rudder when the aeroplane is rolled into and out of a turn and also during the turn. Indeed it feels like one almost has to start applying the rudder as soon as you think about turning! Not true of course, but to a pilot trained on a modern aeroplane it seems that way. The misuse of the Tiger Moth rudder is still killing people from time to time, so this situation begs the question, "Were the pilots trying to steer the aeroplane like a ship"?

In a later lesson I will discuss in more detail the pitfalls of the incorrect use of the rudder. For now just remember to use it only to keep the aeroplane 'pointing into the wind' (balance ball central).

Now we are going to move on to stability and control about the other two axes. First let me attempt to clear up the confusion that many student pilots have about the names of the stability and its corresponding axis. The stability which resists rolling about the longitudinal axis is called the 'lateral stability' whilst the stability which resists pitching about the lateral axis is called the 'longitudinal stability'....Are we confused yet? Hopefully this diagram (Figure Ten) will help.

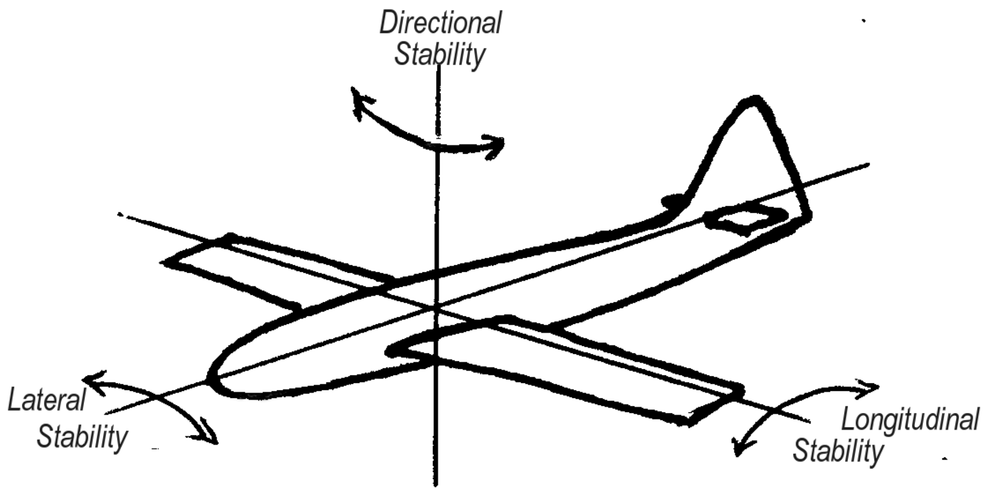


Figure Ten – Lateral and Longitudinal Stability

I guess this has come about because when the aeroplane is rolling about the longitudinal axis it is the lateral axis which actually moves and when pitching about the lateral axis it is the longitudinal axis which moves, but then so does the vertical axis in both cases so for my theory to hold we have to ignore the vertical axis!

Okay, stability and control about the longitudinal axis. The stability is called 'lateral', the control is the 'Ailerons', and the movement caused by the control is called 'rolling'. As mentioned in a previous lesson, the ailerons, which are located on the trailing edge of each wingtip, move in opposition to each other and cause asymmetric, lift on each wing. This asymmetric lift causes the aeroplane to roll. But I have to state at the outset that an aeroplane does not necessarily roll about its longitudinal axis. When the longitudinal axis is aligned with the aeroplane's flight path it appears to, but in fact it rolls around its flight path. The following diagram illustrates this point (Figure Eleven).

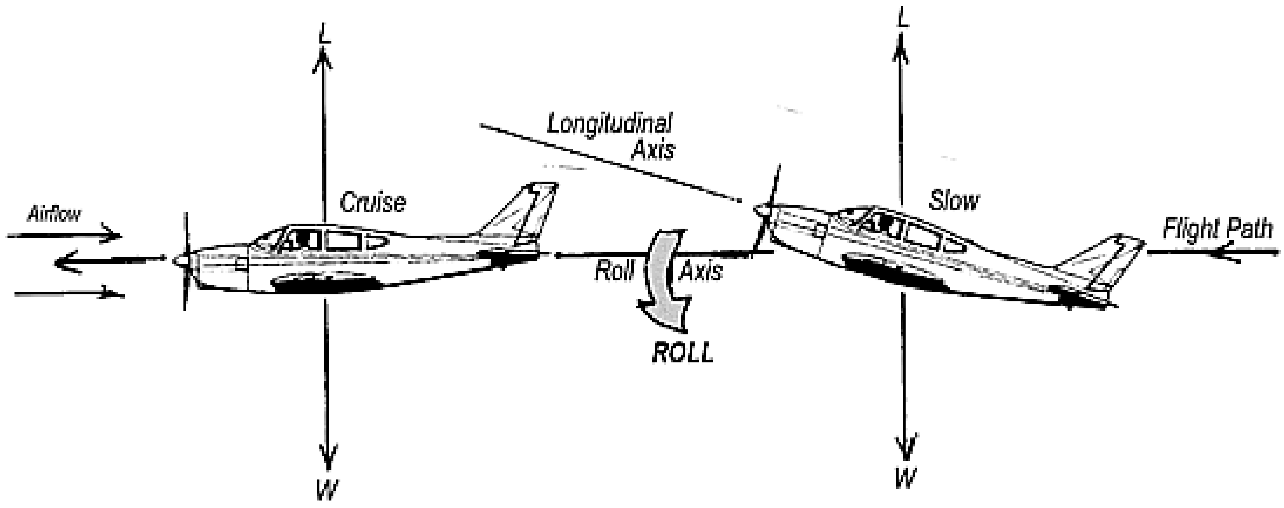


Figure Eleven – Rolling around the Flight Path.

From the foregoing diagram, you can see that in cruising flight the longitudinal axis and the relative airflow, which is the reciprocal of the flight path, are aligned, so roll seems to occur about the longitudinal axis; but if the aeroplane is flying at a high angle of attack at low speed, they are no longer aligned. Since the reaction forces which keep the aeroplane aloft and provide the rolling couple come from the aeroplane's reaction with the airflow, it follows that the axis of roll must be that airflow direction. Another way of looking at it is to recognize that the lift component of the total reaction is always 90º to the relative airflow and ailerons vary lift, so the aeroplane rolls around the flight path!

The effect of this difference of flight path and longitudinal axis is not too much of a problem for a light aeroplane, but modern fighter aircraft which can have very high roll rates at very high angles of attack can suffer disastrously from this difference because of what is called 'Roll Coupling' or 'Inertia Coupling'. Many years ago a friend of mine died after losing control of his aeroplane whilst practicing for an air show in a Mirage fighter which he inadvertently caused to 'Inertia couple' at very low altitude. (See Annex B for a more detail description of 'Inertia Coupling.')

A light aeroplane's lateral stability is primarily achieved by angling the wings up a little on each side of the fuselage (see Figure Twelve); this is called 'lateral dihedral' and the angle the wings are set onto the fuselage is the 'lateral dihedral angle'. Very high speed aeroplanes do it another way, which I will touch on in a moment.

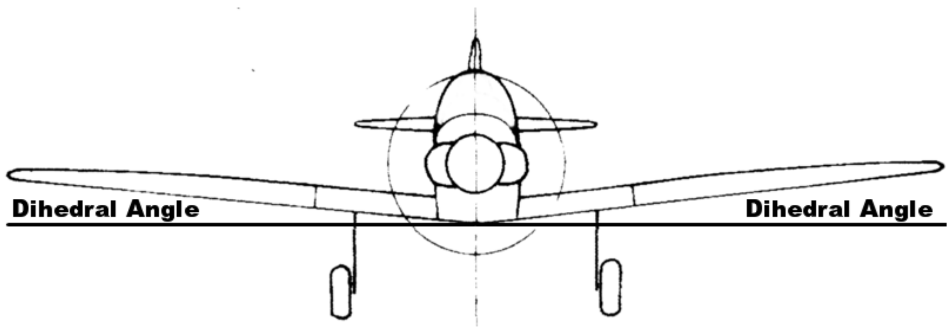


Figure Twelve – Lateral Dihedral Angle

The lift vector from each wing originates from the ‘aerodynamic centre’ of each wing, which is at 25% of the ‘mean aerodynamic chord’ (MAC) and is at 90º to the wing when viewed from ahead or behind (Figure Thirteen) (See Annex C for details on determining the mean aerodynamic chord.)

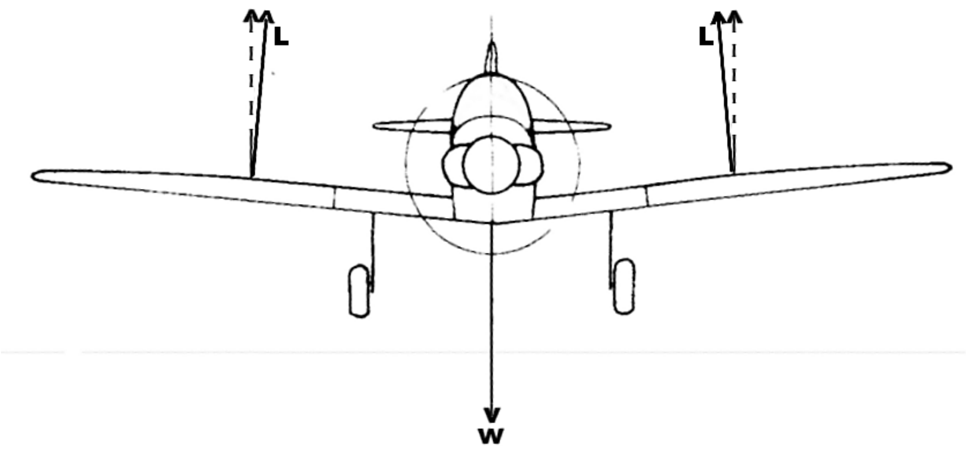


Figure Thirteen – Lift Vector 90º to wing

Now if the aeroplane’s attitude is upset laterally by a transient airflow disturbance the vertical component of the lift changes on each wing creating a ‘couple’ which rolls the aeroplane back to ‘wings level’ again (Figure Fourteen).

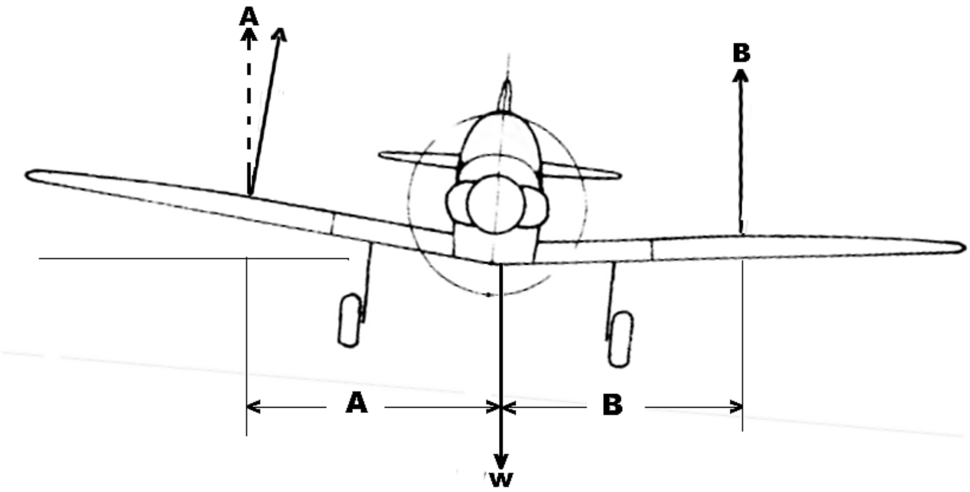


Figure Fourteen – Roll Couple

You will note from Figure Fourteen that the vertical component of lift ‘A’ is now slightly less than ‘B’ and A’s distance from the centre of gravity is also slightly less than B’s. The combined effect of these two factors creates a rolling couple to right the aeroplane. The more pronounce the dihedral the more positive is this stabilizing effect.

The manufacturers of high winged aeroplanes claim superior lateral stability because the centre of lift is above the centre of gravity adding a pendulous component to this asymmetric lift ‘couple’. This pendulous effect is minimal and remember what I said about having too much stability. (The Caribou had a high wing.)

Now those of you who are paying attention should be thinking “hang on, this sounds like boat stability but he said the aeroplane was different”. Correct, but we haven’t finished yet. In addition to the stabilizing effect of the unbalanced vertical components of lift off each wing (and, if you will, the pendulous effect of a high wing) something else happens. As the aeroplane banks, a small sideways component of the lift vector is created. This sideways force causes the aeroplane to ‘slip’ sideways slightly so that momentarily the relative airflow is not from straight ahead but from slightly to one side. This offset airflow impinges on the lower wing at a slightly higher angle of attack than the upper wing due to the dihedral, causing a further lift imbalance (L2) which in turn causes increased roll in the same direction as the initial righting couple, thereby assisting it in returning the aeroplane to its original attitude. The following diagram at Figure Fifteen shows what I mean:

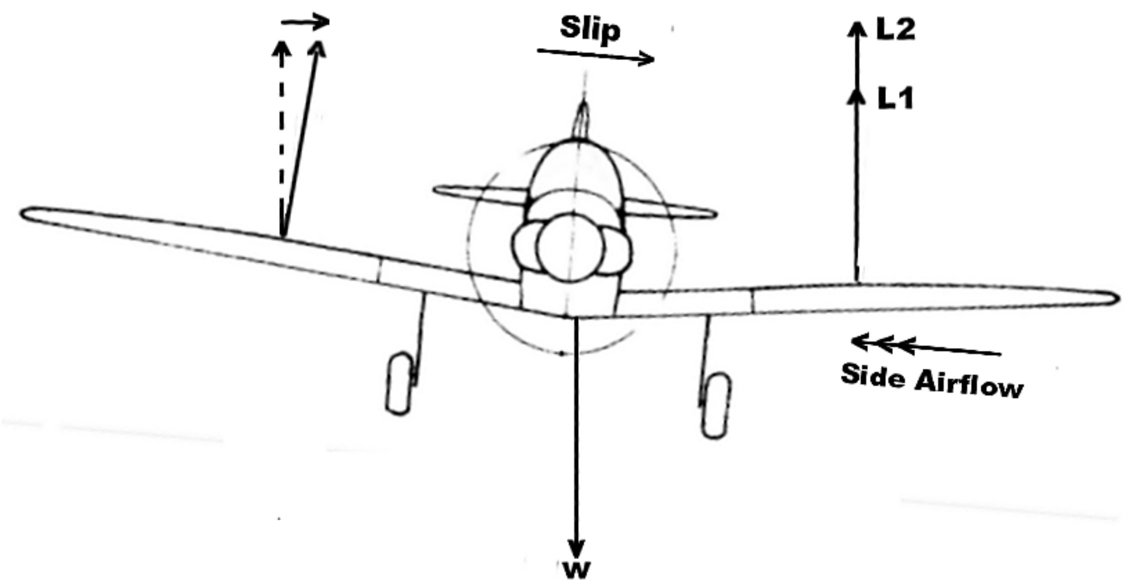


Figure Fifteen – Side Slip

This rolling effect is purely aerodynamic and independent of which way is down. Indeed this is how a side gust of air can upset the aeroplane’s attitude in the first place, which is why too much lateral stability can cause problems.

Earlier I mentioned that the designers of high speed aeroplanes attain lateral stability another way. They 'sweep' the wings back. This sweep back has other advantages at speeds approaching the speed of sound, but that is beyond the scope of this lesson. Take a look at the diagrams at Figure Sixteen.

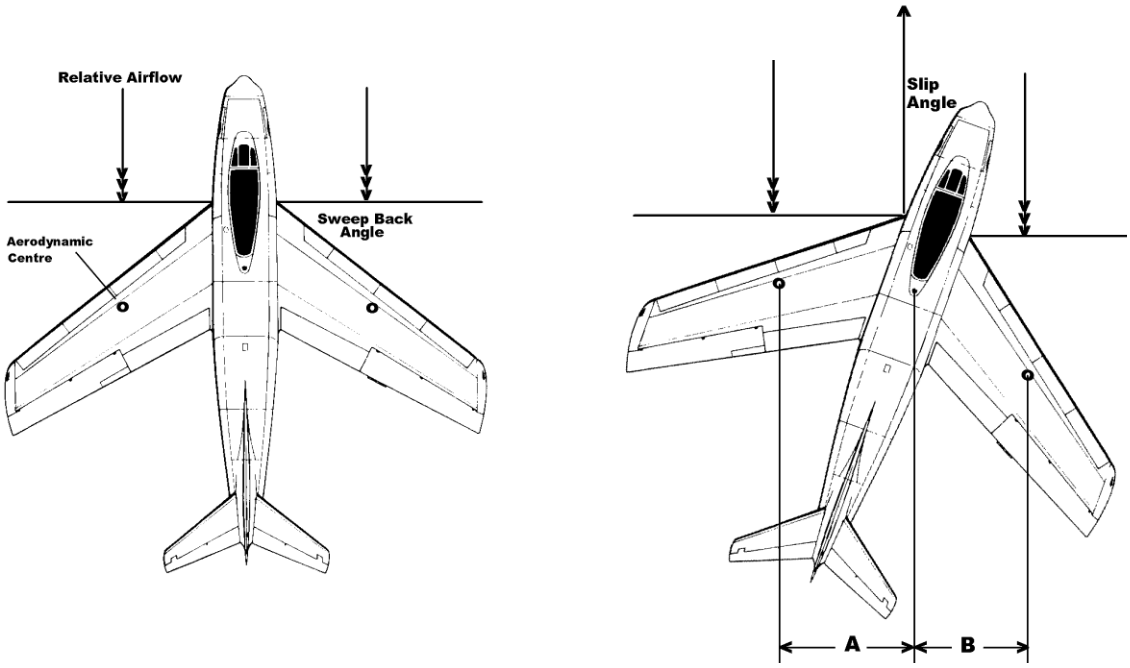


Figure Sixteen – Sweep Back & Lateral Stability

You will note from the diagram that as the swept back wing slips sideways after a disturbance in roll the relative airflow is now slightly from the side causing the centers of lift on each wing to have different moments about the 'new' roll axis which, as I have said previously, is the 'new' relative airflow. As a result the aeroplane rolls to correct the disturbance. On some high speed designs the stability of the sweepback is too great and has to be offset by setting the wings onto the fuselage with negative dihedral (anhedral).

Control about the longitudinal axis is straight forward. The aviator deflects the ailerons and the aeroplane rolls due to the asymmetric lift force created, as mentioned previously. As long as the ailerons remain deflected the aeroplane will continue to roll; only stopping when the ailerons are returned to neutral. (A little rudder may be required during the roll for all of those reasons previously mentioned too.) Of course the attitude that the roll stops at is entirely the choice of the aviator, be it 90º of bank or inverted! Normally it will be some more sedate attitude like 45º of bank, so that the aeroplane can turn (more on turning in the next lesson). The rate of roll at a particular speed will depend upon the effectiveness (size and efficiency) of the ailerons and upon the degree of lateral stability that they have to overcome. (For a more detailed explanation of the factors limiting roll rate see Annex D.)

So far we have looked at directional and lateral static stability independently of each other but they in fact interact. When an aeroplane yaws, whilst the directional stability is in the process of returning it to straight flight, it is momentarily ‘slipping’ which means the lateral stability causes it to roll in the direction of yaw and when an aeroplane ‘slips’ its directional stability causes it to yaw in the direction of slip! The degree of interaction depends upon the relative degree of directional versus lateral stability and will result in one of two possible effects.

If the directional stability is more positive than the lateral stability the aeroplane, once disturbed in roll, will yaw positively into the resulting slip which in turn will cause the wing on the ‘outside’ of the yaw to move faster and develop more lift which will overcome its lateral stability and therefore roll further, causing more slip, more yaw, etc. The result of this sequence of events is a downward spiraling flight path. The overall effect has been given the name ‘spiral instability’, which is a curious name considering that the situation stems from the aeroplane’s positive stability about the two axes in the first place!

If the aeroplane’s lateral stability is more positive than its directional stability the aeroplane, once disturbed in roll, will only yaw into the slip a little but not enough to overcome the lateral stability, and the aeroplane will roll out as it is supposed to. However, the directional stability will lag behind a little when correcting the initial yaw and this will generate a slight roll in the other direction - which will cause the aeroplane to slip and yaw in this new direction - which causes the whole process to repeat itself again and again! This continual subtle rolling and yawing is called ‘Dutch rolling’. Dutch rolling is not often encountered but the early model Boeing 707 would Dutch roll for the entire duration of its flight. As you moved down the cabin from the front, where it was hardly noticed to the rear where it was quite noticeable, you could see the complexions of the passengers getting progressively greener and greener! Aeroplanes which attain their lateral stability from sweepback are more prone to Dutch rolling; however the ‘V tailed’ Beechcraft Bonanza exhibited Dutch roll characteristics too, which is probably why the Beechcraft company reverted to a conventional tail on that model. Usually most statically stable aeroplanes exhibit spiral instability characteristic to some degree.

If the aeroplane exhibits spiral instability after a disturbance the aviator will have to intervene with the use of the ailerons (and perhaps a touch of rudder) to correct the situation. If it exhibits Dutch roll the aviator is in for a long and tedious flight (as are the passengers in the back seat!)

For years designers of aeroplanes have grappled with the problem of too much versus too little directional and lateral stability, which has resulted in an abundance of solutions to suit particular needs, which is why modern aeroplanes come in such a variety of wing shapes and configurations.

Finally let's look at stability and control about the lateral axis. The stability is called 'longitudinal' and the movement caused by the control is called 'pitching'. At first glance it appears that this is just a horizontal version of the fin and rudder. Indeed, way back at the beginning of aeroplane development the control surface which caused the aeroplane to pitch was called the "elevating rudder". This was later shortened to just 'elevator' and this is the name we continue to use for it today.

Longitudinal stability, like directional stability, depends upon the area of the horizontal stabilizer/elevator combination and the moment arm from the aeroplane's centre of gravity, which is, as we have seen, very close to the centre of lift (aerodynamic centre). The area of the horizontal tail multiplied by the moment arm is called 'tail volume'. The greater the tail volume, the greater the longitudinal static stability and the larger the elevator has to be to 'adjust' it.

Essentially, the horizontal tail, often called the 'tailplane', has a similar stabilizing function to the fin (which is also sometimes called the 'vertical stabilizer') and that is to keep the fuselage 'pointing into the wind' (in the vertical plane). But there is a difference. Since the wings are attached to the fuselage, movement in pitch will alter the angle of attack of the wings and therefore the total reaction. This will affect the way longitudinal stability is maintained and I will come back to this important aspect of longitudinal stability shortly.

Since the elevators are used to adjust the pitch of the aeroplane, it follows that they must also give the aviator control of the angle of attack of the wing and, therefore, control of the total reaction which results from any change in this angle.

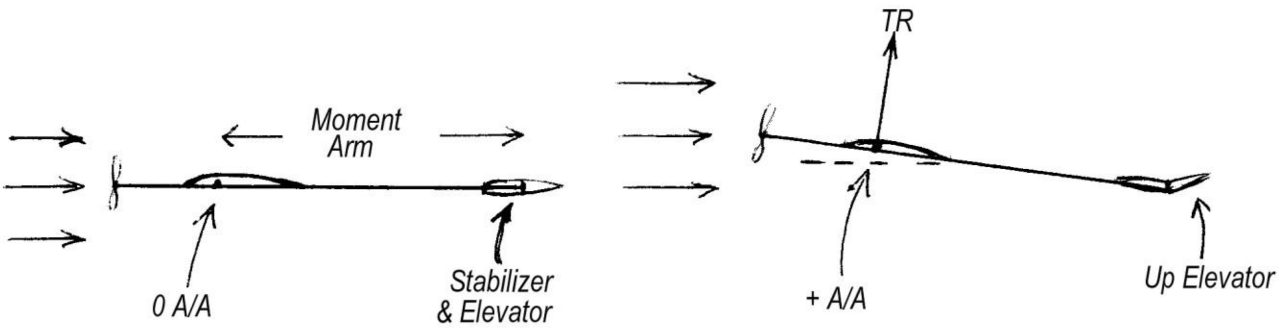


Figure Seventeen – Tail Volume & Pitch Control

The 'tail volume' is fixed by the design of the aeroplane, as is the area of the elevator, so the only thing the aviator can alter is the angle of deflection of the elevator. It follows then, that there is a set relationship between the angular deflection of the elevator and the angle of attack of the wing (the ratio between them depending upon the tail volume and the elevator area) and, since both wing and tail are moving through the air at the same speed, the airspeed has no effect on this relationship. (Read that last sentence again, because understanding this relationship between elevator deflection and angle of attack is crucial to your understanding of how to control an aeroplane.)

Now the designer doesn't set the wings onto the fuselage at zero angle of attack, as this would require the whole aeroplane to fly along with its nose up. (Imagine the flight attendant on an airliner, trying to push the drink trolley up hill from the rear galley. They would soon go on strike. Imagine the drink trolley careering back down the 'hill' whilst she serves a drink. Humorous? Dangerous for the little girl from row 59 playing in the aisle.) No! The designer sets the wings onto the fuselage at an angle equal to the angle of attack he expects them to need in level flight at cruising speed. This is called the 'angle of incidence'. So we need to modify our diagram slightly, as follows (Figure Eighteen).

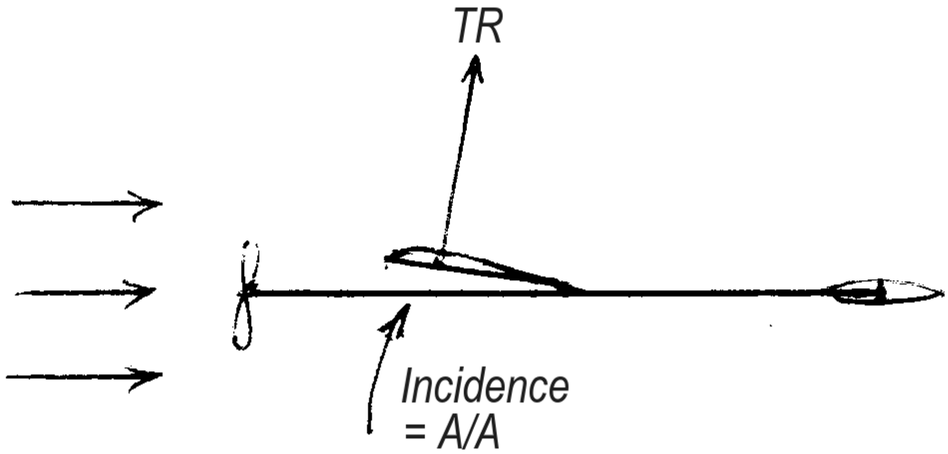


Figure Eighteen – Angle of Incidence

Moving the elevator will still vary the wing angle of attack but now the fuselage is level in level cruising flight, (thus avoiding a flight attendant strike).

Unfortunately it doesn't end there, there is an added complication. Remember the 'Pitching Moment' discussed in the lecture on 'Lift'? Let me refresh your memory. In order to create a total reaction the wing has to deflect the airflow and this deflection can be regarded as a 'turning' of the airflow (Figure Nineteen).

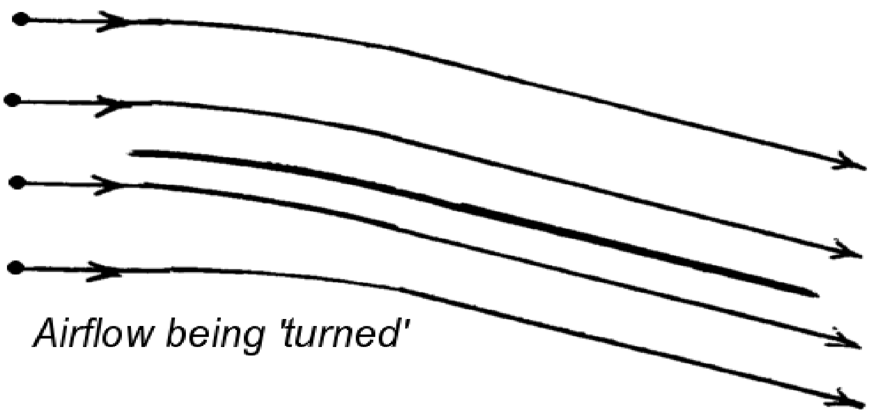


Figure Nineteen – Turning the Airflow

Newton's third law of motion doesn't just apply to linear situations but also to angular situations. That is, if an airflow is turned one way then the wing that turned it experiences an equal and opposite turning force. In general situations this is called a torque reaction, but in the case of a wing it is called an 'aerodynamic pitching moment'. The good news is that this aerodynamic pitching moment is a constant about the wing's aerodynamic centre if we don't change the wing's configuration (like lowering the flaps). See Figure Twenty.

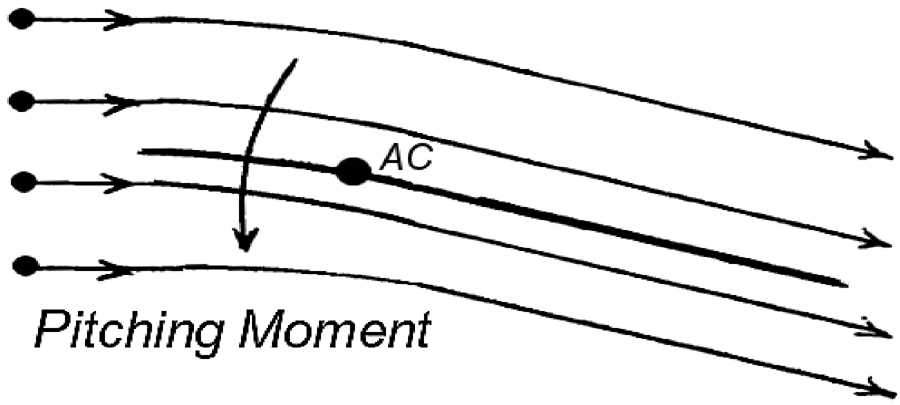


Figure Twenty – Aerodynamic Pitching Moment

This 'aerodynamic pitching moment' will cause a disembodied wing, presented to the airflow, to pitch leading edge down and reduce its angle of attack to zero lift angle of attack. The counter balance to the wing's pitching moment is provided by the horizontal tail. So we have to modify our diagram again (Figure Twenty One).

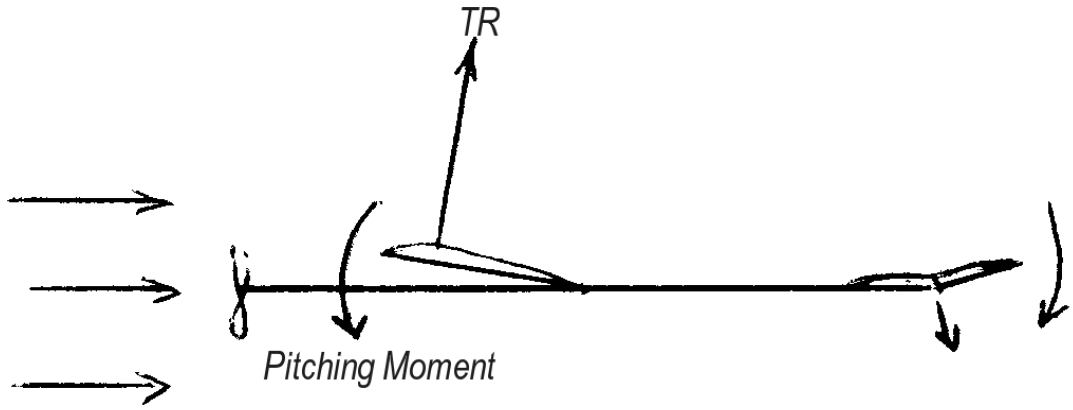


Figure Twenty One – Elevator Counter Moment

In the diagram the elevator is deflected just enough to provide a counter moment to the aerodynamic pitching moment. The amount of elevator deflection will depend upon the tail volume. In fact the designer sets the horizontal stabilizer to a slight negative angle of incidence thereby bringing the stabilizer and elevator back into line for level flight. The difference between the negative incidence of the tailplane and the positive incidence of the wing is called 'Longitudinal Dihedral' (Figure Twenty Two).

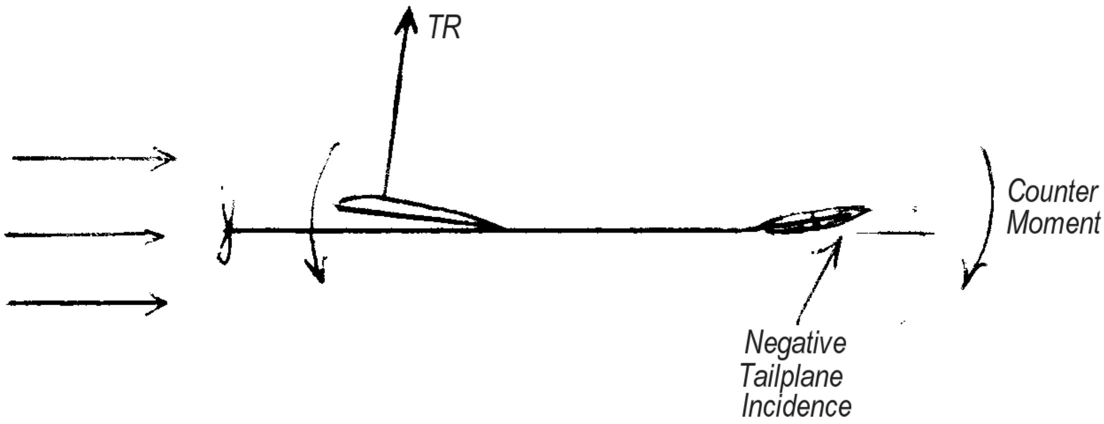


Figure Twenty Two – Longitudinal Dihedral

Deflecting the elevator from this new starting point will still control further angle of attack adjustments. These modifications to the basic configuration (Figure Seventeen) have not altered the elevator deflection/angle of attack relationship.

Are you with me so far? Yes? Good! If not go back and read this section again (and if necessary, again and again) because there is one more complication I now wish to introduce to all of this and I want you with me. But before I do I want to dispel another misconception that most pilots have and that is, that because the center of pressure supposedly moves forward as the wing's angle of attack increases it causes an increasing destabilizing moment about the centre of gravity, requiring a further adjustment of the elevators. Not so! At least, not anymore. As we have already seen in the lesson on Lift, the centre of pressure/total reaction doesn't move as the angle of attack of a modern wing section changes, which is why designers now use 25% of the Mean Aerodynamic Chord (MAC) as the fixed aerodynamic centre of the wing. This means that the **tail angle of attack is proportional to the wing angle of attack at all angles up to the wing's critical angle**. As I have said previously, this relationship has important control implications for the aviator, which we will come to in a later lesson.

So; let's add that further complication. Till now we have assumed that the airflow encountered by the tail is the same as that encountered by the wing, but it isn't! Remember the wing is creating the total reaction by turning and deflecting the airflow, that is, creating downwash; the tail is therefore flying in some of this downwash. The downwash gives the tail a negative angle of attack without requiring a negative angle of incidence! So now the final diagram looks like that at Figure Twenty Three.

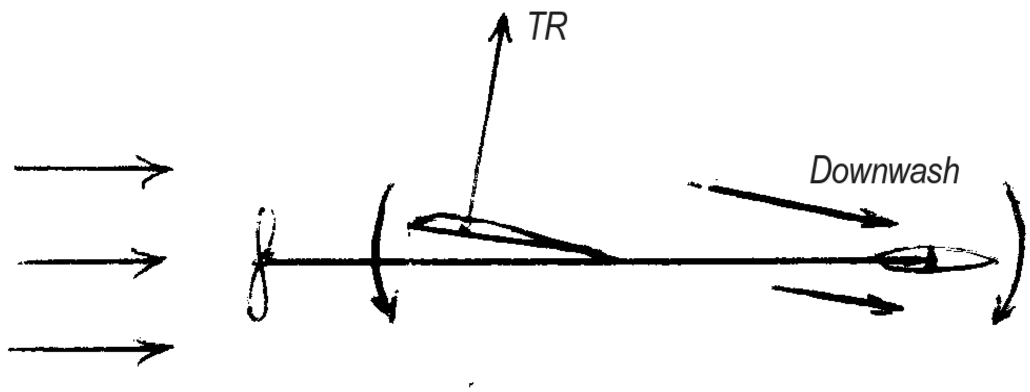


Figure Twenty Three – Downwash over the Tail

You can see that the tail incidence has returned to zero but its A/A is still negative. Does this downwash affect the wing/tail angle of attack relationship? No, because even though an increased wing A/A increases the downwash angle relative to the horizontal, the downwash angle over the tail remains the same because the tail has moved (changed angle) with the wing. The following diagram (Figure Twenty Four) shows the increased wing A/A and downwash but the same negative A/A at the horizontal stabilizer and the same elevator deflection which caused the increased wing A/A in the first place:

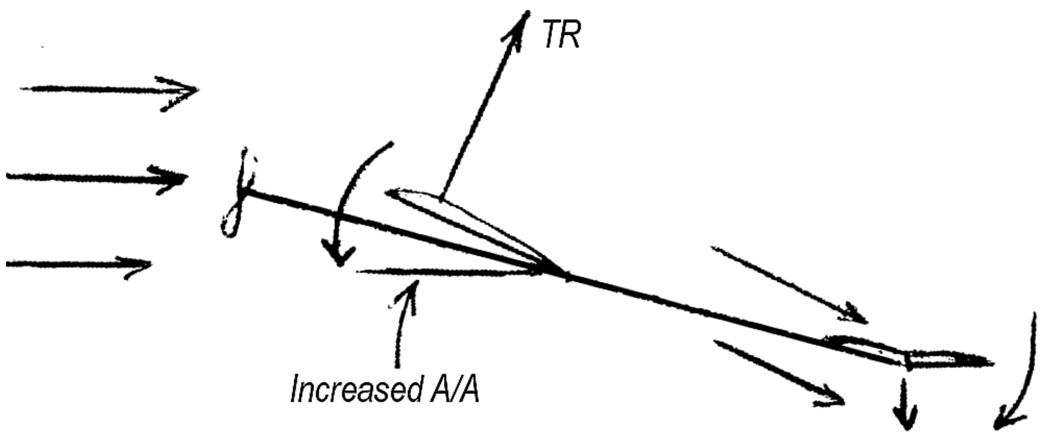


Figure Twenty Four – Downwash over Tail at Increased A/A

Only two things can alter the wing/tail angle of attack relationship: the position of the centre of gravity and the use of flaps. The position of the centre of gravity alters the tail volume (specifically the moment arm) and therefore the longitudinal static stability, whilst flaps change the wing pitching moment and the downwash angle independently of the movement of the elevator. On most light aeroplanes the permitted range of movement of the centre of gravity is not large, so the change in the wing/tail relationship is also not large. However, the flap effect can be quite large depending upon the position and deflection of the flaps and the position of the tailplane.

On a well-designed aeroplane the relative positioning is such that the increased downwash due to the flaps impinges upon the tailplane at a greater 'negative' angle of attack and automatically provides an increased counter moment to the wing's increased pitching moment as shown in Figure Twenty Five.

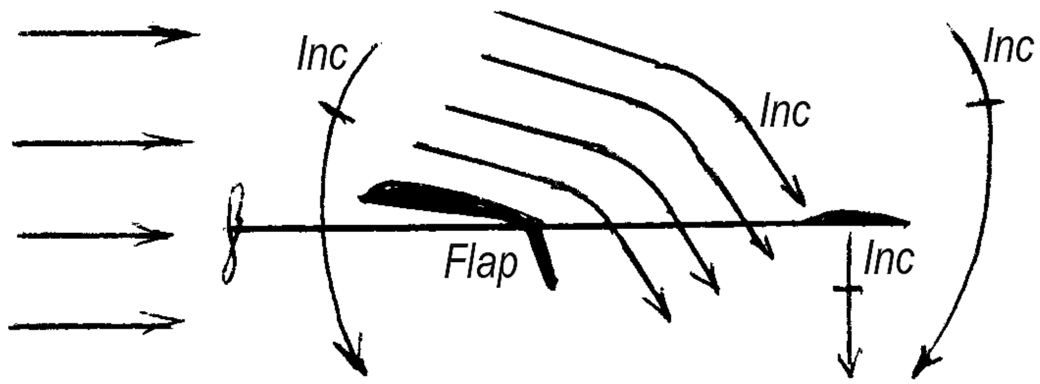


Figure Twenty Five – Changing Downwash with Flap

Not all modern aeroplanes are designed this way. Some low wing aeroplanes have a high set tailplane ('T' tail) so the tail is above the downwash and can be seen to be set at a significant negative angle of incidence (Figure Twenty Six). This type of tail is unable to automatically compensate for the 'nose down' pitching moment when the flaps are extended, requiring an elevator input to correct (stick back).

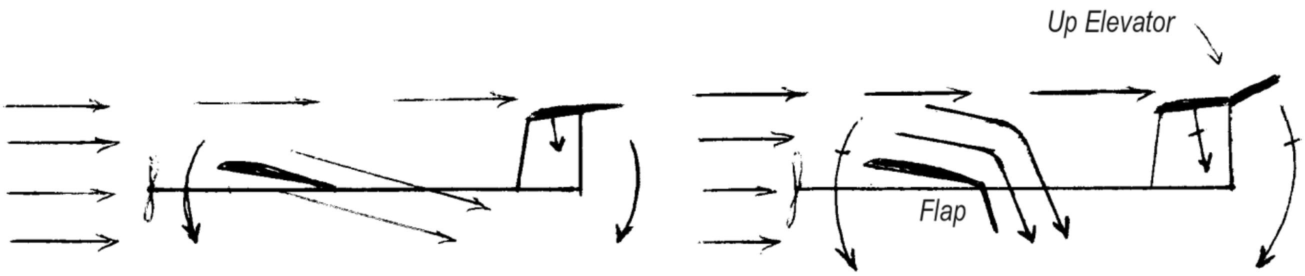


Figure Twenty Six – Downwash Effect with 'T' Tail

Conversely we can have an aeroplane with a high wing and a conventionally placed tail. In this case the tailplane is really 'buried' in the downwash to the extent that even though the tailplane 'flys' at a negative angle of attack the tailplane has to be set at a positive angle of incidence to avoid too powerful a counter moment in cruising flight. On this type of aeroplane the effect of the downwash change over the tail when flap is extended over-compensates for the pitching moment increase and causes a 'nose up' pitch, once again necessitating a positive elevator correction (stick forward). See Figure Twenty Seven.

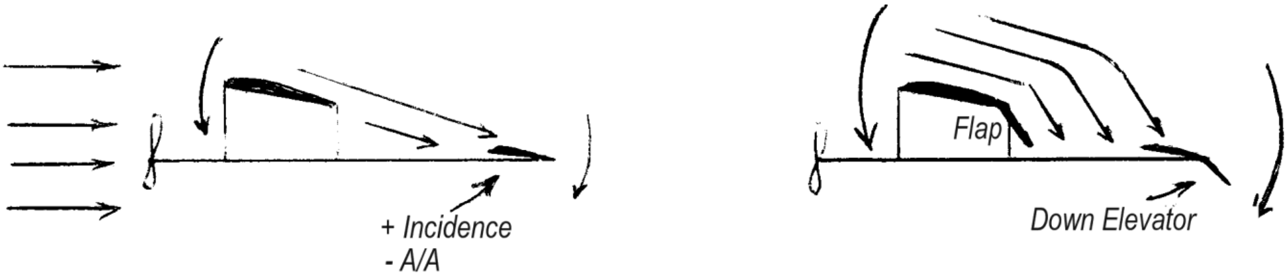


Figure Twenty Seven – Downwash Effect with High Wing

Most aeroplane designers attempt to design an aeroplane that requires minimal corrections when its configuration is changed, which is why there is predominance of low wing/mid tail aeroplanes in the world today.

Up until now I have been assuming that the aeroplane's centre of gravity (C of G) has been coincident with the aerodynamic centre and have only briefly mentioned the effect that the centre of gravity will have if is not. Depending upon how the aeroplane is loaded the C of G may be a little distance from the aerodynamic centre and this will create what is called a 'couple', which causes either a 'nose up' or 'nose down' pitching moment. As long as the aircraft is loaded in such a way that the C of G stays within the design limits, adjusting the elevator will counter these pitching moments in the same way that it counters the aerodynamic pitching moment, and still provide a reserve of elevator authority to enable the pilot to manoeuvre the aeroplane (Figure Twenty Eight).

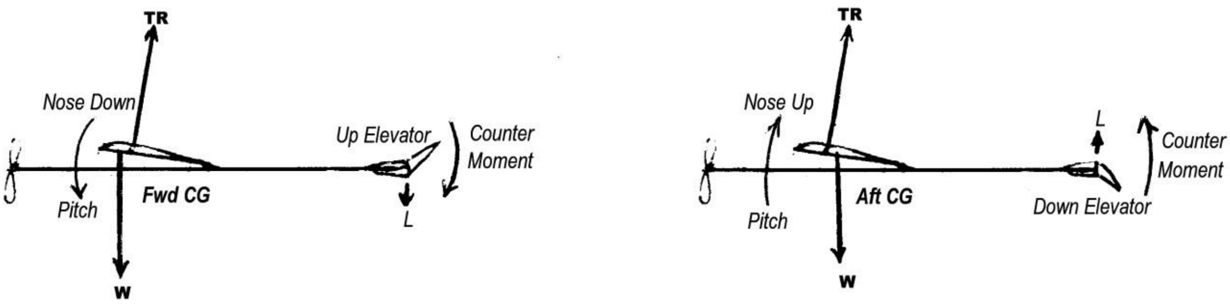


Figure Twenty Eight – Elevator Correction for Cof G Position

The greater the C of G range of a particular aeroplane the greater its tail volume has to be to counter the potential pitching moments, and the greater will be the variation in the elevator deflection/angle of attack relationship.

Okay, so armed with all of this new knowledge lets go back and revisit longitudinal stability.

Any pitch change involves an angle of attack change and its associated total reaction change, so if there is a pitching moment caused by the C of G position this 'couple' will be 'amplified' in turbulence. So the pitching moment caused by C of G position is a significant contributor to the overall static longitudinal stability. Imagine an aeroplane cruising in straight and level flight suddenly encountering a rising current of air. This rising current will momentarily cause an increase in the angle of attack of the wing and a decrease in the negative angle of attack of the tail (Figure Twenty Nine).

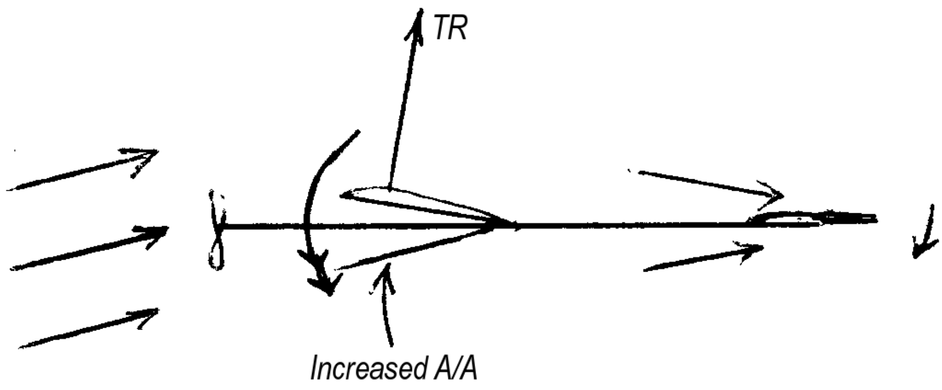


Figure Twenty Nine – Effect of Upward 'Gust' on Wing & Tail A/A

If the C of G is forward of the AC there will be an increase in the nose down pitching moment and a decrease in the tail's counter moment, which in turn will cause a more positive nose down pitch into the disturbance, that is, the longitudinal static stability is increased. The change in the angle of attack of the tail is similar in effect to what we have seen with the fin and the 'flights' of an arrow, but the addition of the wing pitching moment adds a unique extra stabilizing effect. If, however the C of G is aft of the AC the reverse situation applies and the longitudinal static stability is decreased. What happens if the centre of gravity is too far aft, that is, aft of its aft limit? Take a look at Figure Thirty below.

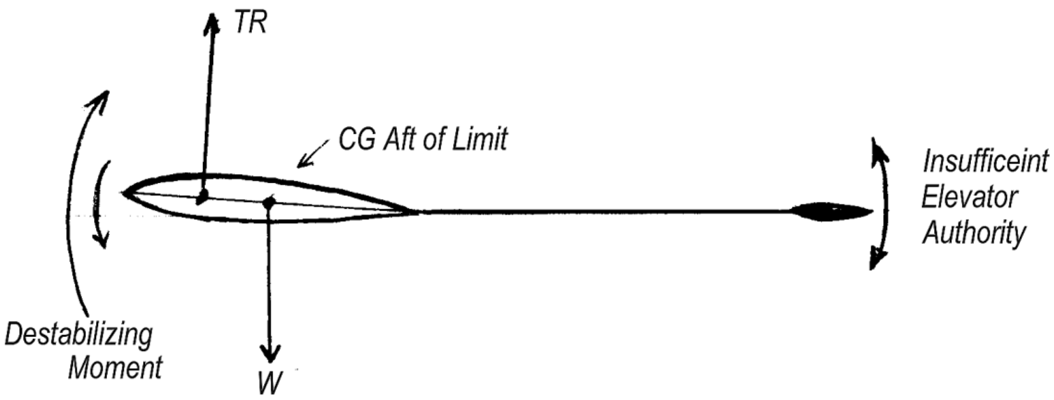


Figure Thirty – Effect on Stability of Aft Cof G

From the foregoing diagram you can see that a C of G which is too far aft not only reduces the moment arm of the tailplane and hence the tail volume, but the wing now has a significant (nose up) destabilizing moment – a moment which opposes the stabilizing effect of the aerodynamic pitching moment. Since the wing is the primary producer of all the reaction forces required for the aeroplane to fly it can produce very powerful forces and equally powerful destabilizing moments even if the C of G is only slightly aft of its limit. These destabilizing moments can easily overcome the wing pitching moment and the elevator 'authority' and render the aeroplane uncontrollable!

The Beechcraft Bonanza series of aircraft have all of their fuel tanks in the leading edge of their wings, forward of the C of G so that as the flight progresses and fuel is burned, the C of G moves aft! If the aeroplane is loaded in such a way that with full tanks the C of G is already at the aft limit before take-off then it will become longitudinally statically unstable during flight to the extent that it could become uncontrollable! A fatal crash of a fully loaded Beechcraft Baron, which has a similar fuel tank configuration, near Canberra in Australia not long ago, was attributed to this problem.

Aircraft stability is a complex subject but understanding the fundamentals of aircraft stability and control and the loading limits of your aeroplane is your best insurance policy against this sort of thing happening to you.

Aeroplane designers have a challenging job balancing the competing role requirements of modern aeroplanes with all of the aerodynamic compromises forced upon them by basic physics, fluid dynamics and structural engineering. Sometimes they create surprising 'fixes' for some of the problems encountered. The DH-4 Caribou, that I had many adventures in, was such an aeroplane, so for those of you who are interested I have, at Annex E, given a more detailed description of the 'fixes' that help a Caribou fly like a 'normal' aeroplane. But whatever the aeroplane is that you are flying you can be sure that someone has spent a lot of time making sure it flies the way it is meant to, provided you keep it within its design limits. Outside of those limits, "all bets are off".

List of Annexes to the lesson on: Stability and Control

Annex A. Early Control Techniques and Configurations

Annex B. The recipe for a good 'Inertia Couple'

Annex C. Finding the 'Mean Aerodynamic Chord' Line

Annex D. Roll Rate Damping

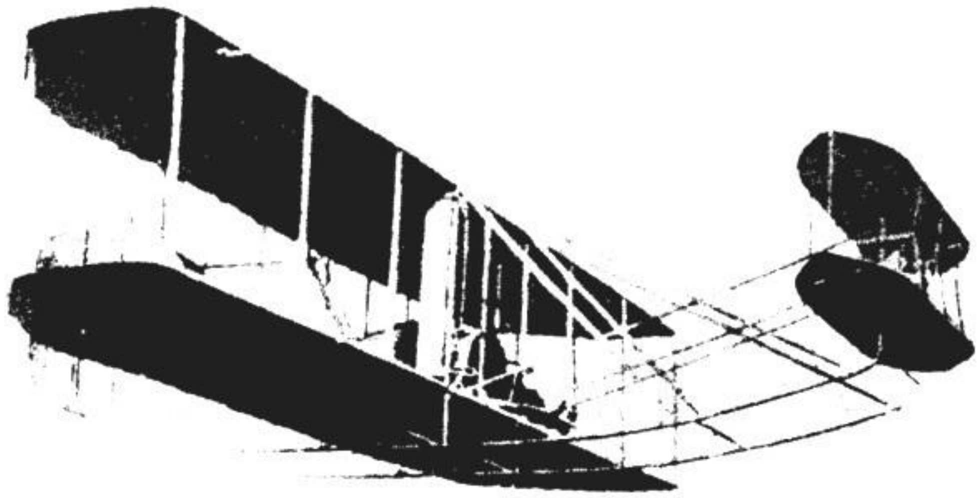
Annex E. Aerodynamic 'fixes' of the DH-4 Caribou

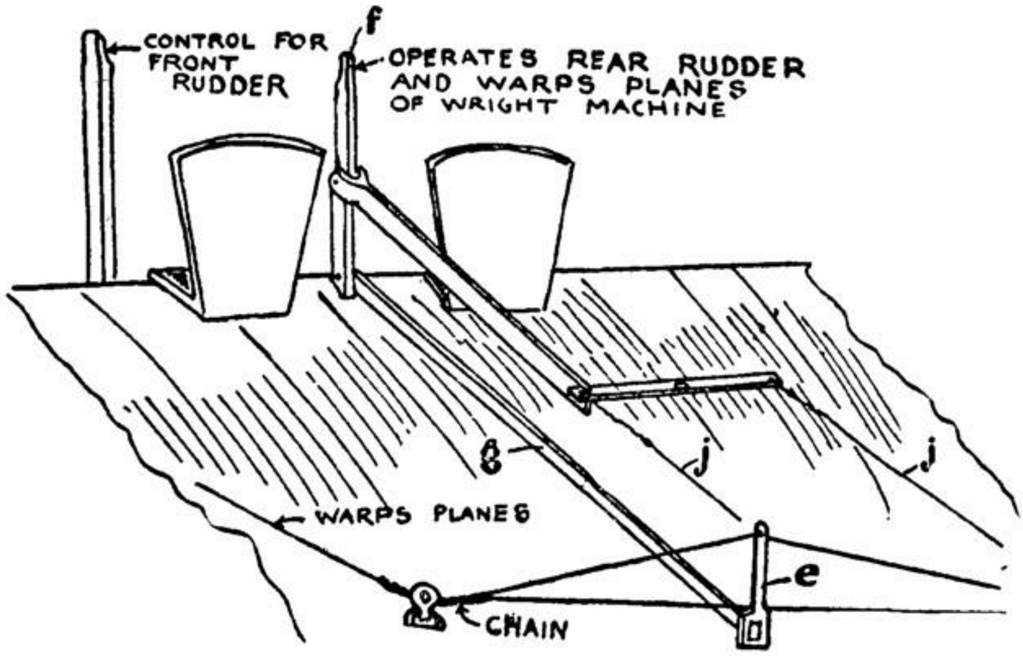
Annex A.

Early Control Techniques and Configurations

The following is a series of extracts from pre World War One books on flying machines and how to fly them. I have selected extracts which describe the different control techniques and configurations employed by the early pioneers of flight; I trust you will find them interesting.

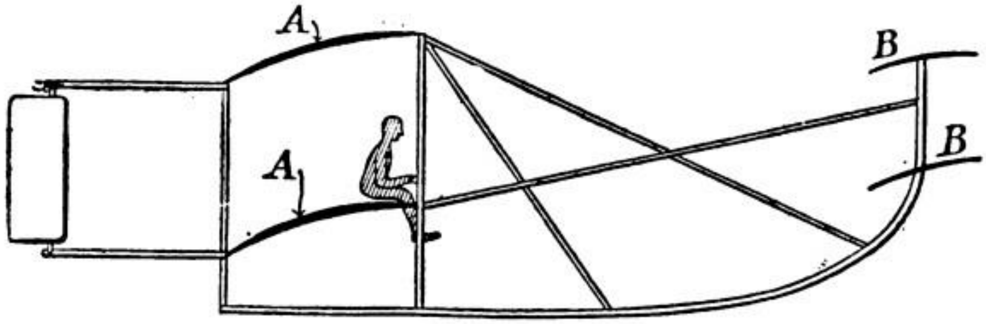
Wilbur and Orville Wright.





How the Wrights Control Their Machine.

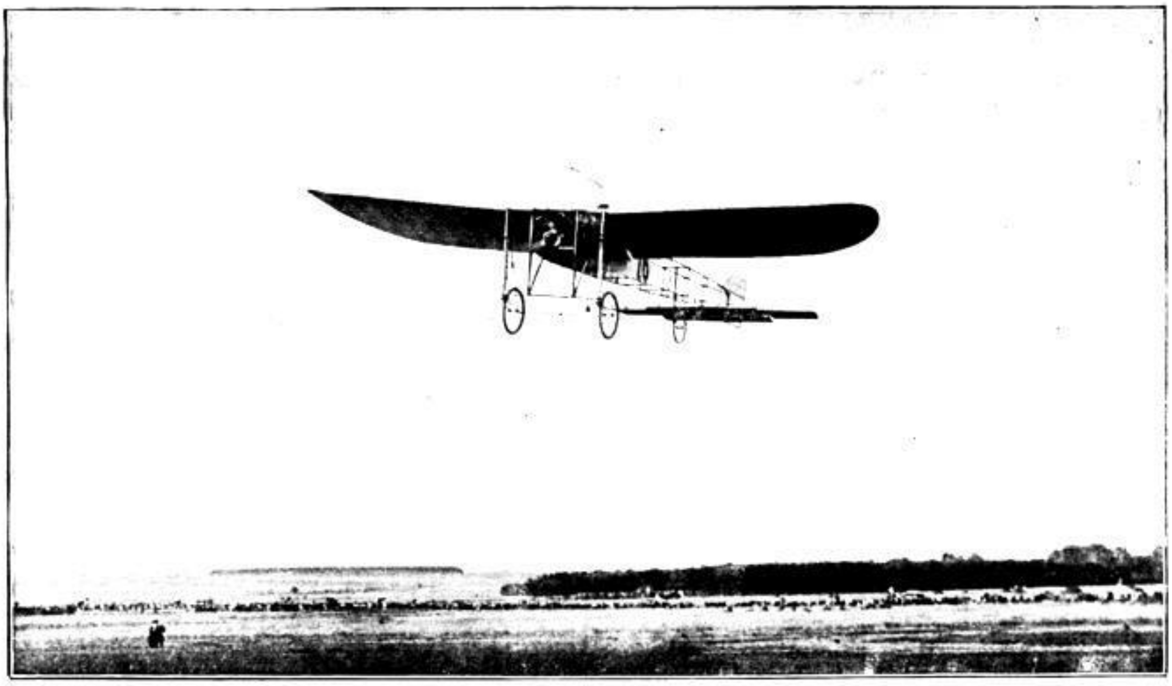
The wing-warping controls are actuated by the lever at the right hand of the pilot, which also turns the rudder at the rear—that which steers the machine to right or to left. The lever at the left



Sketch showing relative positions of planes and of the operator in the Wright machine: *A*, *A*, the main planes; *B*, *B*, the elevator planes. The motor is placed beside the operator.

hand of the pilot moves the elevating planes at the front of the machine.

Louis Bleriot



A Bleriot monoplane, "No. XI," in flight.

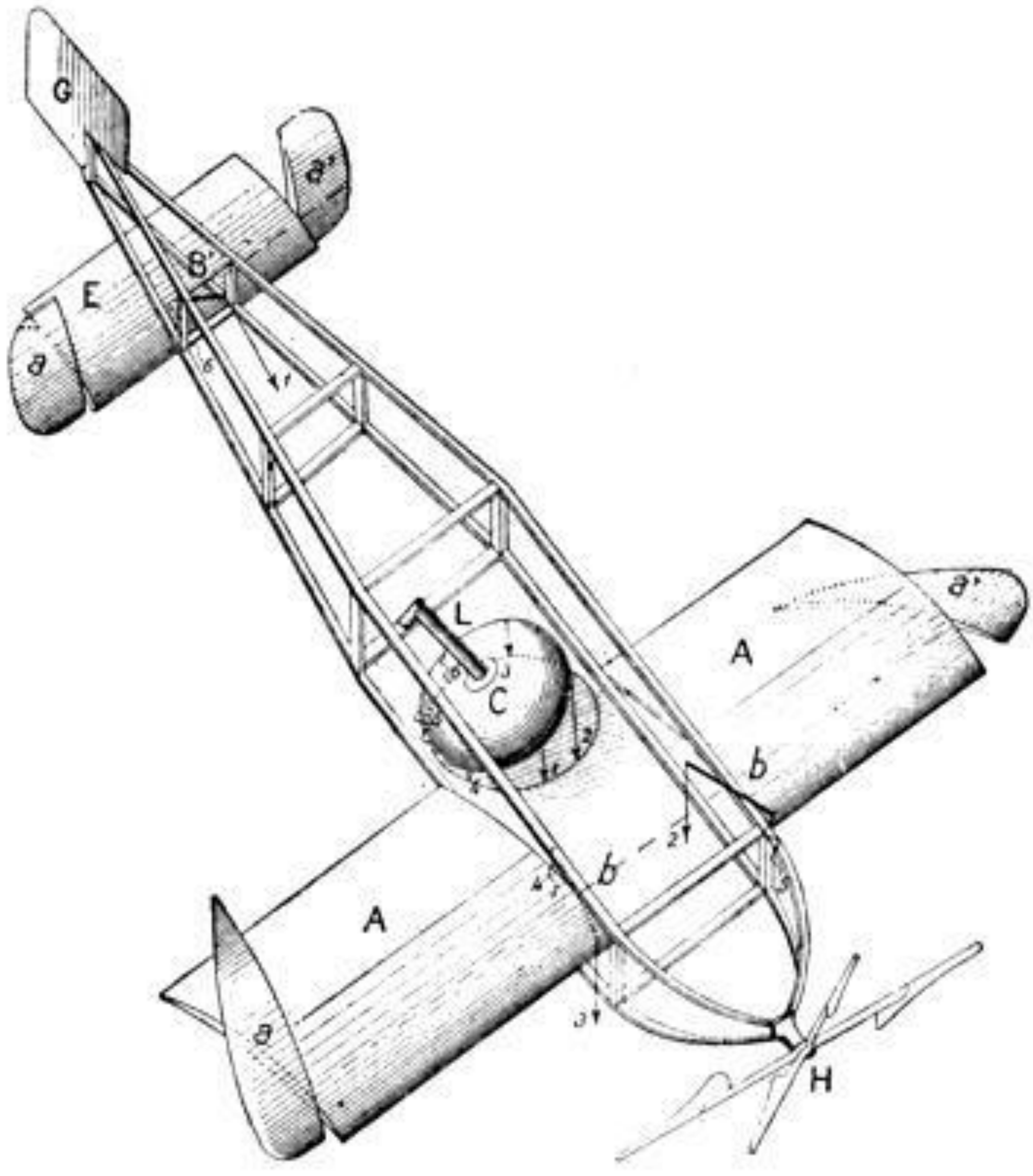
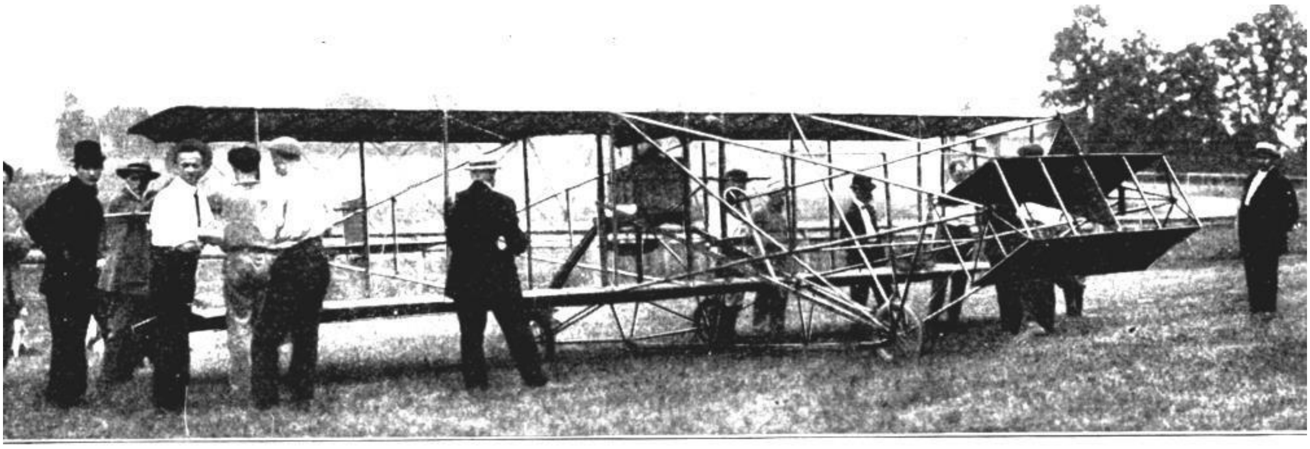
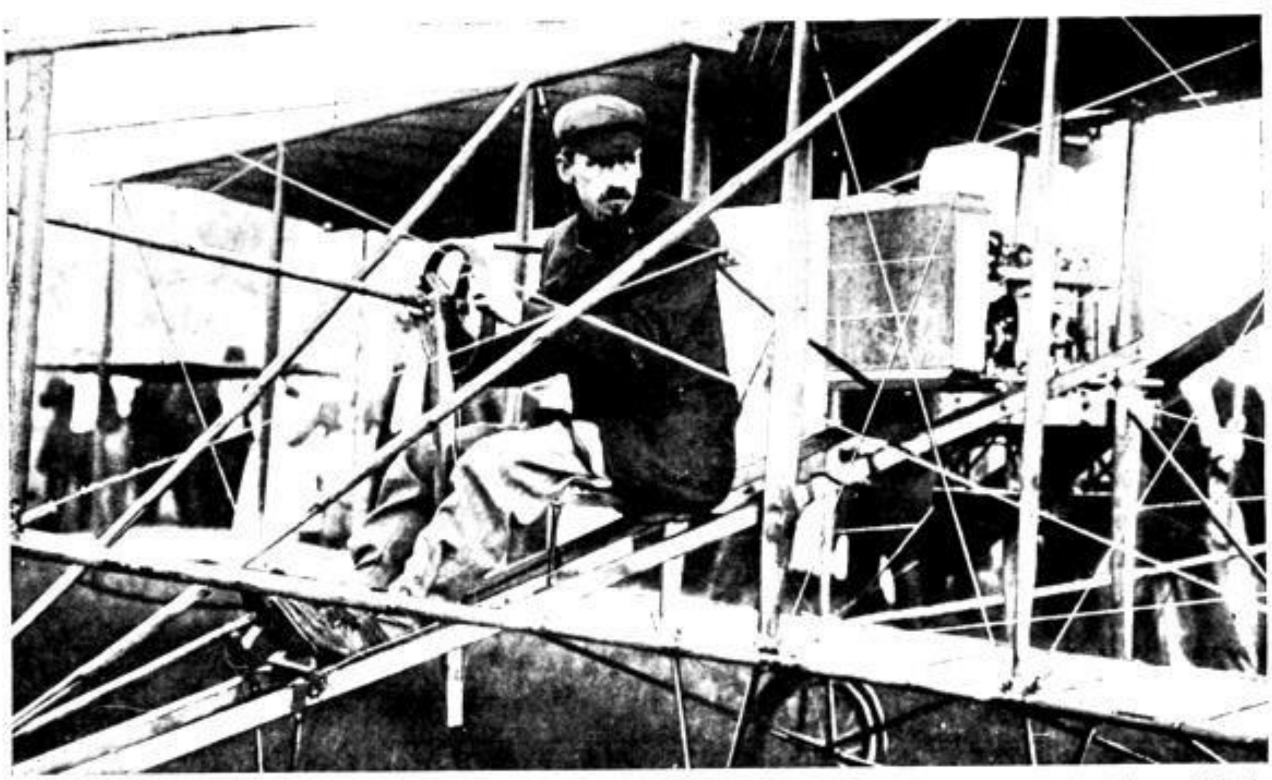


Diagram of Bleriot monoplane, showing controlling lever *L* and bell-shaped drum *C*, to which all controlling wires are attached. When the bell is rocked back and forward the elevator tips on the rear plane are moved; rocking from side to side moves the stabilizing tips of the main plane. Turning the bell around moves the rudder.

Glen Curtiss



Curtiss Biplane Ready for Flight



Glenn H. Curtiss in his machine ready to start. The fork of the balancing lever is plainly seen at his shoulders. Behind him is the radiator, with the engine still further back.

The caption reads, *"Glen H Curtiss in his machine ready to start. The fork of the balancing lever is plainly seen at his shoulders. Behind him is the radiator, with the engine further back".*

Having attained the art of balancing, the aviator has to learn the mechanism by which he may control his machine. While all of the principal machines are but different embodiments of the same principles, there is a diversity of design in the arrangement of the means of control. We shall describe that of the Curtiss biplane, as largely typical of them all.

In general, the biplane consists of two large sustaining planes, one above the other. Between the planes is the motor which operates a propeller located in the rear of the planes. Projecting behind the planes, and held by a framework of bamboo rods, is a small horizontal plane, called the tail. The rudder which guides the aeroplane to the right or the left is partially bisected by the tail. This rudder is worked by wires which run to a steering wheel located in front of the pilot's seat. This wheel is similar in size and appearance to the steering wheel of an automobile, and is used in the same way for guiding the aeroplane to the right or left. (See illustration of the Curtiss machine in Chapter V.)

In front of the planes, supported on a shorter projecting framework, is the altitude rudder, a pair of planes hinged horizontally, so that their front edges may tip up or down. When they tilt up, the air through which the machine is passing catches on the under sides and lifts them up, thus elevating the front of the whole aeroplane and causing it to glide upward. The opposite action takes place when these altitude planes are tilted downward. This altitude rudder is controlled by a long rod which runs to the steering wheel. By pushing on the wheel the rod is shoved forward and turns the altitude planes upward. Pulling the wheel turns the rudder planes downward. This rod has a backward and forward thrust of over two feet, but the usual movement in ordinary wind currents is rarely more than an inch. In climbing to high levels or swooping down rapidly the extreme play of the rod is about four or five inches.

Thus the steering wheel controls both the horizontal and vertical movements of the aeroplane. More than this, it is a feeler to the aviator, warning him of the condition of the air currents, and for this reason must not be grasped too firmly. It is to be held steady, yet loosely enough to transmit any wavering force in the air to the sensitive touch of the pilot, enabling him instinctively to rise or dip as the current compels.

The preserving of an even keel is accomplished in the Curtiss machine by small planes hinged between the main planes at the outer ends. They serve to prevent the machine from tipping over sideways. They are operated by arms, projecting from the back of the aviator's seat, which embrace his shoulders on each side, and are moved by the swaying of his body. In a measure, they are automatic in action, for when the aeroplane sags downward on one side, the pilot naturally leans the other way to preserve his balance, and that motion swings the ailerons (as these small stabilizing planes are called) in such a way that the pressure of the wind restores the aeroplane to an even keel. The wires which connect them with the back of the seat are so arranged that when one aileron is being pulled down at its rear edge the rear of the other one is being raised, thus doubling the effect. As the machine is righted the aviator comes back to an upright position, and the ailerons become level once more.

There are other controls which the pilot must operate consciously. In the Curtiss machine these are levers moved by the feet. With a pressure of the right foot he short-circuits the magneto, thus cutting off the spark in the engine cylinders and stopping the motor. This lever also puts a brake on the forward landing wheels, and checks the speed of the machine as it touches the ground. The right foot also controls the pump which forces the lubricating oil faster or slower to the points where it is needed.

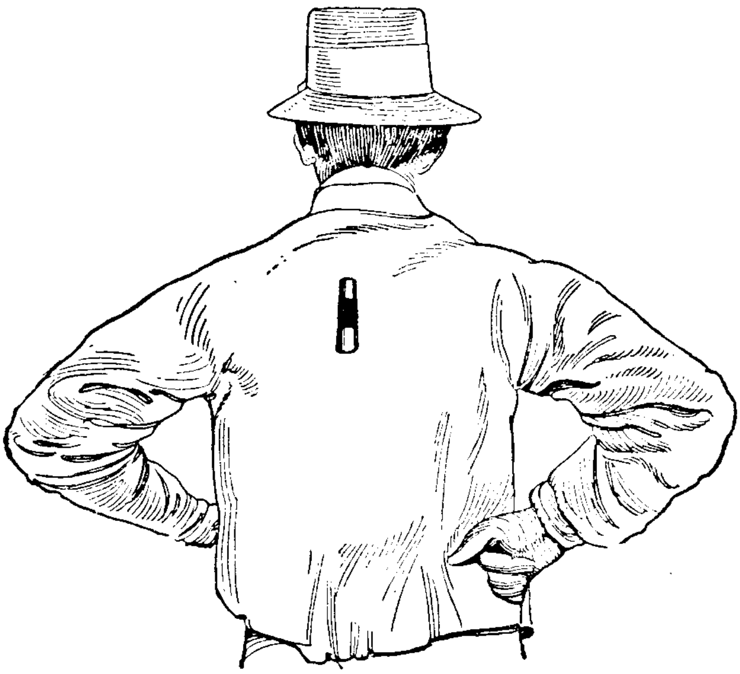
The left foot operates the lever which controls the throttle by which the aviator can regulate the flow of gas to the engine cylinders. The average speed of the 7-foot propeller is 1,100 revolutions per minute. With the throttle it may be cut down to 100 revolutions per minute, which is not fast enough to keep afloat, but will help along when gliding.

Do you think you could fly a Curtiss Biplane!? The control configuration is significantly different to a modern aeroplane. Note the description of the control of the 'Altitude Rudder' (Elevators); it is the reverse of that which a modern aviator is used to.

THE HERRING BIPLANE.

At the Boston Aircraft Exhibition in February, 1910, the Herring biplane attracted much attention, not only because of its superiority of mechanical finish, but also on account of its six triangular stabilizing fins set upright on the upper plane. Subsequent trials proved that this machine was quite out of the ordinary in action.

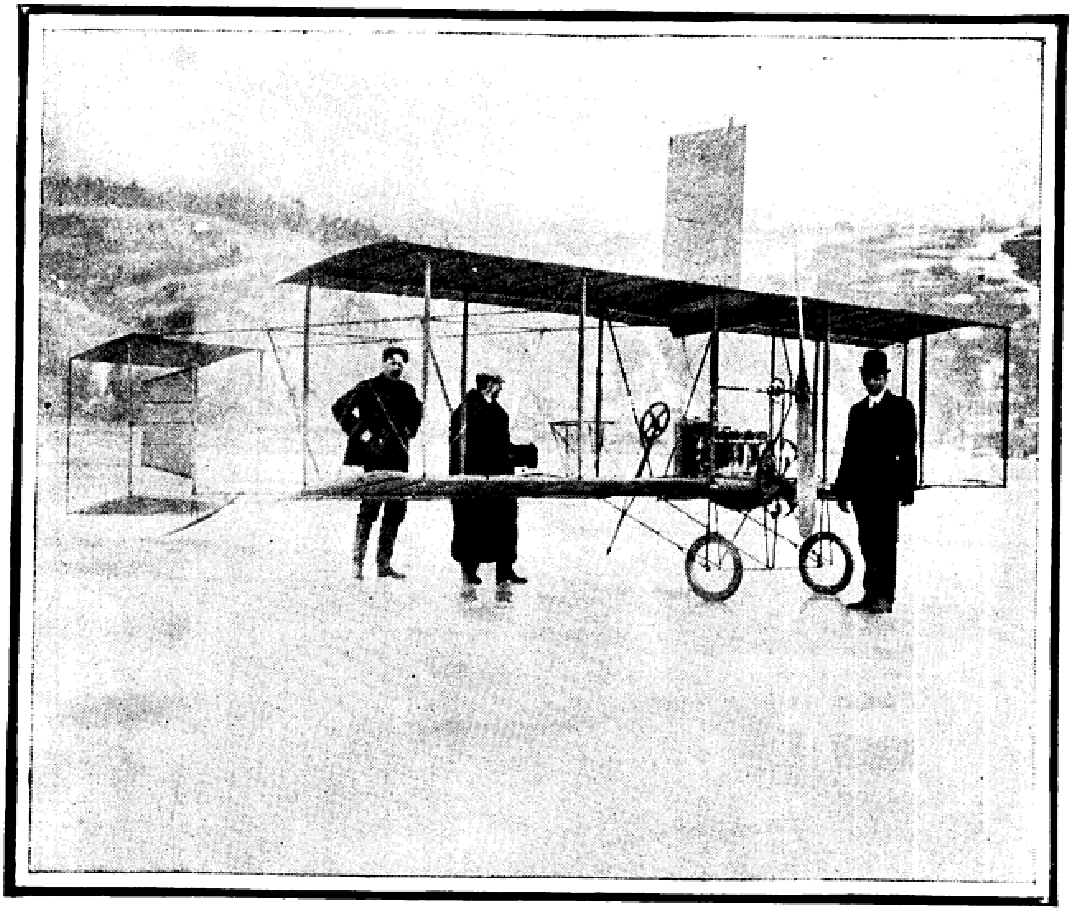
The stabilizing fins act in this manner: when the machine tips to one side, it has a tendency to slide down an incline of air toward the ground. The fins offer resistance to this sliding, retarding the upper plane, while the lower plane slides on and swings as a pendulum into equilibrium again.



Device on Back of Santos-Dumont's Shirt.

Wires run from this in both directions so the auxiliary planes may be manipulated by a mere movement of the body to the right or left.

main planes is 31 feet 3 inches, and their depth 4 feet 6 inches. A balancing plane of 9 square feet is set upright (like a fin) above the upper main plane, on a swivel. This is worked by a fork fitting



The Baldwin biplane, showing balancing plane above upper main plane.

on the shoulders of the pilot, and is designed to restore equilibrium by its swinging into head-resistance on one side or the other as may be necessary.

Henri Farman

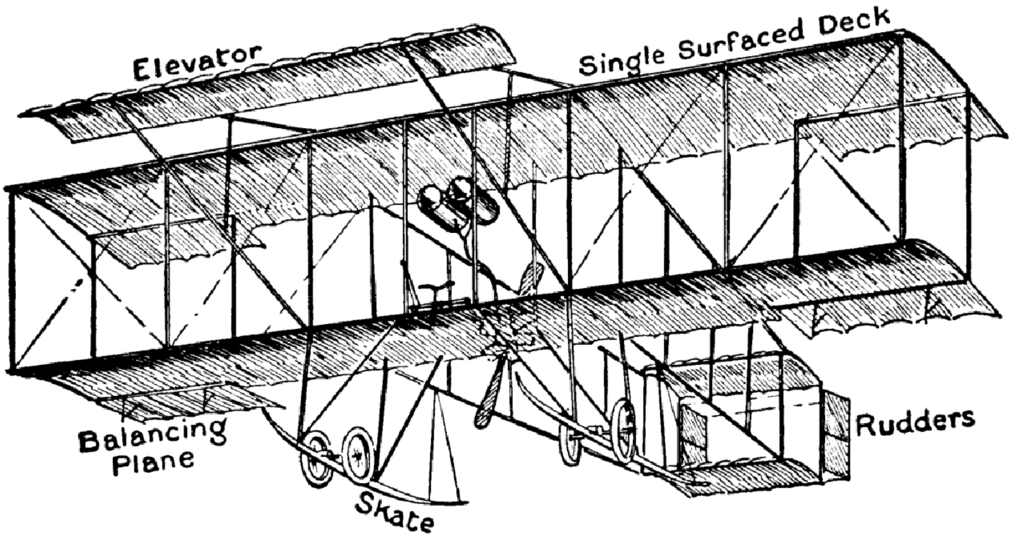
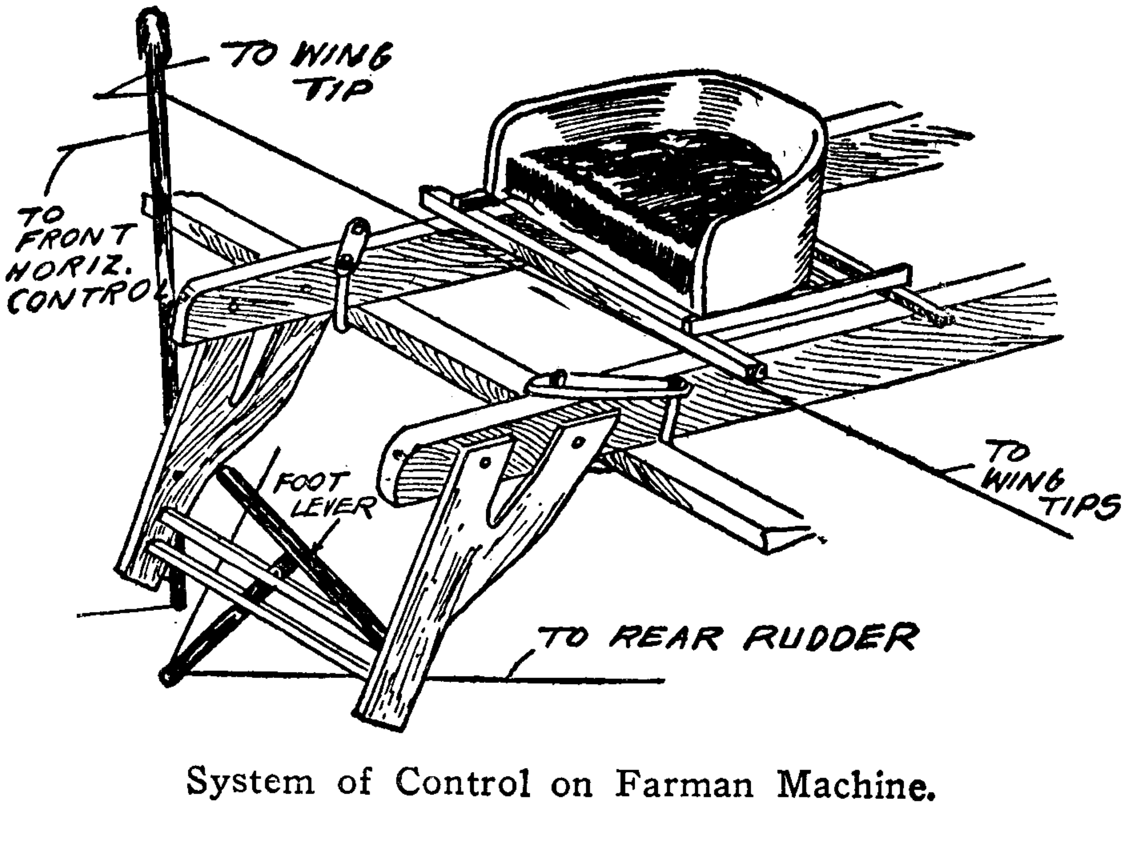
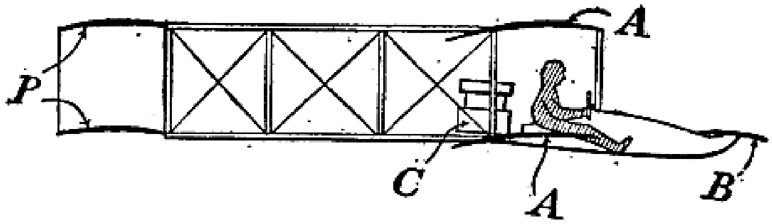


Diagram of the Farman biplane. A later type has the hinged ailerons also on the tail planes



System of Control on Farman Machine.

The "racing Farman" is slightly different, having the hinged ailerons only on one of the main planes. The reason for this is obvious. Every depression of the ailerons acts as a drag on the air



Sketch of Farman machine, showing position of operator. *A*, *A*, main planes; *B*, elevator; *C*, motor; *P*, tail planes.

flowing under the planes, increasing the lift at the expense of the speed.

The whole structure is mounted upon skids with wheels attached by a flexible connection. In case of a severe jar, the wheels are pushed up against the springs until the skids come into play.

The elevator and the wing naps are controlled by a lever at the right hand of the pilot. This lever moves on a universal joint, the side-to-side movement working the flaps, and the forward-and-back motion the elevator. Steering to right or left is done with a bar operated by the feet.

Note: The word 'Flaps' in this extract (and the typographical error "naps") refers to 'Stabilizing Flaps' or 'Ailerons'.......

This is the modern control configuration.

Annex B.

The recipe for a good ‘Inertia Couple’

Ingredients

1. Ability to generate high Angle of Attack.
2. Ability to roll very fast
3. High mass distribution along the fuselage.

Typical Aircraft - Mirage III.

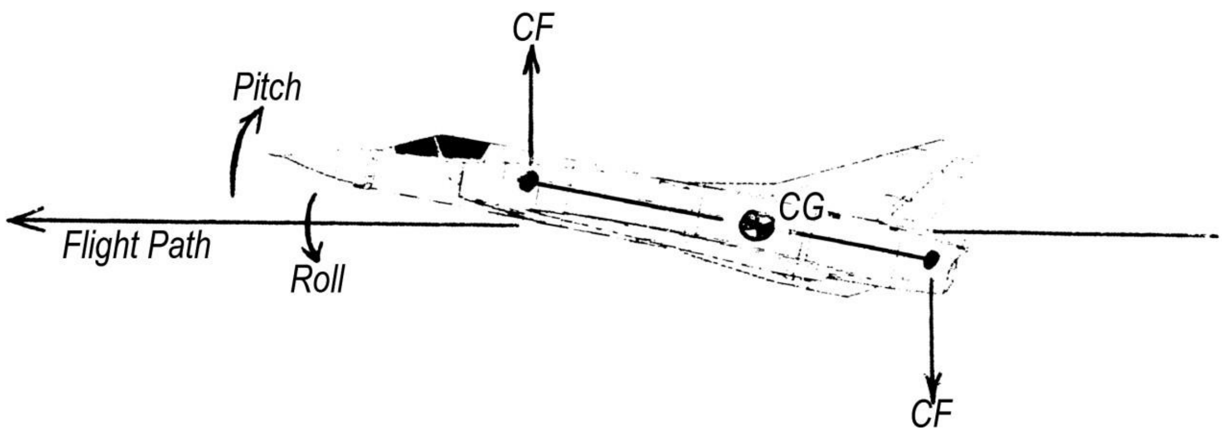
1. Delta wing capable of flying to about 25+ degrees A/A
2. Short wing span and full span ailerons (Elevons)
3. 70-80% of mass distributed along fuselage.

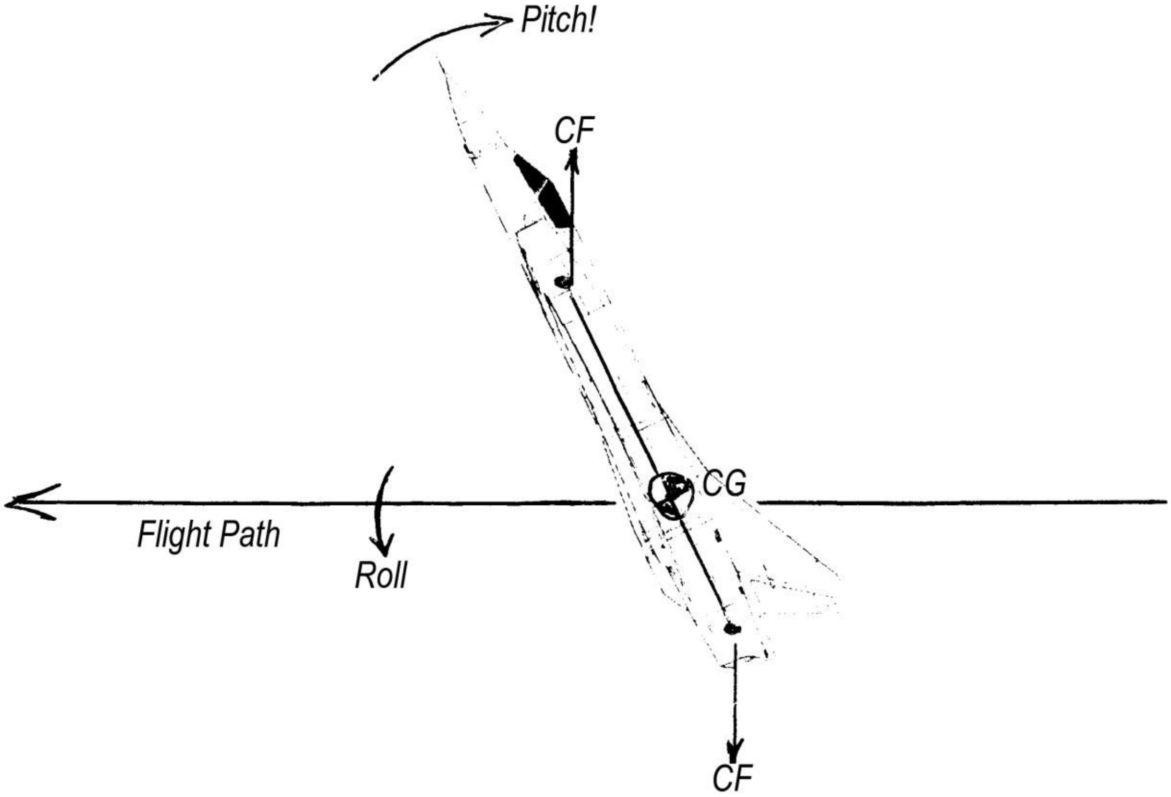
Procedure

1. ‘Pull’ a high A/A manoeuvre, such as a tight turn.
2. Whilst holding A/A, apply full aileron.
3. Sit back and ‘enjoy’ the ride!

The aerodynamics/ dynamics

The aeroplane will roll rapidly about its flight path. Since the flight path is 25º from the longitudinal axis, which is the axis of the mass distribution, the fuselage is subjected to very high centrifugal forces which overcome the static stability and cause the aeroplane to pitch to 90º A/A!





Depending upon the structural strength of the aeroplane, one of two things will happen at this point.

1. The aircraft will break up. (John Derry, DH-110, Farnborough Airshow Circa 1952)

2. The aircraft will depart from controlled flight and crash. (My friend practicing for a RAAF air show, Mirage III, Circa 1965 and several Russian Air Force flying displays, MiGs, Sukois et al, in Europe over the past decades.)

This annex is not intended to discuss in detail the advanced handling characteristics of Jet Fighters, but to simply illustrate my point that aeroplanes roll around their flight path not their longitudinal axis.

It is interesting to note that Air Shows seem to play a dominant part in these examples.

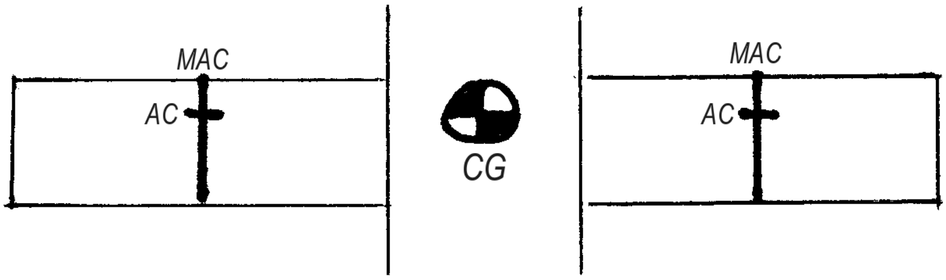
I will return to the effects of inertia coupling in the lesson on Spinning.

Annex C.

Finding the 'Mean Aerodynamic Chord' Line

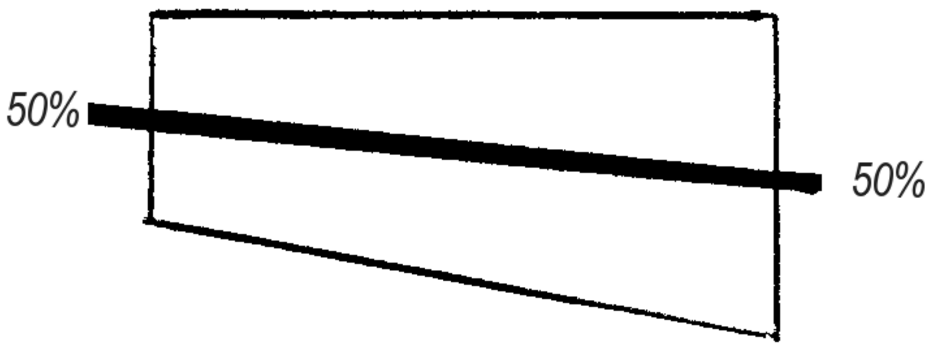
In order to position the wings onto the fuselage of an aeroplane so that a line between the aerodynamic centers of each wing is coincident with the centre of gravity, the designer must know what the 'Mean Aerodynamic Chord' line of each wing is, because the aerodynamic centre of each wing is at 25% of this chord line, (in subsonic flight).

On a straight, un-tapered wing this is obvious; the MAC is half way out along each wing.

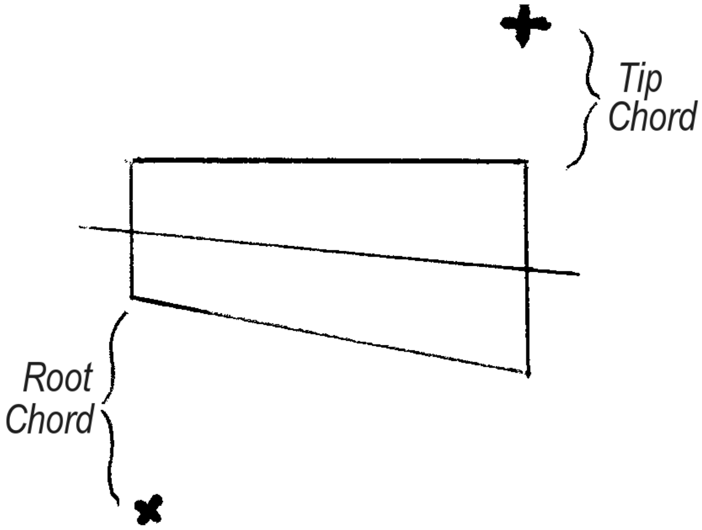


But if the wing is tapered it is not so obvious. This is how it is found:

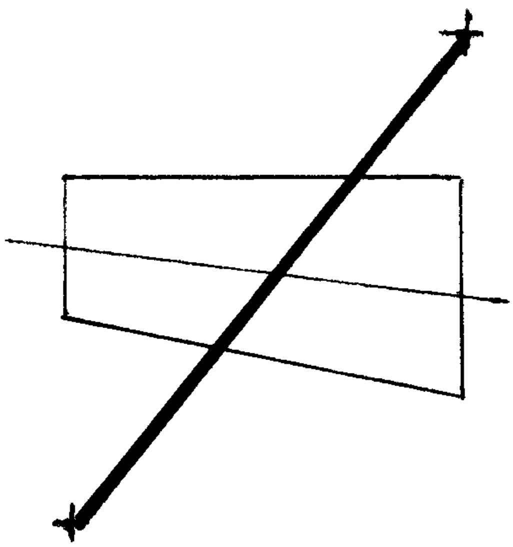
First on a plan of one of the wings draw a straight line from a point at 50% of the root chord line to a point at 50% of the tip chord line:



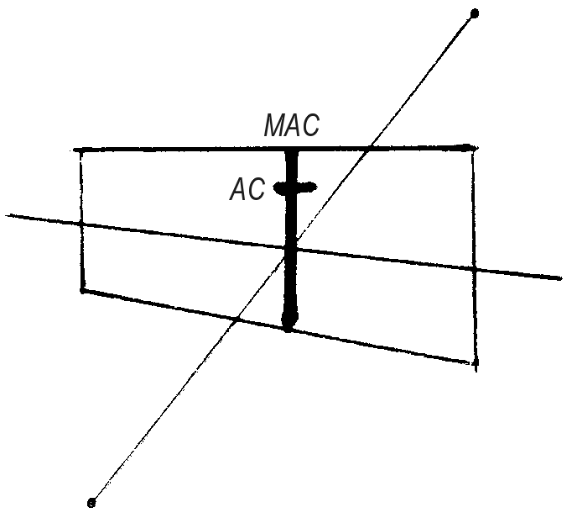
Then mark a point ahead of the leading edge at the wing root a distance equal to the length of the tip chord and a point behind the trailing edge of the tip a distance equal to the length of the root chord, as follows:



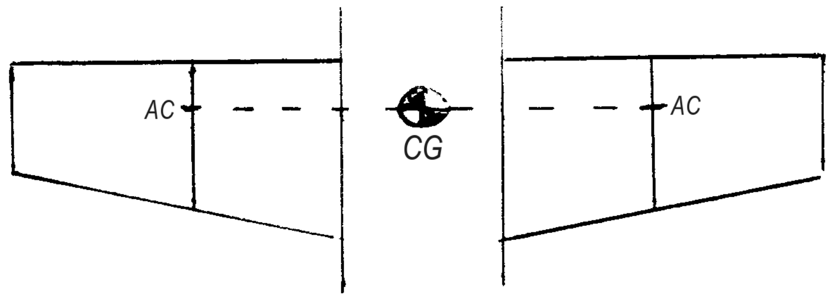
Now draw a straight line linking these two points:



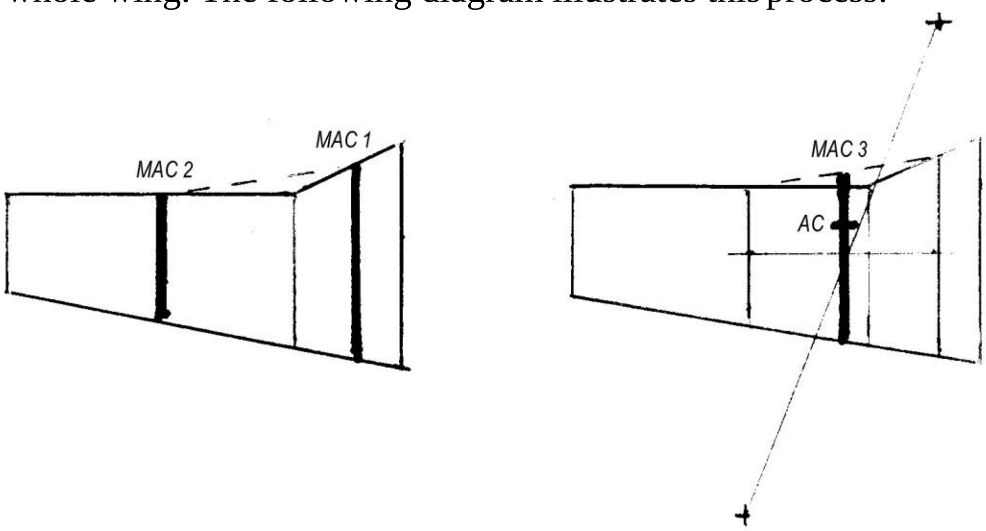
The point of intersection of these two lines is the position of the MAC for that wing.



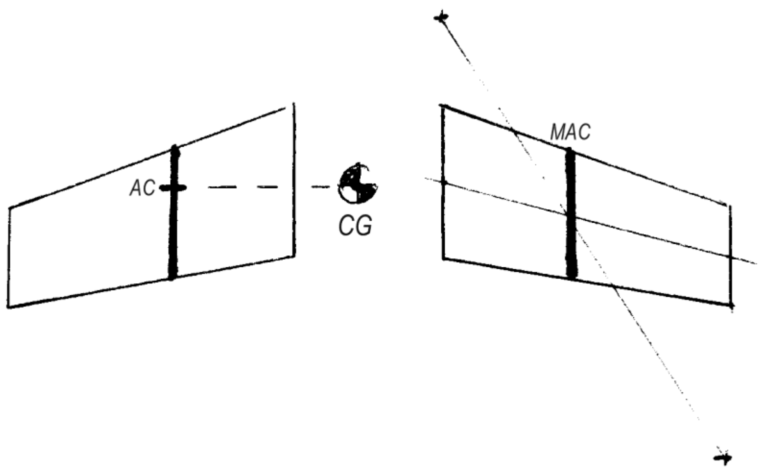
The aerodynamic centre at 25% of the MAC is now the aerodynamic centre for the whole wing and a line between the Aerodynamic centers of each wing should pass through the C of G in order that the lift and weight of the aeroplane are in 'balance'.



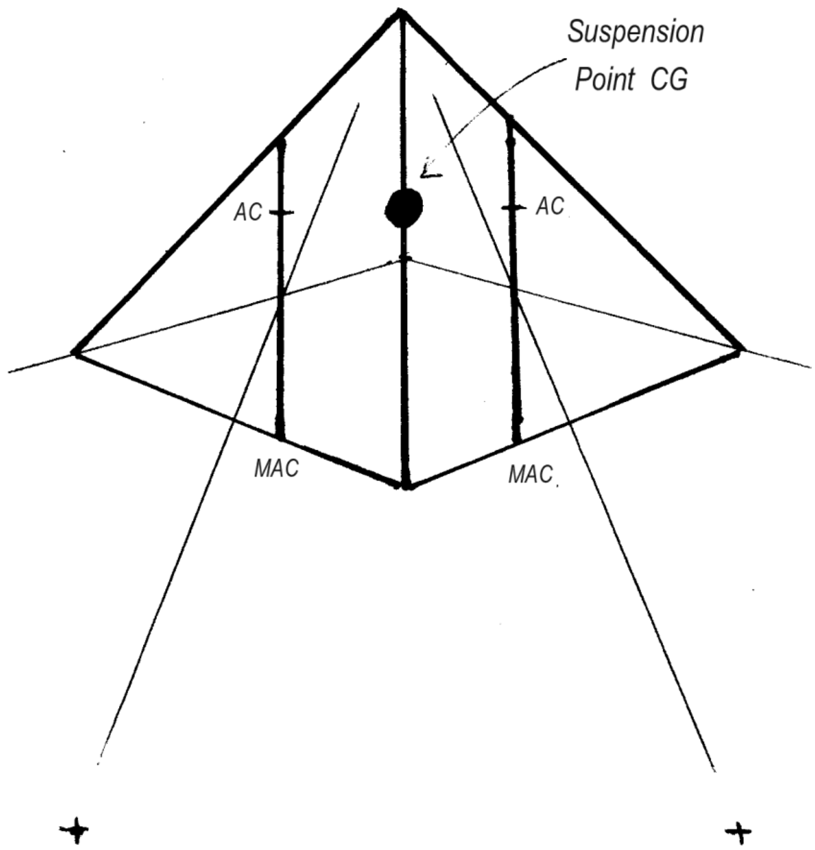
If the wing has a more complex shape, like the Beechcraft Bonanza or the P-51 Mustang, it is necessary to find the MAC of each section of the wing first, using the foregoing procedure, and then treat the inner MAC as the root and the outer MAC as the tip of a new imaginary wing, and then find the MAC of it. This will be the MAC of the whole wing and the 25% point of this MAC will be the AC of the whole wing. The following diagram illustrates this process:



How about swept wings? No problems, use the same method:



This is how I found the harness suspension point for my Rogallo Hang glider:



There is no tip chord, so just the root chord is plotted back from the tips. This works on any delta wing.

So what is the point of knowing how to find the mean aerodynamic chord and the aerodynamic centre of a wing? It is so you can easily visualize where the centre of lift is on the wing of your aeroplane and in this way you can get a better ‘feel’ for the position of the forces acting to keep you ‘up there’. (You can also calculate the wing area of an aeroplane by multiplying its MAC by its Span, too.)

Annex D

Roll Rate Damping

If the ailerons of an aircraft in flight are deflected a certain amount and then held in that position, the aeroplane will start to roll, and the roll rate will quickly stabilize at a particular rate. This begs the question, "why, if the ailerons continue to be deflected, doesn't the roll rate continue to increase? What 'damping effect' stops this happening?"

To help you visualize what I am about to say, I want you to imagine that you are outboard of an aeroplane's wing and looking back at the wingtip as it rolls around, (a bit like a racing skiff sailor hanging out on a 'trapeze' and looking back at the boat as it heels over). First, let's look at the wingtip section at the instant the ailerons are deflected, but before the roll commences (which is impossible, but I have split the action and its effect for clarity.) See Figure One.

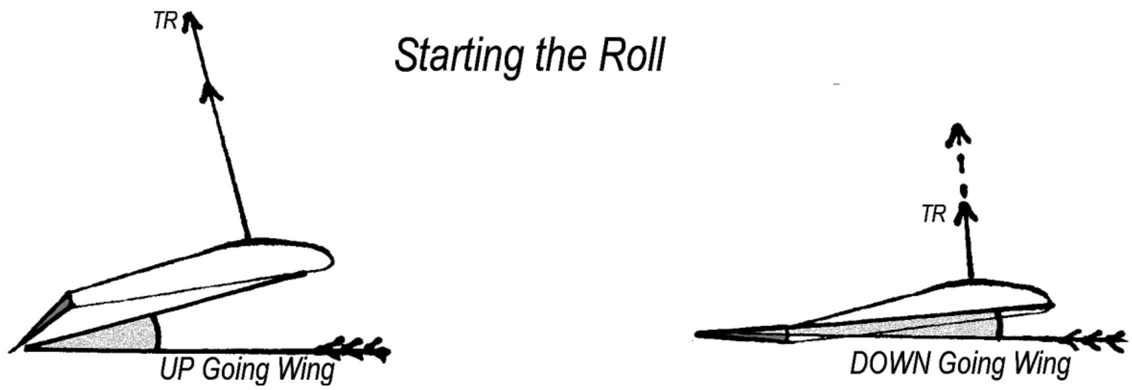


Figure One – A/A at the commencement of the Roll

You will see from Figure One that the angle of attack of one wing (the 'up going' wing) has been increased by the downward deflection of the aileron, causing a lift increase, whilst the angle of attack of the other wing (the 'down going' wing), has been decreased by the upward deflection of its aileron, causing a reduction in lift. This lift asymmetry causes the aeroplane to roll - all of which you should already understand - but, as soon as the aeroplane starts to roll, the direction of the airflow encountered by each wing changes (Figure Two)

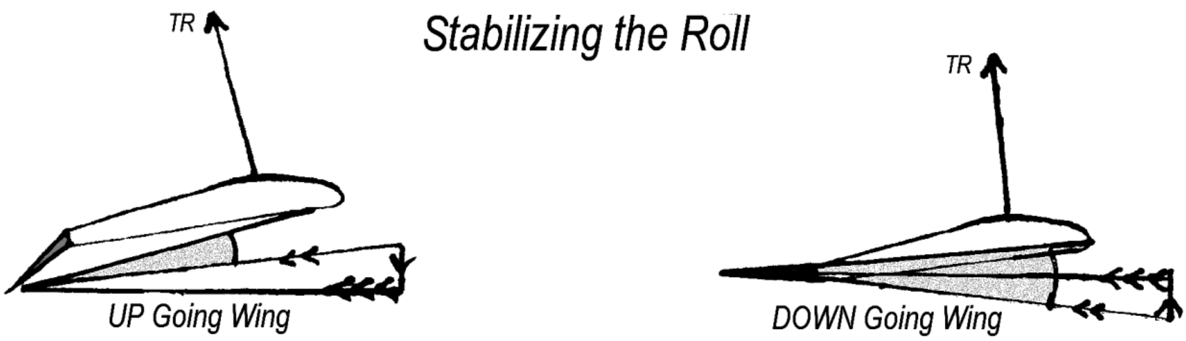


Figure Two – A/A during the Roll

Compare the diagram at Figure Two with the one at Figure One. You can see that the 'up going' wing now encounters an additional airflow coming down from above, and this changes the resultant relative airflow direction such that the wing's angle of attack is reduced. (These airflows are depicted by the vector diagram below the wing section.) Conversely, the 'down going' wing encounters an additional airflow from below, thereby increasing its angle of attack.

Very quickly a situation develops where the increased angle of attack caused by the 'down' aileron will be offset by the decreased angle of attack caused by the changed relative airflow and vice versa (on the other wing). At this point the lift asymmetry vanishes and the roll rate stabilizes and remains constant. (Remember, in the preceding diagrams you have to visualize that you are 'whizzing around' with the wingtip so that you can see the direction of the relative airflow approaching the rolling wings...so hang on!)

When we decide to stop the roll we simply centralize the 'stick' and the ailerons are returned to neutral whilst the aeroplane is still rolling. Compare the diagram at Figure Three with the previous one at Figure Two, and you can see that there is now an angle of attack difference on each wing because, whilst the direction of the resultant relative airflow hasn't changed, **the chord line has**. This angle of attack difference causes a lift asymmetry which opposes the roll, so the aeroplane stops rolling. At the instant the roll stops the relative airflow is once again from straight ahead on both wings, so the lift asymmetry once again vanishes, leaving the aeroplane in a stable attitude.

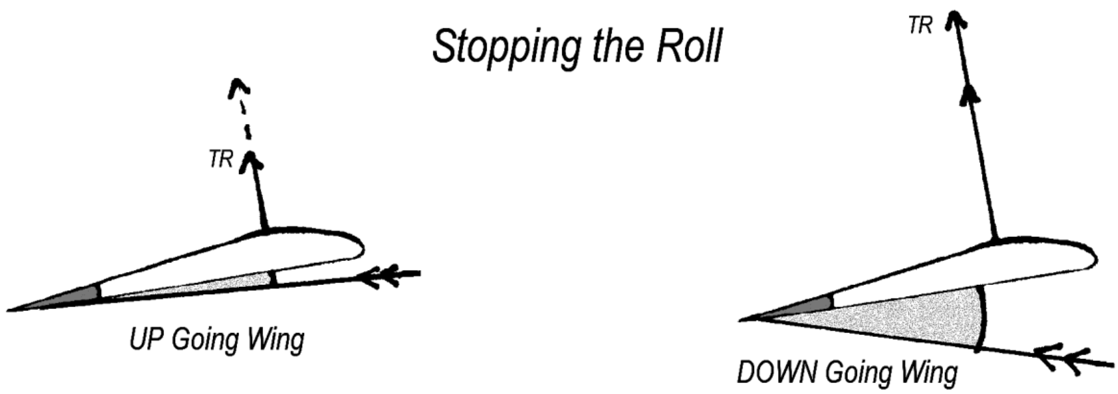


Figure Three – Stopping the Roll

Now remember, the ailerons only affect the airflow on the outboard section of the wing. The rest of the wing also experiences these angle of attack changes during the roll too, and, even though the effect diminishes toward the wing root, because of its 'inbuilt' lateral stability, the remaining wing is continually trying to stop the roll. I said at the beginning of this lesson that "stability and control are the antithesis of one other" and this is a specific example of that statement.

The roll rate at which an aeroplane stabilizes depends upon its wingspan, how large the ailerons are (as a percentage of the whole wing), how much of the span they cover, how much they have been deflected by the pilot, (the maximum angle of aileron deflection on most aeroplanes is about 20º-25º) and the TAS.

The TAS/IAS relationship is a factor which I will not dwell upon too much except to say that at high altitude the difference between the speed on the airspeed indicator (IAS) and the true speed at which the aeroplane is flying (TAS) is significant, and it reduces the 'damping' angle of attack change during the roll and allows the aeroplane to roll faster at a particular indicated airspeed. Since most light training aeroplanes are not capable of going high enough for this effect to be noticeable we will not explore it any further here.

The maximum roll rate of a light training aeroplane is about 45º per second, whilst the maximum roll rate of a modern fighter aircraft or the latest competition aerobatic aircraft is in the order of 400º+ per second! (Which means that before the stick is hard over the aeroplane is already in the desired attitude and it's time to stop rolling!) On the other hand the pilot of an airliner, when rolling into and out of turns, will try to keep the roll rate at about 5º per second to avoid upsetting the passengers. Which can be a bit boring.

Annex E.

Aerodynamic ‘fixes’ of the DH-4 Caribou

The Caribou is a twin engine short range STOL (Short Take-Off and Landing) transport aeroplane designed for easy loading and an ability to operate from short unprepared strips in inhospitable terrain. It fulfills this role admirably.

DH-4 Caribou

In the design process a number of interesting compromises and ‘fixes’ had to be introduced. The aeroplane’s maximum weight is 28,500 pounds including a disposable load of 7,000 pounds. It has a convenient rear loading ramp necessitating the tail be set quite high. It has a 98 foot wingspan with double slotted full span flaps divided into four sections on each wing. The ailerons are the rearmost panel of the outer flap section and they ‘droop’ with the flaps. As a result aileron responsiveness at slow speed with full flap extended is not great!

Caribou Flaps

A later variant of the Caribou called the Buffalo has spoilers to augment the slow speed roll control. The Buffalo also has a ‘T’ tail to move the tailplane up and out of the way of the huge downwash effect those flaps have on the Caribou tailplane.

The Caribou tailplane is set as low as the rear loading doors would allow, for structural reasons, so it suffers the same ‘pitch up with flap’ explained in the lesson, and with the full 80º of flap extended the elevators alone are not sufficient to overcome this pitch up. The incidence of the stabilizer has to be adjusted to maintain control, but the pilot does not have control of the incidence adjustment, it is automatic. A torque tube linking the flaps to the stabilizer moves the leading edge of the stabilizer up as the flaps extend. This gives the whole tailplane about 10º more positive incidence to help compensate for the increased negative angle of attack caused by the downwash off the flaps. Even with this link the pilot still has to shove the stick forward positively on initial flap extension to maintain attitude, and if the flap/tailplane interconnect were to fail the aircraft would be uncontrollable with the flaps extended so a flapless landing would be necessary.

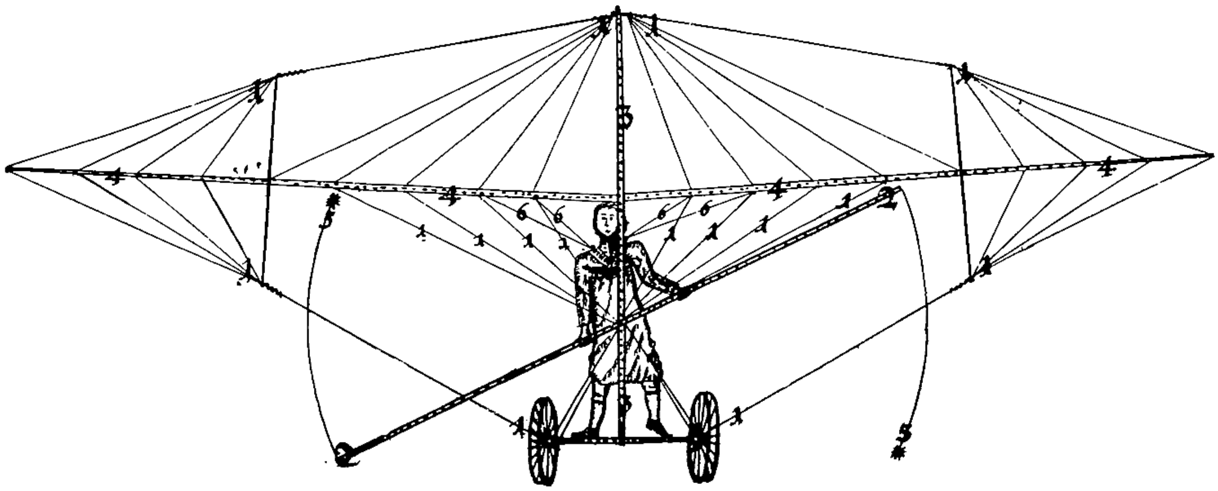
The Caribou rudder is set so high above the longitudinal axis that its secondary effect (the primary of course being yaw) is to roll the aeroplane in the opposite direction to the yaw! The designers decided that this would feel ‘strange’ to pilots used to aeroplanes which, due to their lateral stability, roll in the same direction as yaw so they included a rudder/aileron interconnect system so that when rudder is applied an aileron tab automatically moves to deflect the ailerons to roll the aeroplane in the ‘conventional’ sense.

The Caribou also has ‘servo’ balance tabs on its control surfaces to make them lighter for the pilot to operate and trim tabs on all controls, so when we add all of these tabs to the number of standard control surfaces, plus the four sections of double slotted flaps on each wing, the Caribou has 30 moving surfaces on its wings and tail, all of which are driven mechanically by cables and torque tubes! It sounds like a mechanical nightmare but the aeroplane is particularly rugged and fulfilled its role reliably for over 50 years.

Oh, and it was easy to fly.

Lesson Seven

MANOEUVRING



I use the term 'Manoeuvring' to mean any deviation of the aeroplane's flight path from straight. That is, from straight and level, straight descent or straight climb. Go back to the lesson on Lift and re-read Newton's first and second laws of motion and you will realize that in order to deviate from a straight flight path a force must be applied to the aeroplane, and the rate of deviation (acceleration) will depend upon the mass of the aeroplane and the size of the force. For the purposes of this lecture I do not include 'Rolling' in my definition of manoeuvring. I know that all of the aerobatic pilots amongst you will immediately put your hand up and beg to differ with me. Don't worry, in the book on aerobatics it will be reinstated, but for now, since a properly executed roll does not deviate from a straight flight path (you wish!), I have excluded it.

There is a simple formula for calculating the amount of force required to accelerate anything of known mass; it is:

F=MA

Which means that the **'Force'** required equals the **'Mass'** of the thing multiplied by the **'Acceleration'** and by rearranging this formula we can also calculate the acceleration if we already know the force.

A=F/M

Now a light aeroplane weighing about 800kg and traveling at about 120kts in a straight line has a great tendency to keep on doing just that (Newton's 1st law). This tendency is called 'inertia', which is a Latin word meaning "resistance to change". To overcome the inertia of this aeroplane and have it deviate from its straight flight path at any significant rate, quite a large force is required. This force, even in a moderate manoeuvre, can equal 40% of the aeroplanes total mass, and in a basic aerobatic manoeuvre, 4 times its mass!

What is the source of such huge forces? The engine? No. The rudder? Absolutely not. The wings? Yes! The wings' ability to generate the total reaction force required, are the source. After all, they have to generate a force equal to the aeroplane's weight just to keep the aeroplane in straight and level flight and they are capable of generating much much more.

Now if the aeroplane in the example is flying straight and level its wings will have an angle of attack of about 3º. If the aviator suddenly increases the angle of attack of the wings to almost the critical angle, by moving the 'stick' back to that position, they will generate a lifting force about 5 times that required for straight and level flight, that is, 5 times the weight of the aeroplane! They will also generate 'lift induced drag' 25 times greater than it was experiencing in straight and level flight, so the aeroplane will not sustain 120kts for long!

Since this aeroplane needs one 'lot' of lift to fly straight and level, generating five 'lots' will leave an excess of four, that is, a residual force four time greater than its mass, so it will deviate from its straight flight path quite rapidly. So by pointing the aeroplane's 'lift vector' in the appropriate direction and varying its magnitude by varying the angle of attack of the wings the aviator can follow any flight path through the sky that he or she wishes. How do we do this? Let's start very simply, by changing flight path on a constant heading: changing from straight and level flight to a straight climb and then coming back to straight and level again.

Now the average young flying instructor will tell his student that the way to enter a straight climb is to ease back on the 'stick' until the nose reaches the climb attitude and then hold it there (adding power and adjusting trim too). He is not wrong but the instruction hardly explains what is going on. So what is going on?

From straight and level flight the student eases back on the stick, which moves the elevator up, causing it to have an increased negative angle of attack, which in turn causes a downward 'lift' on the tailplane. This generates a pitching moment about the centre of gravity, causing the nose to rise a little and the angle of attack of the wing to increase. This increased angle of attack generates an increased lift force and the excess lift causes the aeroplane's flight path to deviate from straight and level. In this case it will curve upward. The student will see the initial angle of attack changing pitch and the subsequent upward curving flight path as a smooth continuous 'nose up' pitch, not realizing that a whole lot more is going on 'behind the scenes'(See Figure One).

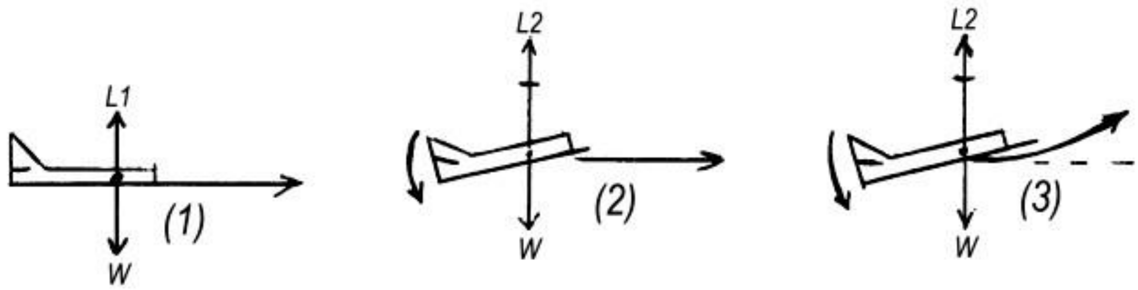


Figure One – Pitching the Nose Up

In the Figure One diagram I have once again exaggerated the angles for clarity and at step (2) I have split the 'action' in two and showed the increased angle of attack and lift at the instant 'prior to' the flight path deviating when in fact no such 'split' is possible as the aeroplane reacts instantly to the excess lift force. Note that in step (3) you can see that the aircraft's longitudinal axis is pointing slightly ahead of the tangent to its curved flight path. This angle is of course equal to the extra angle of attack needed to generate the excess lift. Indeed it reminds me of a very simple definition of angle of attack that I often use with my aerobatic students who fly aeroplanes with no wing incidence, and that is that the angle of attack is the difference between where the aeroplane is pointing and where it is going....... think about it.

To change flight path from a climb to level, the reverse of the aforementioned process occurs.

1. Student eases forward on the stick.
2. Elevator moves down.
3. Tailplane negative angle of attack is reduced
4. Tailplane negative 'lift' is reduced.
5. The counter moment generated by the tailplane is reduced
6. Aeroplane starts to pitch nose down under the influence of the wing pitching moment. (Seen by the pilot)
7. Wing angle of attack is reduced.
8. Wing lift is reduced to less than that required for a straight climb.
9. Weight now exceeds lift and excess weight causes the flight path to curve downward (also seen by the pilot).

The same processes occur when the aeroplane goes from straight and level flight into a descent and then returns to straight and level flight, so there is no need to spell them out any further.

Let us now move on to the most common manoeuvre performed in an aeroplane, the turn. A turn is an acceleration (because the aeroplane is changing direction), so in accordance with Newton's second law of motion a turn requires an applied force and the force required to turn an aeroplane comes from the wings, not, I repeat **not** from the rudder. But in straight and level flight the lift 'vector' is straight up and therefore cannot act to turn the aeroplane, so it has to be inclined in the direction we want to turn by rolling the aeroplane to an appropriate angle of bank. (Once the desired bank angle is reached the aileron control is returned to neutral to stop further roll, and thereafter remains neutral - well almost - a point I will return to later in the lesson.) See Figure Two.

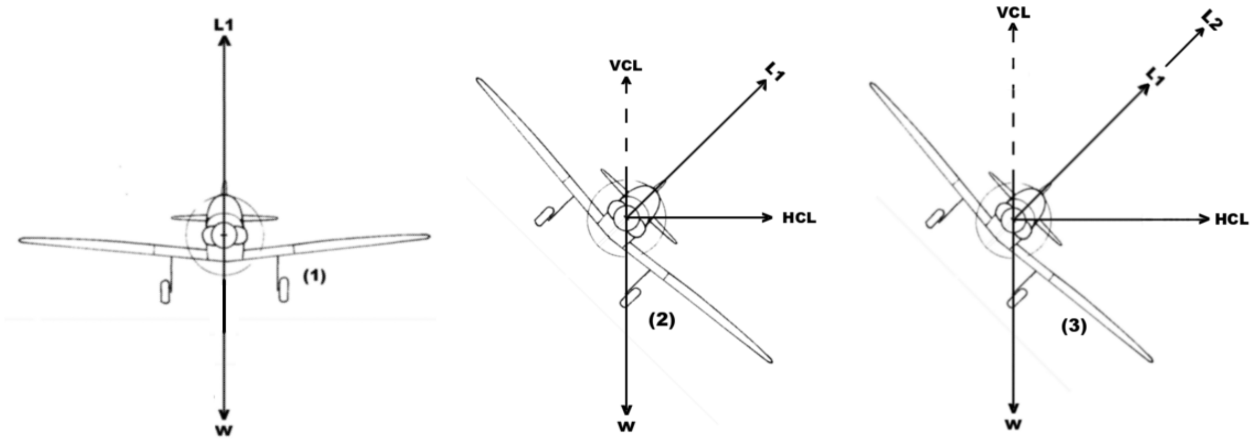


Figure Two – Inclining the Lift Vector

This inclined lift vector (L1) can now be resolved into two components, one horizontal (HCL) which will become the turning force and one vertical (VCL) to balance the weight of the aeroplane. But that is just the beginning. In the preceding diagram you will note that at step (2) the vertical component no longer equals the weight so unless something more is done, the aeroplane's flight path will, in addition to turning, curve downward into a descent as previously described. So the inclined lift vector has to be increased such that the vertical component equals the weight as shown at step (3), and it has to be increased progressively as the bank angle increases in order to maintain level flight as the turn is entered. This increased lift (L2) is attained by increasing the angle of attack progressively by easing the stick back more and more (and moving the elevator up, changing the tail angle, pitching moment etc......) and holding it there during the turn.

But wait! There is more. When an aeroplane or anything else turns, the turning force has to be focused on the centre of the turn. This is called a 'centripetal' (centre seeking) force. The horizontal component of lift is just a sideways force and not yet a centripetal force. What does this mean?

Imagine driving a car across a bridge on a very windy day (Figure Three) and the wind is blowing down the river valley at 90^{o} to the road. The approach to the bridge is sheltered by a cutting through a hill so the car (A1) is protected from the 'cross wind' initially, but suddenly it emerges from the cutting and is exposed to a very strong crosswind. This crosswind generates a large sideways force on the car (zero lift drag!)(A2) but the car has no tendency to turn, it will just drift sideways into the oncoming traffic lane!....Disaster (A3)!

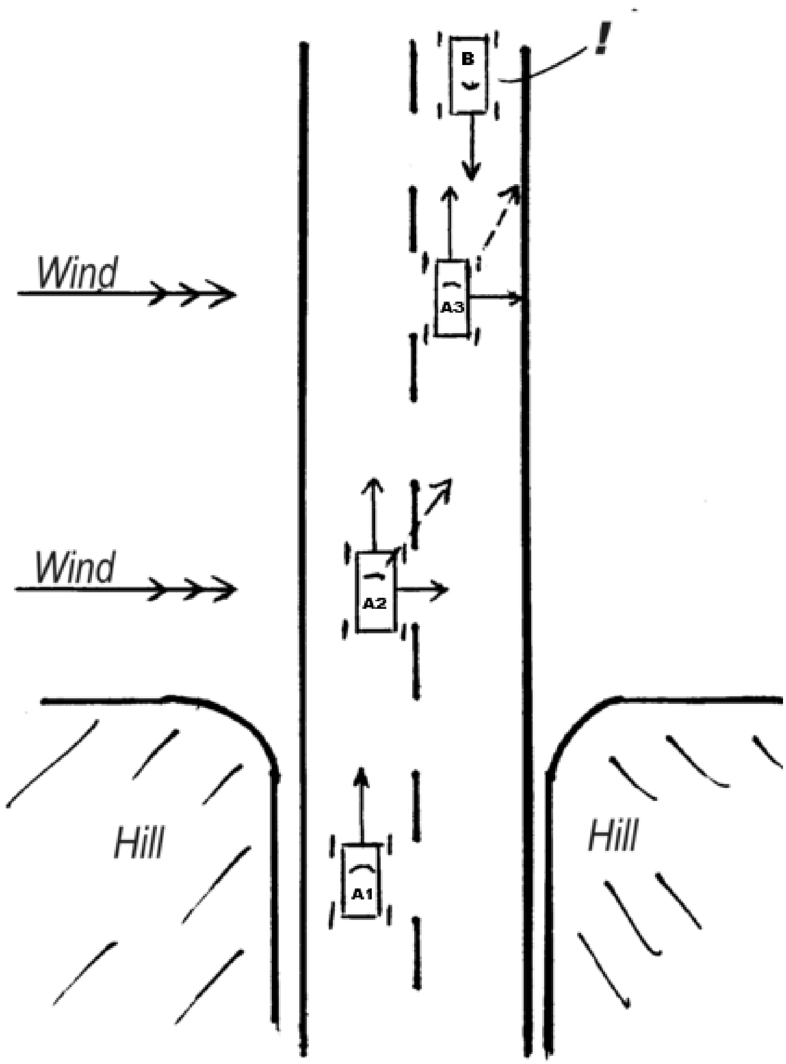


Figure Three – Car in a Cross Wind

From what I have described so far about the horizontal component of the lift vector, the aeroplane, when banked, will also just slip sideways through the air, but the aeroplane has something the car doesn't: directional stability.

As soon as the aeroplane slips sideways the relative airflow is no longer coming from straight ahead but is coming from an angle slightly to the side. Now remember the primary purpose of the fin is to keep the aeroplane pointing into the relative airflow, so under the influence of the fin the aeroplane continually yaws into the 'wind' and redirects the horizontal component of the lift toward a central point thus making it a centripetal force. The following diagrams at Figure Four (A, B & C) illustrate this process:

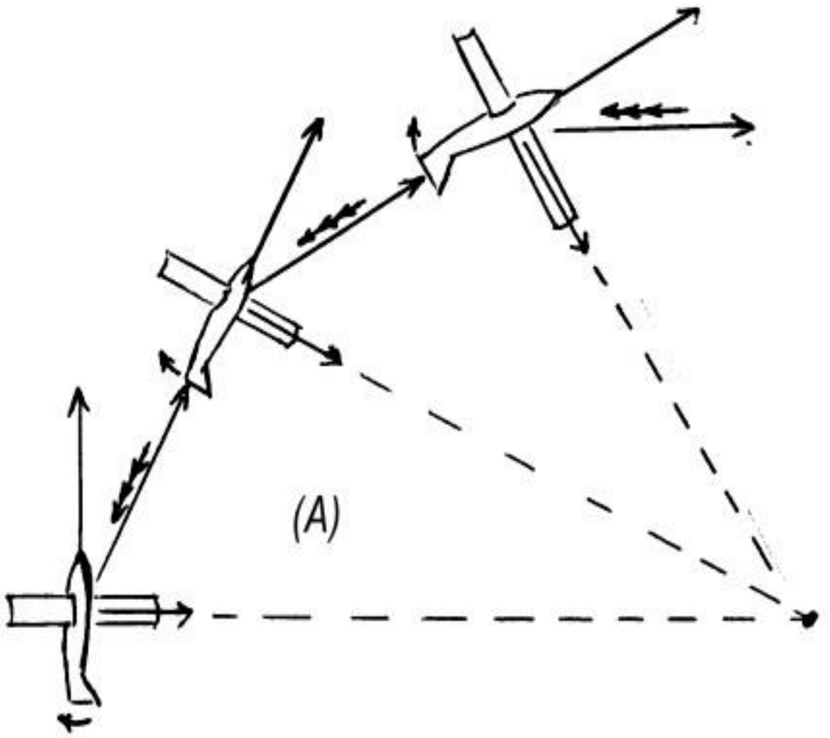


Figure Four (A) – Centripetal Lift Components

Study the diagram above. Note that the sideways force makes the aeroplane slip sideways just like the car but in doing so shifts the relative airflow away from head on. The aeroplane's directional stability aligns the aeroplane with this new airflow direction and causes the sideways force to become a centripetal force. Diagram (A) has broken this process up into large 'chunks' for clarity, whereas from the instant bank is applied (and angle of attack 'adjusted') it is a smooth, continuous process.

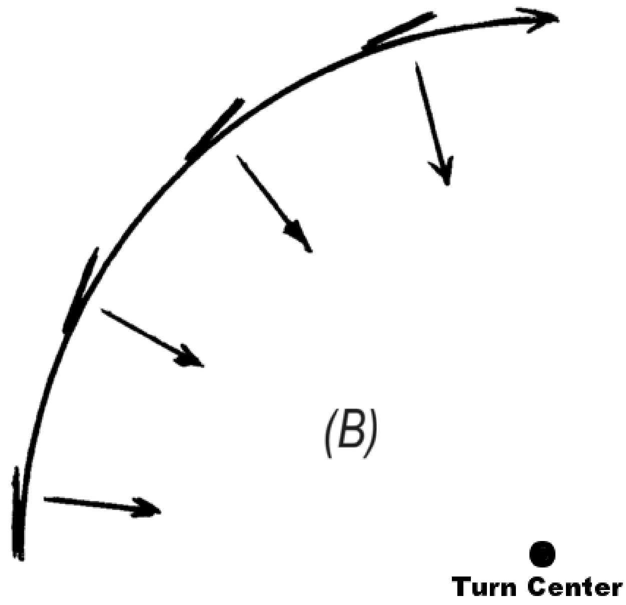


Figure Four (B) – Continuous Centripetal Force

The diagram at Figure Four (B) attempts to depict this smooth, continuous process a little better. Note that in diagram (B) I have shown the aeroplane's longitudinal axis lagging a small angle behind the tangent to the turning circle. This lagging angle has to be, because this angle is the angle of attack the fin needs to generate the sideways 'lift' to continually yaw the aeroplane into the 'wind'. We can improve on this and align the longitudinal axis with the tangent of the turn circle by 'augmenting' the directional stability by the application of a little rudder (Figure Four C). In this way the angle of attack caused by the small amount of rudder replaces that caused by the lag. We do this to minimize the zero lift drag of the fuselage during the turn. How do we know when we have applied the correct amount of rudder? In the 'good old open cockpit days' pilots would apply just enough rudder to keep the wind directly on their face. But nowadays pilots of enclosed cockpit aeroplanes use just enough rudder to keep the 'balance ball' in the centre. (Glider pilots still use a 'Yaw String' taped to the windscreen in front of them because there is no propeller slipstream to 'confuse' the airflow.)

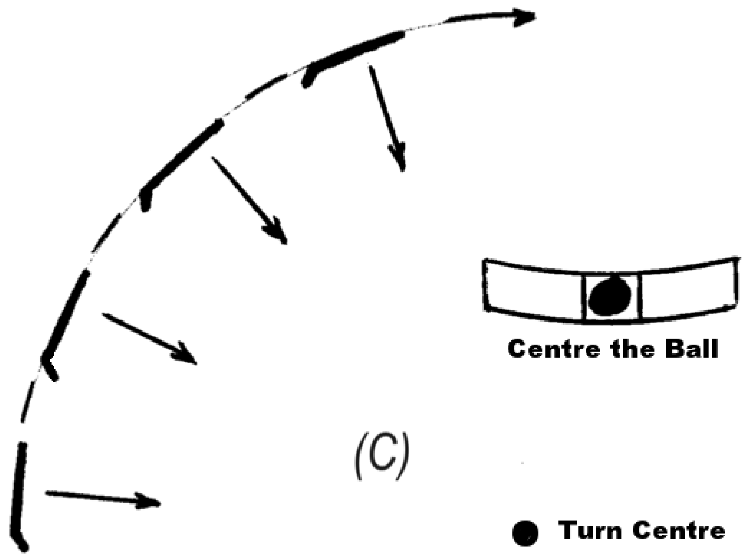


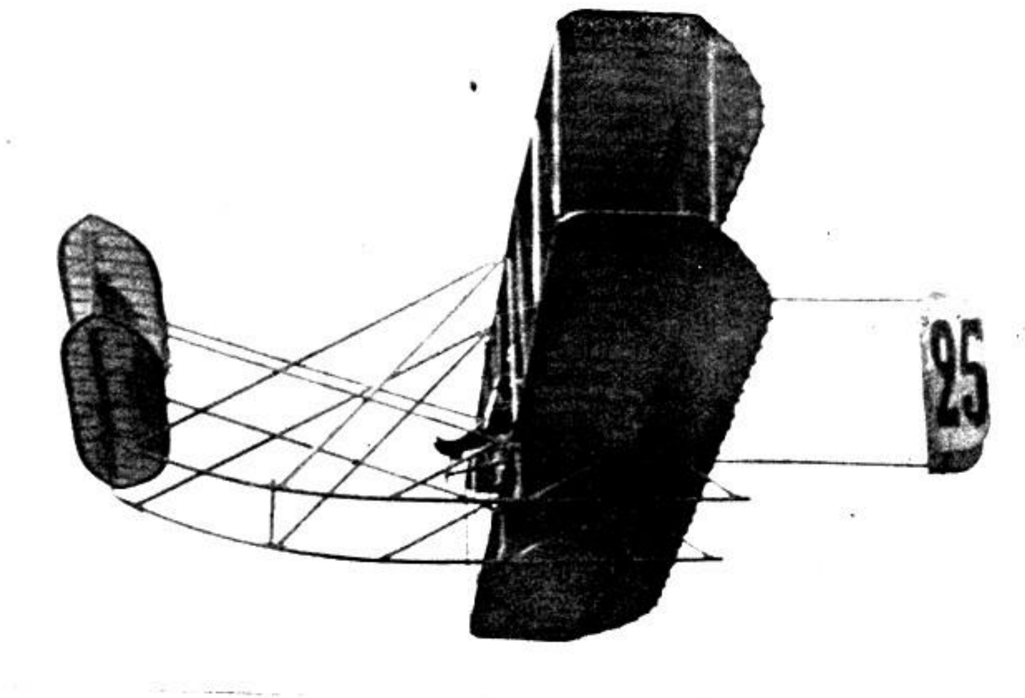
Figure Four (C) – Keeping the 'Ball' Centered with Rudder

Please note that diagram (C) exaggerates the rudder deflection for clarity. In a modern aeroplane with reasonable directional stability the amount of rudder deflection required to 'balance' the turn is small.

If the lift force which creates the centripetal force is equal to twice the weight of the aeroplane, then in accordance with Newton's first law, the aeroplane will accelerate at twice the acceleration due to gravity, that is, at a rate of 2G. The symbol 'G' is used to express multiples of acceleration, i.e. 2G, 3G etc, but 'G' is not the force which causes this acceleration but the acceleration itself! However, the term 'G' is often used, inaccurately, to indicate the force required to produce the acceleration. (More on this in a moment.)

So let me summarize what I have said so far. An aeroplane turns as a result of the horizontal component of the inclined lift vector being made into a centripetal force by the action of the directional stability, augmented slightly (if necessary) by a small amount of rudder. The size of the centripetal force will determine the rate and radius of the turn (acceleration).

Now back at the beginning of aeroplane development, the Wright Biplanes had no fixed fin and no enclosed rear fuselage (see Figure Five), so the aeroplane had no inherent directional stability at all! When a Wright Biplane was banked it simply slipped sideways through the air with no tendency to turn, (just like the car in the crosswind). The only way the pilot could make the sideways force a centripetal force was by the positive use of rudder to bring the 'wind' back onto the pilot's face. So without the use of rudder a Wright Biplane wouldn't turn at all and with the use of rudder it would. No wonder understanding the proper use of the rudder 'got off on the wrong foot'. Wilbur and Orville knew what they were doing with the rudder but the rest of the world at that time didn't (see Annex A) and a number of poorly trained pilots since then still don't!



The Wright biplane in flight.

Figure Five – Wright Biplane

I now want to discuss another force experienced in a turn (or indeed in any manoeuvre). Let's revisit Newton's Third Law again. "To every action there is an equal and opposite reaction." When an aeroplane turns a centripetal force must be created to do the job (as we have just seen), so, in accordance with Newton's third law, we must have also created an equal and opposite force and we have: it is called a 'centrifugal' force (see Figure Six). This is the force you feel throwing you sideways when cornering in a motor car.

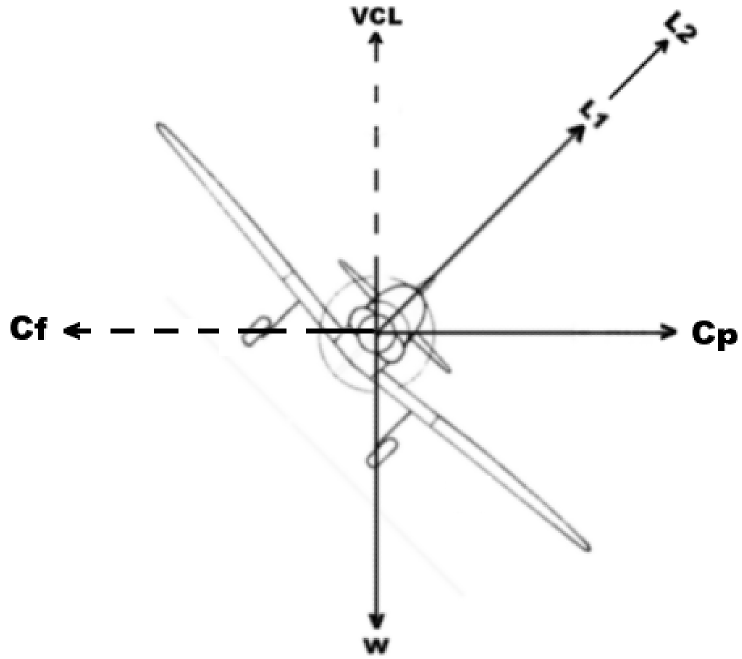


Figure Six – Centrifugal Force

In the diagram at Figure Six above, the broken line opposing the centripetal force (Cp) is the centrifugal force (Cf). Now earlier in the lecture we resolved the lift force into two components, one vertical and one horizontal (Cp), so let's reverse this process on the other side of the aeroplane by integrating the weight with the centrifugal force (Cf) and see what we get (Figure Seven).

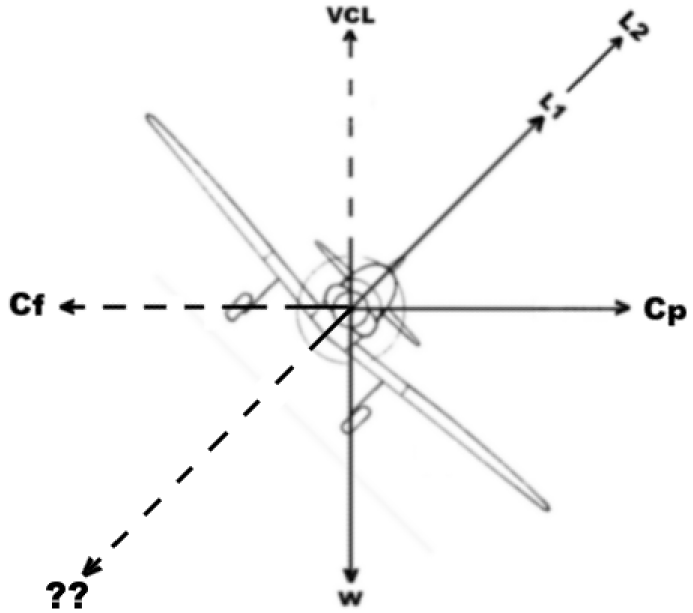


Figure Seven – Integrating Centrifugal Force & Weight

No prizes for guessing that the resultant is the equal and opposite of the lift. The aeroplane and the aviator 'feel' this resultant force as an apparent increase in weight and it has become common practice amongst aviators to express this 'apparent weight' as a 'G Force', which is not exactly correct because 'G' is, as I said above, an expression of acceleration, not force; but since its misuse is so common I will, to keep the explanation simple, go along with this common (mis)usage here. So, we express this apparent increase in weight as multiples of our 'at rest' weight, so if our 'at rest' weight is 1, that is, just the effect of the earth's gravitational force (G), then an apparent weight twice that would be expressed as 2G; four times as 4G, and so on.

In a 45º banked turn as depicted in Figure Seven, the amount of lift required to sustain a level turn is 1.41 times that required for straight and level flight so the equal and opposite reaction is 1.41G. The ?? = 1.41G, so the aviator feels 41% heavier! The amount of lift required to sustain a 60º banked level turn is twice that required for straight and level flight so the aviator experiences an apparent weight of 2G (twice as heavy). The following diagram at Figure Eight shows the forces in a 60º banked, 2G turn:

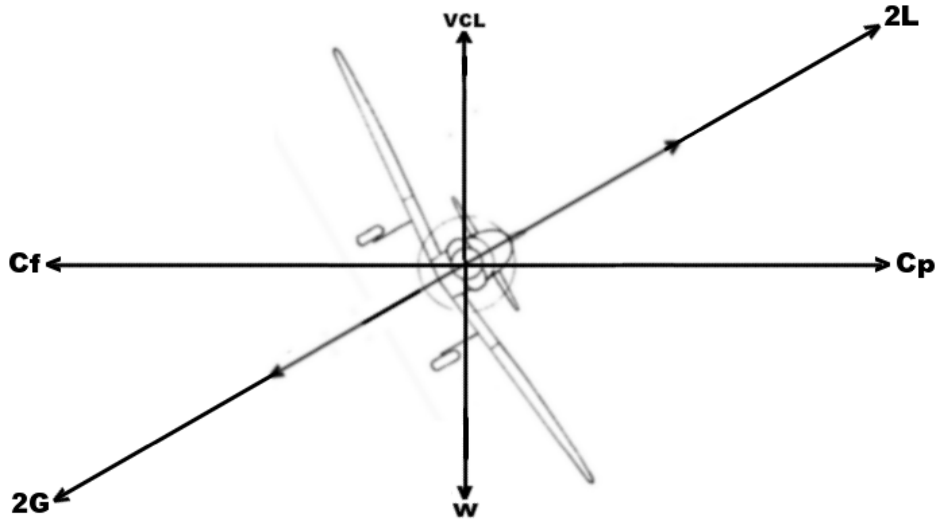


Figure Eight – 60º banked, 2G turn

During aerobatic maneuvers much greater 'G forces' will be experienced and we are going to come to that in more detail in a later lesson.

Most aerobatic aeroplanes have an instrument on the 'panel' called an 'accelerometer'. This is simply a weighted spring balance calibrated in multiples of G, so it is often also called a 'G Meter'. It is a handy device which is primarily used to indicate to the aviator how close his or her manoeuvres take the aeroplane toward its structural limits. (See the lesson on Structural Limits). I believe that every aeroplane should be fitted with one of these instruments and it should be mounted in a prominent place. Why? Well if you have been following my discussion on Newton's third law, you will know that the G meter is also a LIFT METER! It tells the aviator how much lift the wings are generating as multiples of their straight and level lift, at any time, in any attitude, instantly. Do you think this might be a handy thing to know??

Remember my friend who had to light up the afterburner whilst turning final? Let's discuss his situation a little more. As we have said, in order to turn the aeroplane it is necessary to increase the lift by increasing the A/A, which also means that the induced drag increases significantly. The graph of total drag that we created during the lecture on 'Drag' assumed the aeroplane was in level flight, that is, 1G flight, but what does it look like when this aeroplane starts turning?

If the aeroplane is making a 45º banked level turn, the lift must be increased by 41%. To achieve this increase the angle of attack of the wing would have to be increased by 41%, and our lift/G meter (if we had one) would indicate 1.41G. Now remember, induced drag increases as the square of the lift/angle of attack and 1.41 'squared' equals 2! So, in a 45º banked turn the induced drag is double what it is in level flight! This is not the increase in the total drag, just the lift induced component, but it obviously does affect the total. Let's draw the total drag graph at 45º of bank and see (Figure Nine).

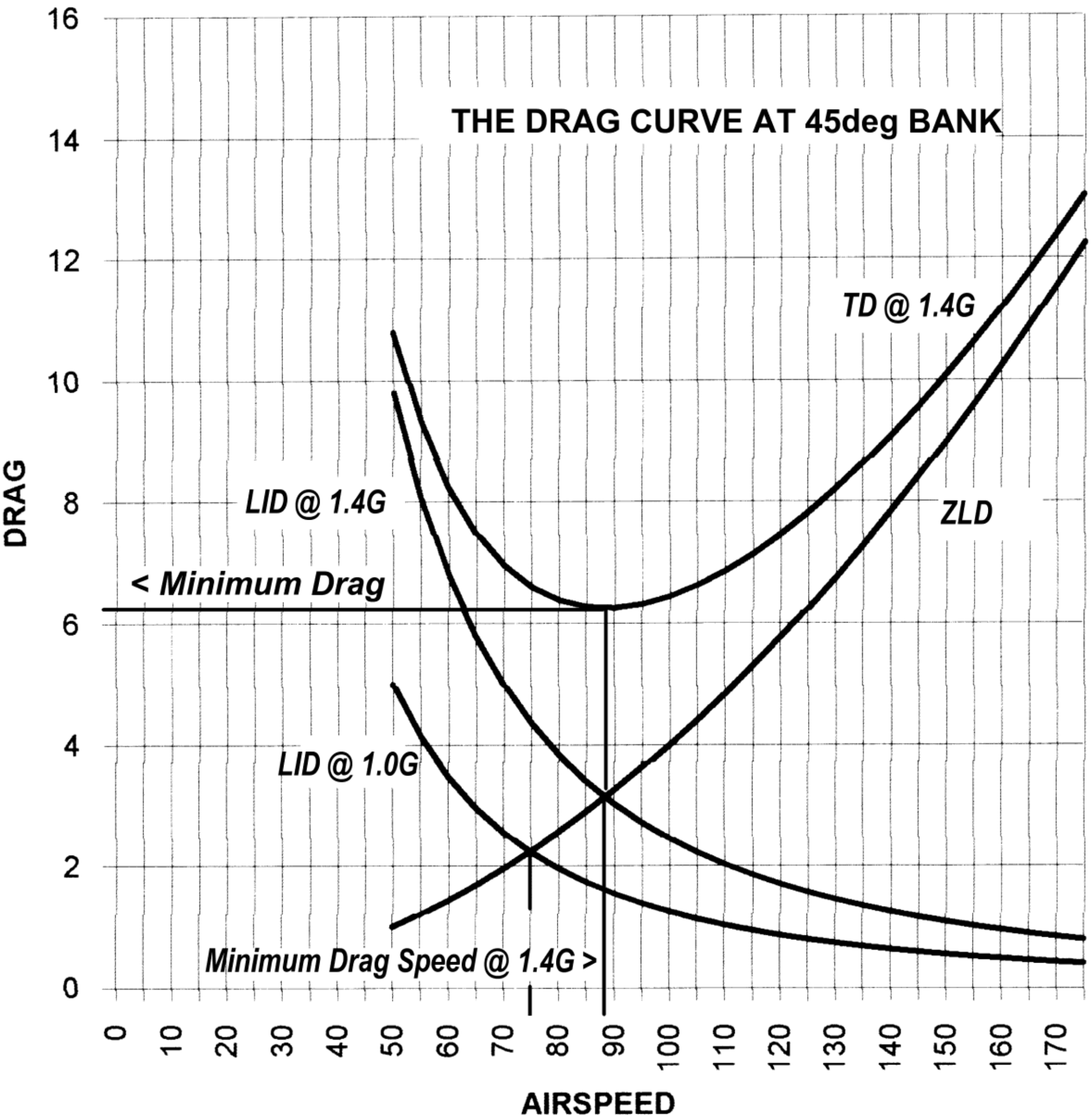


Figure Nine – Increased Drag in a 45º Banked Turn

In the diagram at Figure Nine I have shown the LID at 1G for reference, and the LID at 1.4G. Note that the Total Drag curve that results from this increase in LID has moved up and to the right with the minimum drag speed moving from 75 to 88kts, which is moving closer to the cruise speed of the aeroplane. The drag at cruise speed may now be such that even with full power the aeroplane may not be able to maintain this speed. Let's superimpose the Thrust and Power curves onto this graph and see if it can (Figure Ten).

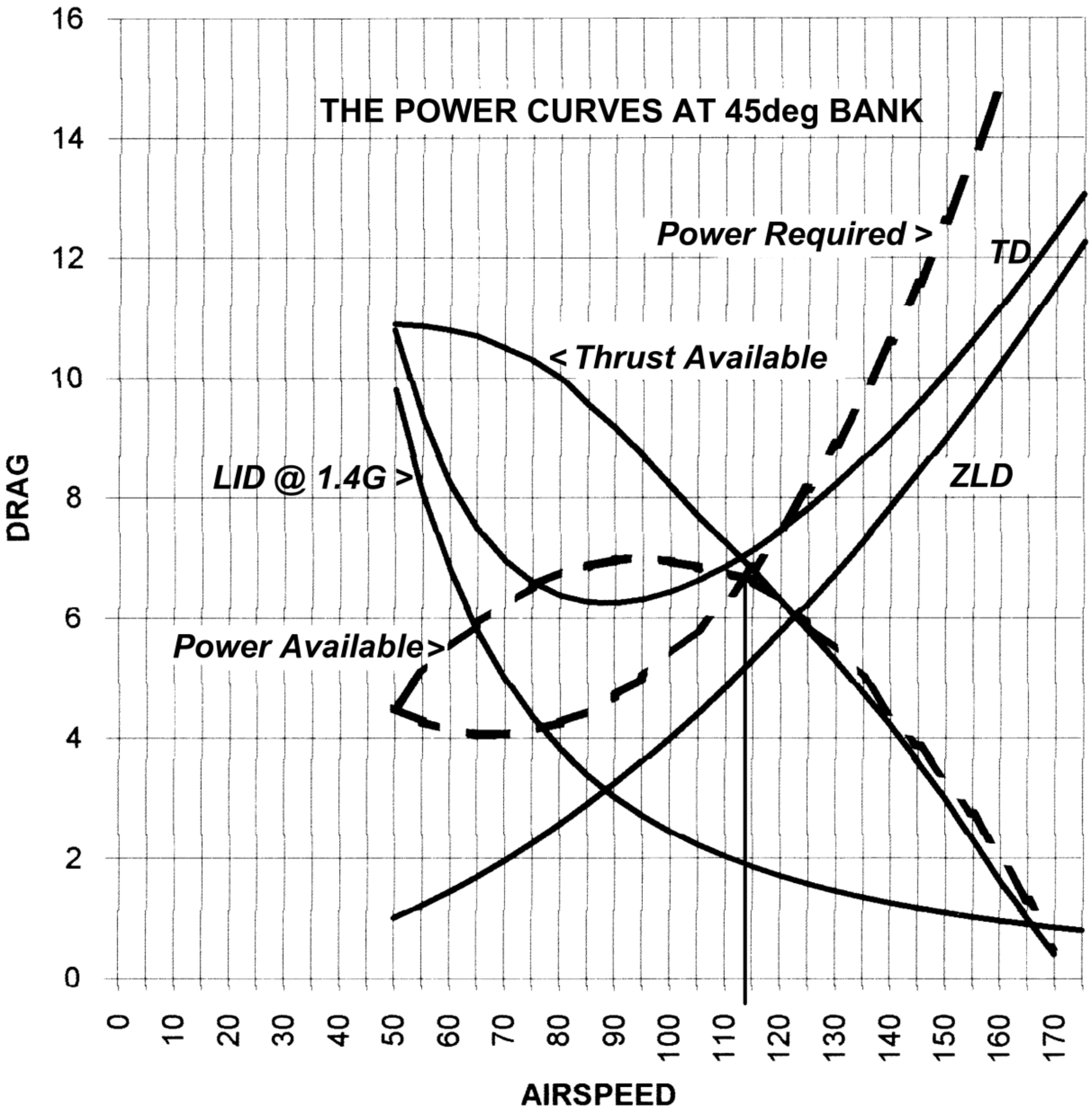


Figure Ten – Thrust & Power at 45° Bank

Now I know there are a lot of lines on this graph so stay focused. Remember that the Total Drag curve is also the Thrust Required curve, and note that the Thrust Required and the Thrust Available curves cross at 114kts; as do the Power Required and the Power Available curves (broken lines). 114kts is now the maximum speed that this aeroplane can attain in a 45° banked turn, and only if full power is used. It can of course sustain slower speeds because at those speeds there is an excess of power available. So, if the aeroplane's straight and level cruise speed is 120kts, it cannot maintain cruise speed in a 45° banked turn.

What do the graphs look like in a 60º banked level turn? (Figure Eleven.)

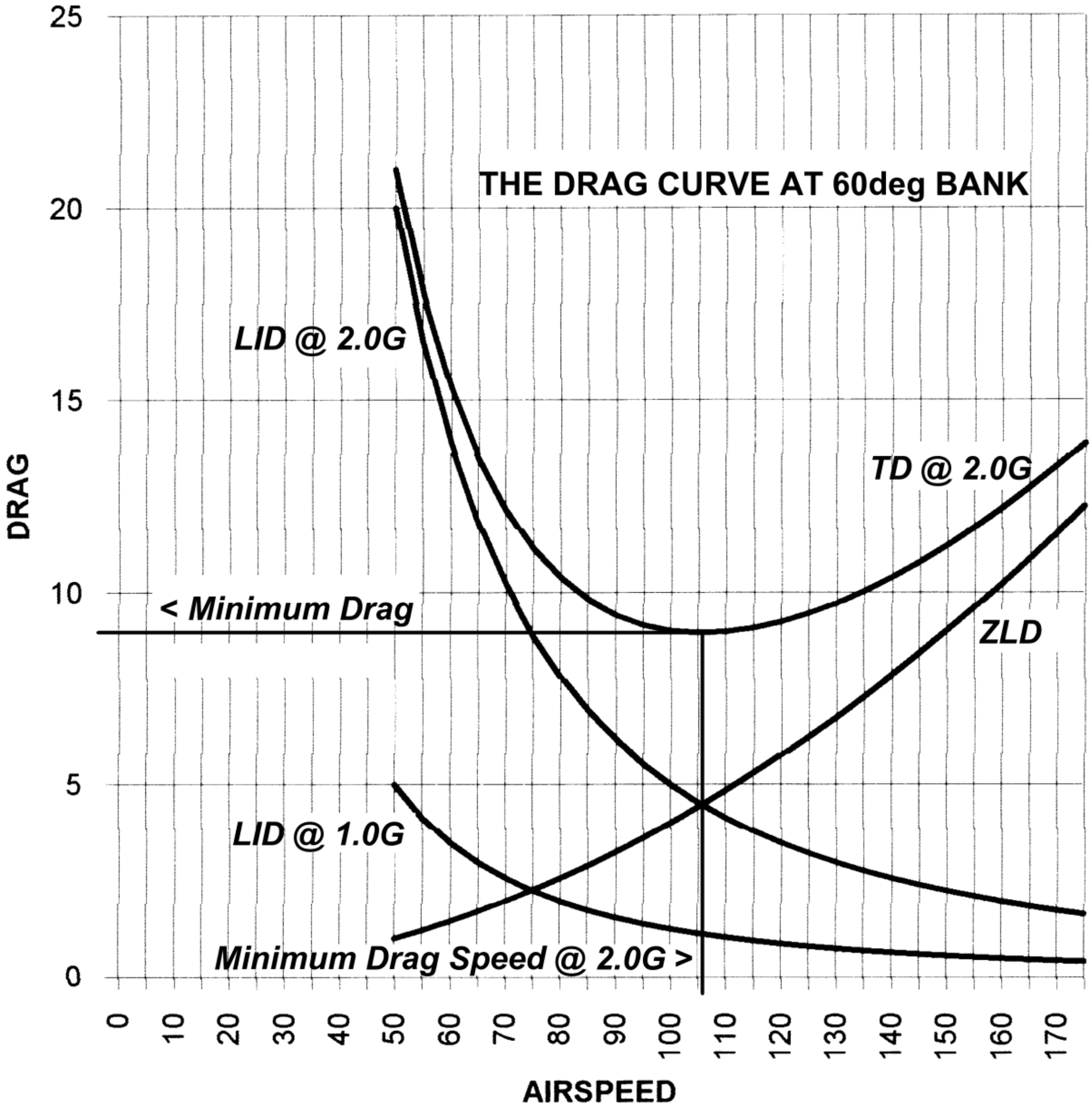


Figure Eleven – Increased Drag in a 60º Banked Turn

In a 60º banked level turn it is necessary to double the lift, so the induced drag has increased by a factor of 4 and the total drag has doubled! Note that increasing bank angle from 45º to 60º, a mere 15º, has doubled the induced drag and the minimum drag speed is now 106kts. (The drag scale on the left side of the graph has been changed to accommodate this increase in order to keep the diagram within the page borders.) The average light aeroplane definitely does not have sufficient thrust available to sustain cruise speed in this situation, so it will slow down and may slip to the' back side' of the drag curve. Let's superimpose the Thrust and Power curves onto this graph and see what we get (Figure Twelve).

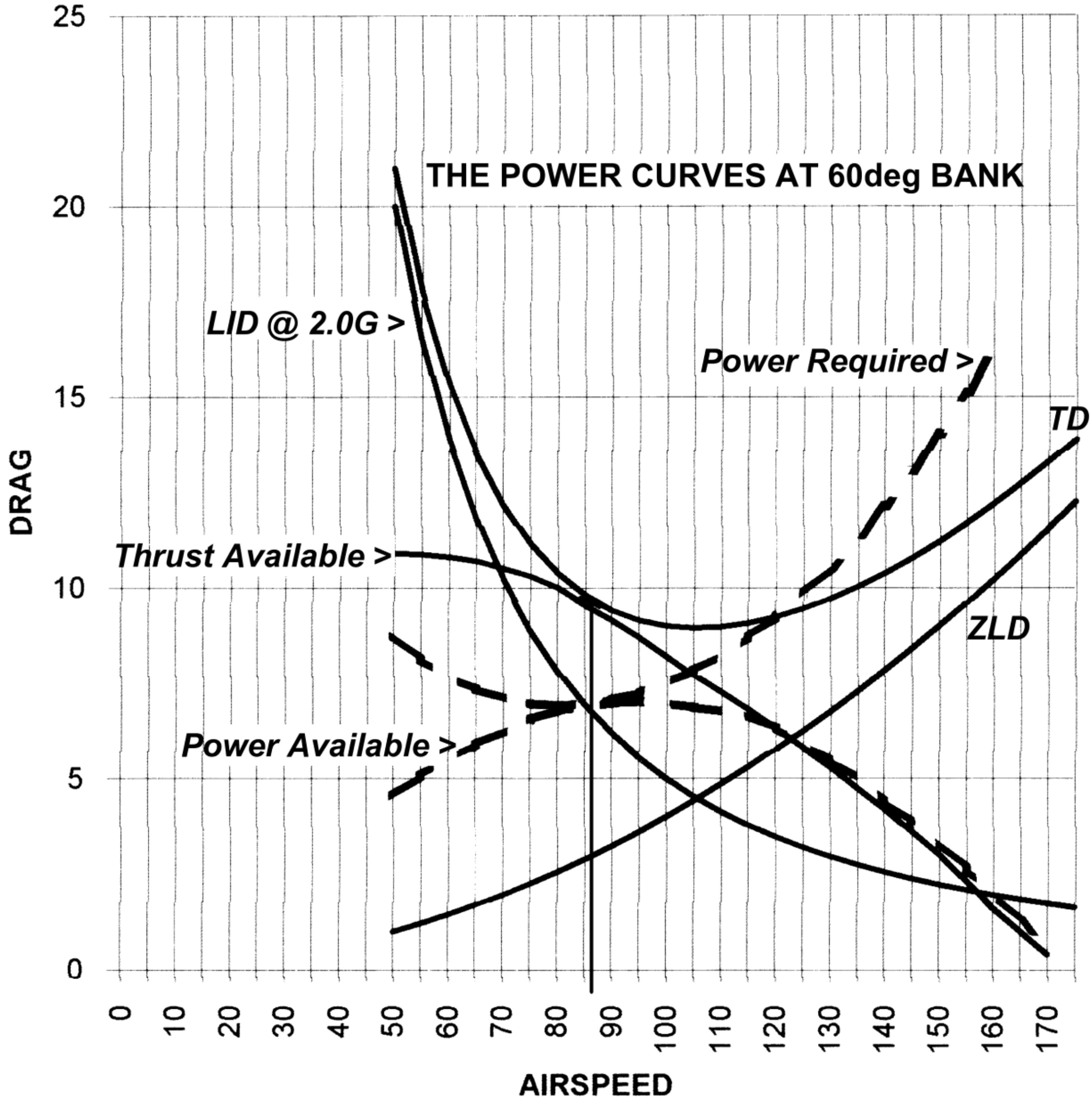


Figure Twelve – Thrust & Power at 60º Bank

Note that the Thrust Required (TD) and the Thrust Available curves just touch at 86kts, as do the Power Required and the Power Available curves. So this aeroplane can maintain 86kts at 60º bank with full power applied, but it cannot fly any faster or sustain any slower speed! I say sustain, as it can fly slower for a very little while as it slips further and further down the backside of the power curve. From that point on it is all 'downhill'.... literally. (This is the point where you would wish you had an afterburner to 'light up'!)

In a 4G aerobatic manoeuvre the graph goes 'off the chart' which is why 'serious' aerobatic aeroplanes need a lot of power and why 'not so serious' aerobatic aeroplanes lose a lot of altitude when doing aerobatics.

Okay, so how do we relate all of these graphs to actually flying an aeroplane and getting a 'feel' for what happens to our airspeed in a turn? Take another look at the forgoing graphs and compare them to the one in 1G flight in the lesson on Drag (Figure Seven in that lesson). You will note that at 2G the Total Drag at minimum drag speed has doubled, and at 1.4G it has increased by about 40%! So a simple, handy and 'rough' 'Rule of Thumb' for aviators is this: "If you double the A/A / Lift / G you will double the total drag at min drag speed". That is, 2G on the meter also means about twice the 1G total drag. Indeed any G reading on the meter also represents the total drag as multiples of the 1G total drag. Now I say "rough" because whilst this relationship of G to total drag works at minimum drag speed it doesn't hold up so well as we go faster and faster, but since at high G a 'normal' GA aeroplane is going to slow toward minimum drag speed anyway, and since the minimum drag speed also increases significantly, the 'rule of thumb' becomes useful soon enough!

This is another good reason for having a 'G meter' in the cockpit: it is not only a Lift Meter, but a 'rough' Drag Meter! If your aeroplane doesn't have a 'G meter' fitted think of it this way: the extra weight you feel in a turn pulling you down into the seat, is felt by the aeroplane as extra drag pulling it 'back' in the air, with the resulting loss of airspeed and lift. This, I am sure, is where the term 'flying by the seat of your pants' came from.

In the lesson on drag I said that this phenomenon is not properly understood by most pilots and therefore they cannot anticipate it. It has been the cause of many crashes and many fatalities. In Annex B I have recreated a typical scenario of how these pilots have 'achieved' this disastrous result.

Unfortunately this lack of understanding has also led to a completely erroneous 'aviation myth' which has been spread by some pilots as a demonstration of their supreme ignorance and which has confused many otherwise intelligent pilots, and that is the myth of the 'Dreaded Downwind Turn'. It sounds like the title of the next Harry Potter book and that is about where the truth of it lies, although even Harry, being the smart young man that he is, would not believe it. If you have never heard of it fine, don't read annex C. But if you have and are confused by it (despite all that I have taught you so far) then <u>do</u> read annex C.

So how 'tight' can an aeroplane really turn? By 'tight' I mean two things: what is the smallest radius and what is the maximum rate (degrees per second)? In theory, the faster the aeroplane can go and the greater the 'G' it can sustain the smaller is the radius and the greater is the rate of turn.....in theory. There are some serious limits on this theoretical proposition and they relate to the aeroplane's ability to sustain the 'G'. First, as we have seen, the total drag increases significantly with 'G' and there are few aeroplanes that have the thrust to sustain even a 6G turn. Secondly, the structure of the aeroplane cannot withstand unlimited 'G' forces. Sure, there are a few 'top of the line' aerobatic aeroplanes that regularly 'pull' 9 or 10G, but they cannot sustain it, and they suffer significant speed loss when they do. In Lesson 14 I have discussed minimum radius and maximum rate turning in more detail. So before you rush out there and try a 'min radius/max rate turn' and rip the wings off your aeroplane, please read the lessons on Structural Limits and Turning at the Limit.

I would now like to address another more subtle phenomenon that happens to an aeroplane during a turn, and that is its tendency to either increase or decrease the angle of bank as the turn progresses. Remember I said at the beginning of this lesson that you enter a turn by rolling to the desired angle of bank, and then stop the roll by centralizing the ailerons, and thereafter holding them neutral? Well, that is not entirely correct.

During a level turn the wing on the 'outside' of the turn, because it is traveling on a path with a slightly larger radius than the 'inside wing', must be traveling a little faster than the inside wing. It will therefore be producing slightly more lift which will tend to increase the angle of bank further. This is the 'Spiral Instability' mentioned in the lesson on Stability and Control. This 'roll on bank' tendency can be easily offset by moving the aileron control slightly 'out' of the turn; this action is commonly called 'holding off bank'. The rudder may also have to be adjusted slightly to rebalance any further drag imbalance caused.

During a climbing turn this tendency to increase bank is exacerbated by another phenomenon, and that is the difference in the angle of attack of the two wings. Let me explain. Since, during a climb, the whole aeroplane is going up at the same rate, the 'inside' wing is making a slightly steeper helical flight path than the 'outside' wing, so the relative airflow is approaching the 'inside wing' at a slightly reduced angle of attack and is therefore creating slightly less lift than the 'outside wing'. This also has the effect of causing the aeroplane to 'roll on' more bank, and so necessitates a further 'out of the turn' aileron correction (Figure Thirteen).

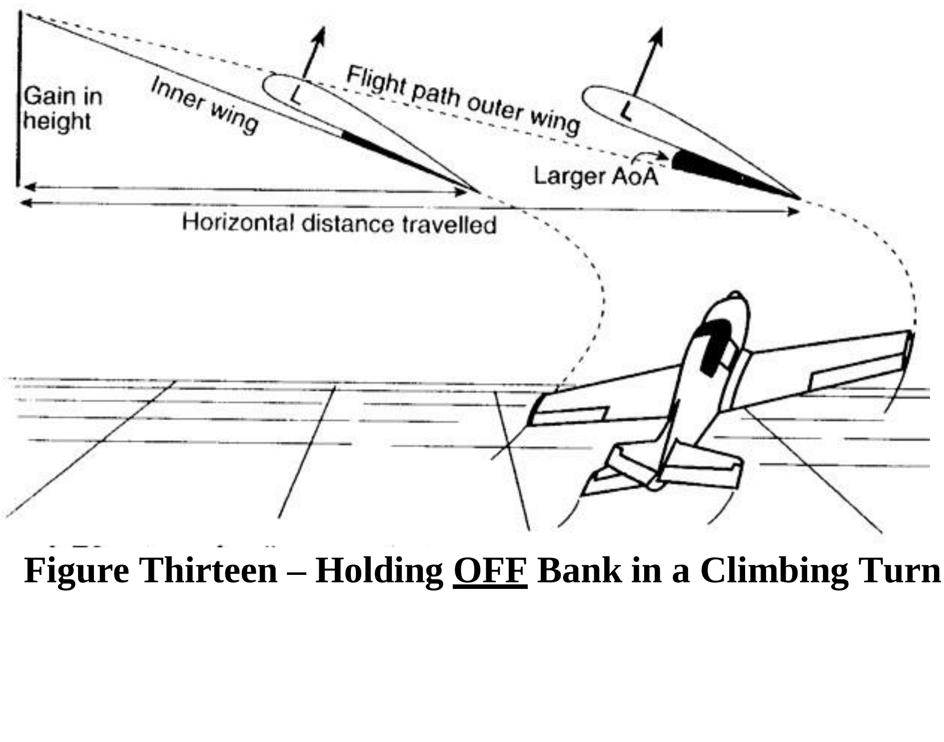


Figure Thirteen – Holding OFF Bank in a Climbing Turn

If this is hard to visualize, imagine carrying a large model aeroplane up a spiral staircase. Imagine that the wing span of the model is large enough that you can rest its wingtips on the balustrades with the model pointing in the direction of your ascent. If you hold the model so that the inside wing is flat against its hand rail you will find that the outside wing is at a positive angle to its handrail. Now imagine the relative airflow 'sliding down' each handrail. This airflow will encounter each wing at a different angle. This is the angle of attack difference I am talking about. During a descending turn this spiral staircase effect is reversed (Figure Fourteen). The angle of attack of the inner wing is the greater, and so is the lift.

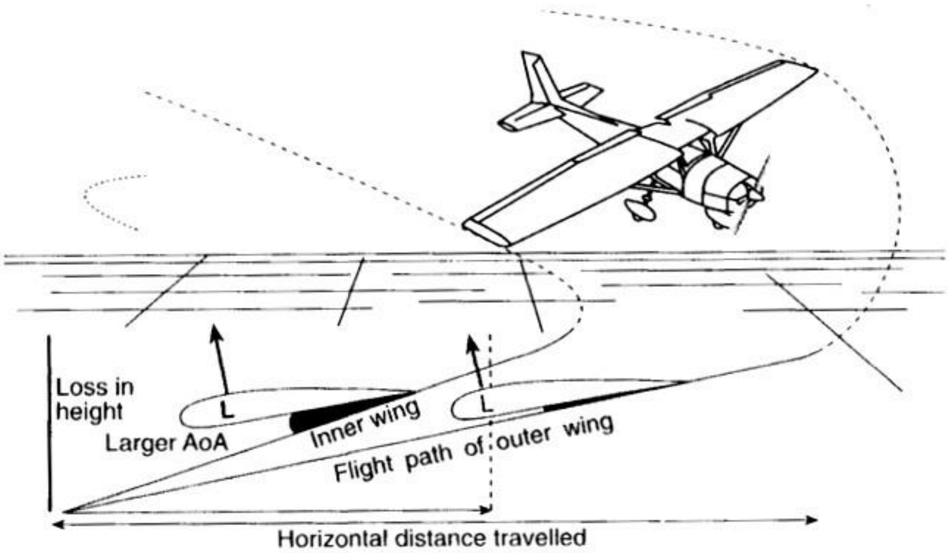


Figure Fourteen – Holding ON Bank in a Descending Turn

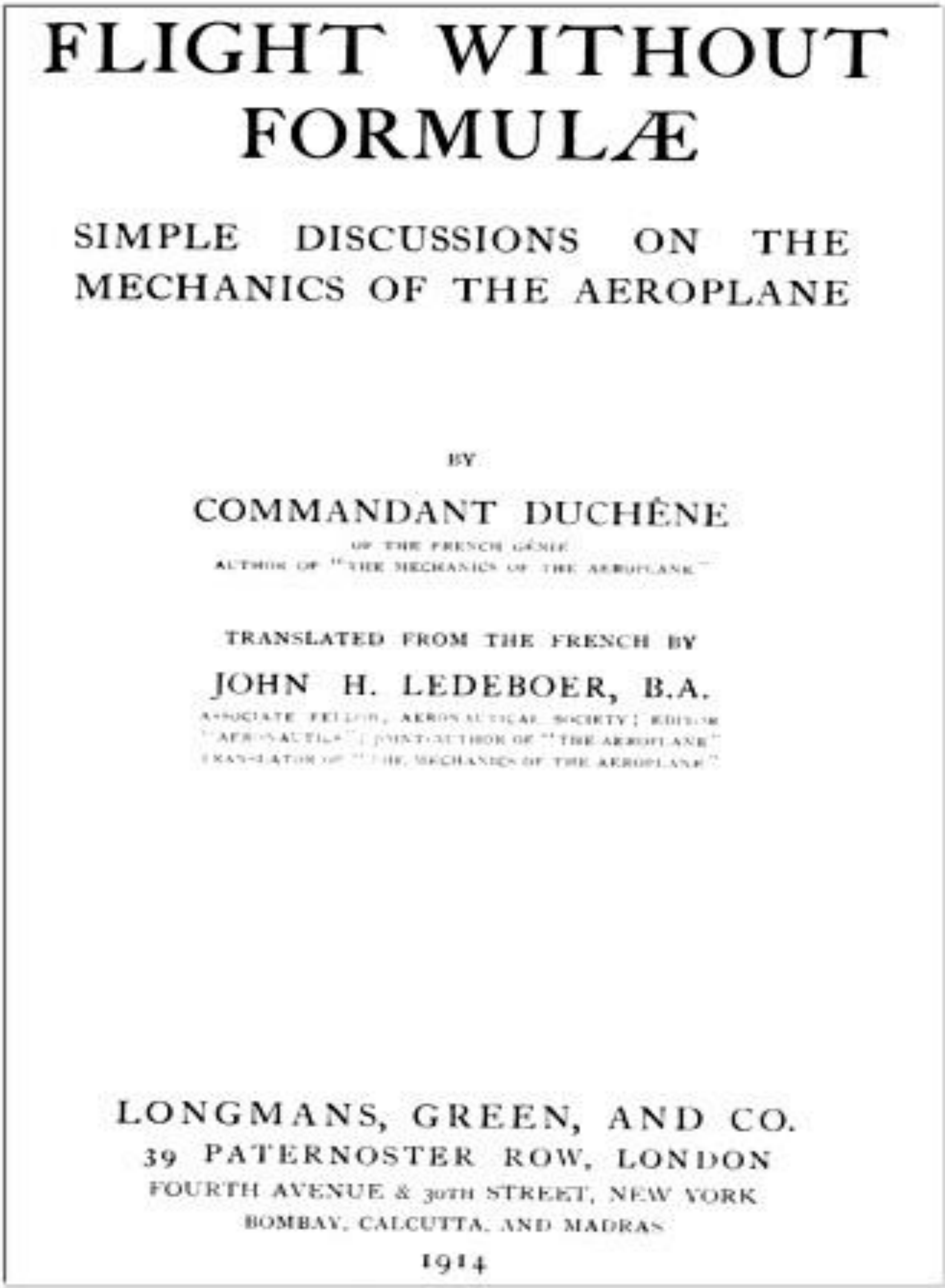
Once again imagine you are carrying the model aeroplane down the spiral staircase with the model pointing in the direction of your descent. Place the outer wing flat on the hand rail and see that the inner wing now has the greater positive angle of attack. The effect of this angle of attack difference can be so great that it can override the 'roll on' effect caused by the wings flying at different airspeeds, and can result in the aeroplane having a tendency to 'roll out' of the turn. In this case the correction is to 'hold on bank' with the ailerons. (Aeroplanes with very high aspect ratio wings and very 'flat' glide angles, such as sailplanes, exhibit a different roll tendency in a gliding turn and this will be discussed in more detail in the 'Sailplane Supplement' at the end of this book.)

These 'roll on', 'roll off' tendencies are not great at cruising speed, but at slow speed, particularly in a glide, they are. We will revisit them in both the lesson on Gliding and the lesson on Spinning. Also, at Annex D to this lesson, I have included further discussion on Spiral Instability, and the Spiral Dive which can result.

List of Annexes to the lesson on: Manoeuvring

Annex A.

The following are extracts from the book entitled “Flight without Formulae” which was published in English in 1914 as a translation of an earlier French work, in which the virtues of the rudder as the primary turning control are espoused. If you have understood all that I have said in this lecture you should find the misconceptions in the following articles quite interesting. You may even begin to wonder how anyone learned to fly in those days!



FLIGHT WITHOUT FORMULÆ

SIMPLE DISCUSSIONS ON THE MECHANICS OF THE AEROPLANE

BY

COMMANDANT DUCHÊNE

OF THE FRENCH GÉNIE
AUTHOR OF "THE MECHANICS OF THE AEROPLANE"

TRANSLATED FROM THE FRENCH BY

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LONGMANS, GREEN, AND CO.
39 PATERNOSTER ROW, LONDON
FOURTH AVENUE & 30TH STREET, NEW YORK
BOMBAY, CALCUTTA, AND MADRAS
1914

The lead up to this extract was a discussion of Newton's Second Law of Motion and Centripetal Force, now read on......

From this it is clear that in order to curve the flight-path of an aeroplane, that is, to make it turn, it is necessary to exert upon it by some means or other a centripetal force directed from the side in which the turn is to be made. This can be done by creating, through movable controlling surfaces, a certain lack of symmetry in the shape of the aeroplane which will result in a corresponding lack of symmetry in the reactions of the air upon it.

The most obvious proceeding is to provide the aeroplane with the same device by which ships are steered and to equip it with a *rudder*. But, just as a ship without a keel responds only in a slight measure to the action of a rudder, so an aeroplane offering little lateral resistance—that is, having but little *keel surface*—only responds to the rudder in a minor degree.

If the rudder is moved to the position CD′, the aeroplane will turn about its centre of gravity until the rudder lies parallel with the wind. But there will not be exerted on the centre of gravity any unsymmetrical reaction, any *centripetal force* capable of curving the flight-path.

The aeroplane will therefore still proceed in a straight line, and the only effect of the displacement of the rudder will be to make the aeroplane advance crabwise, without any tendency to turn on its flight-path.

But if the machine is equipped with a keel surface AB (fig. 77), directional equilibrium necessitates that this keel surface should present an angle to the wind, and become thereby subjected to a pressure Q, whose couple relatively

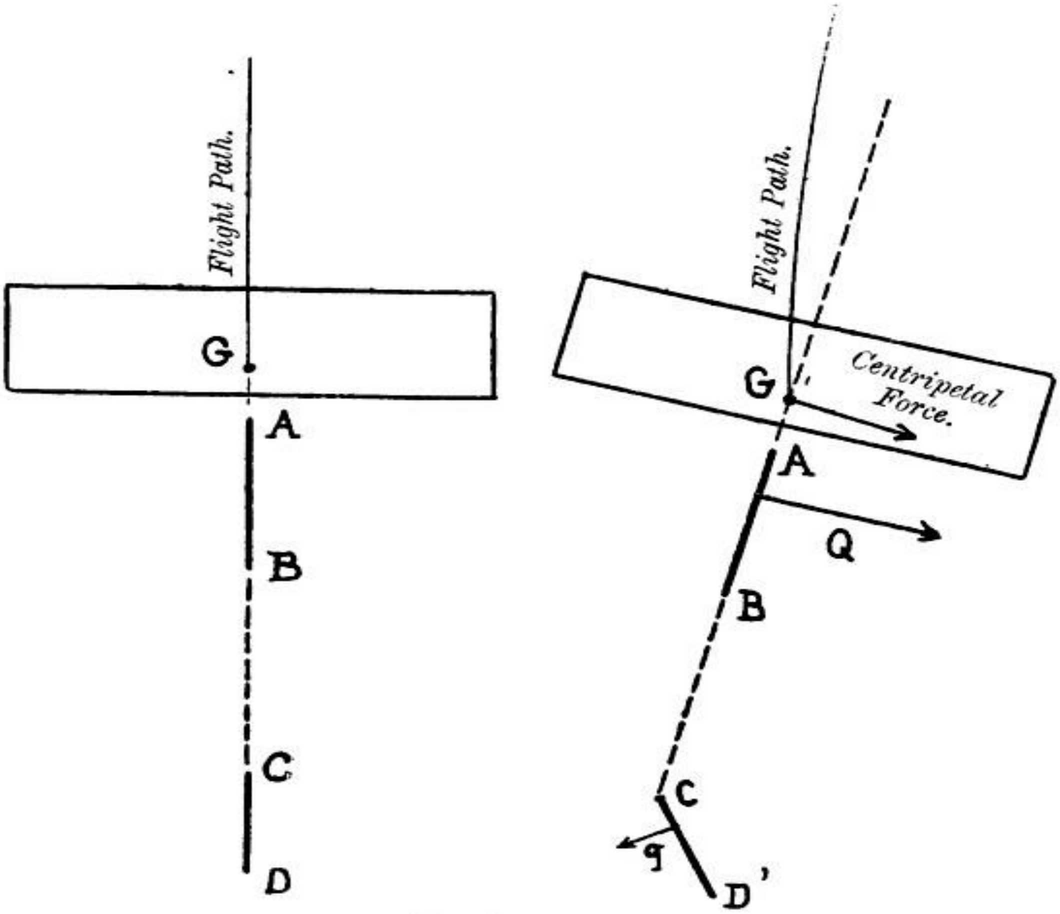


FIG. 77.—Plan.

to the centre of gravity is equal and opposite to the pressure q exerted on the displaced rudder CD′. Since Q is considerably greater than q, there is exerted on the centre of gravity, as the result of their simultaneous effect, a resultant pressure approximately equal to their difference (which could be found by compounding the forces), and this forms a centripetal reaction capable of curving the flight-path—that is, of making the machine turn.

As a rule, the warp is not used for producing a turn, for the majority of machines possess sufficient keel surface to answer the rudder perfectly.

Often the rudder aids the warp in maintaining lateral balance: for instance, by turning to the left a downward tilt of the right wing may be overcome.

Possibly in future the warp will become even less important, so that this device, which is generally thought to have been imitated from birds (which have no vertical rudder), may eventually vanish altogether.* The Paulhan-Tatin "Torpille," referred to in previous chapters, had no warp, neither had the old Voisin biplane, one of the first aeroplanes that ever flew. This was due to the fact that in both cases the keel surface (a pronounced curved dihedral in the "Torpille," and curtains in the Voisin) was sufficient to render the rudder highly effective.

(*Note, the term 'Warp' in this extract means the 'Wright' type of roll control. Note also that the author is suggesting that in the future roll control may be dispensed with completely!)

Annex B.

A case of "Get-home-itus".

Imagine that you and three friends have gone away for the weekend in a Cessna 210 that you hired for the occasion. A great weekend was had by all and now you are heading home on Sunday afternoon. The weather forecast at your destination is okay but across your path enroute some low cloud and rain are forecast. Your friends have to be home this afternoon so they can be at work on Monday morning; so have you, and the Aero Club wants its aeroplane back. You choose to head off and defer deciding about continuing the flight until you have assessed the conditions for yourself. About two thirds of the way home there it is, low and black, as forecast. You decide to descend and try to find a way through underneath.

At 200 feet and still doing 140kts, the visibility is deteriorating rapidly, so despite the objections of your friends you decide to turn back. You roll the aeroplane into a 45º banked turn to the left and pull back on the wheel. "Heavy beast this 210" you think to yourself as the aeroplane, unbeknown to you because of the poor visibility out the front (no horizon!), 'rolls on' bank to 60º. Now at 60º of bank almost 45% more angle of attack is needed than at 45º of bank, and you haven't applied nearly enough 'back stick' to this "heavy beast" to achieve it. Also under the influence of the increased induced drag the aeroplane starts to slow and therefore lose lift. You can't see forward to check your attitude and you can't see into the turn to assess its progress because that high wing, which affords such a great view in straight and level flight, is now blocking your view. You glance inside at the instruments but before you can comprehend what they are telling you, you are alerted to the situation by a gasp from your friend sitting behind you. You look sideways and down through the side window and see the ground not 200 ft below you as you expected, but 50 ft and getting rapidly closer. You immediately apply full right aileron, but as the aeroplane starts to roll out of the turn the left wingtip hits the ground, the left aileron which was deflected fully down, is ripped off and the control wheel is wrenched from your hand shattering your left wrist. Before the pain of this wrist injury can be registered, your brain is ripped from your skull by the propeller as it and the engine carve their way back through the cabin.

Modern aeroplanes are reasonably fast. They can get you into trouble quickly. The majority have poor visibility 'into' a turn of more than about 30º of bank, either due to a high wing or a solid roof. They are all very stable in pitch and very few pilots ever practice 2G turns, let alone 'limit turns', or experience the quite heavy control forces required to make such a steep turn in them.

The forgoing scenario has actually happened.....more than once. And it happened in less time than it took you to read about it!

Annex C.

The "Dreaded Downwind Turn" Myth

The myth goes something like this: If you are flying into a strong wind and you do a quick 'U turn' so that the head wind rapidly becomes a tail wind you will lose airspeed equal to twice the wind speed and you will "fall out of the sky!"

I am staggered by the number of pilots of all experience levels that I have met who believe this myth, or variations of it. It stems from the belief that the 'wind' has something to do with the aerodynamics of an aeroplane. It doesn't. Let me explain.

'Wind' is the term we give to the relative airflow which results from the relative motion of the air mass and the Earth. We feel this airflow when we stand outside on a 'Windy' day. However, if we were airborne in a balloon, we would not feel this wind at all; but we would see the ground below moving relative to us. From the balloon's 'point of view' it is the Earth that is moving, not the air mass. Indeed, from the balloon's perspective, it is the Earth that is moving through the air mass, and this is a perspective you should retain as we discuss this myth. Aeroplanes move (fly) within this air mass too, and develop their aerodynamic forces from their reaction with it, completely independent of how other objects, like balloons or the planet Earth, are moving.

If I said to you "imagine two aeroplanes flying along side by side, aeroplane A and aeroplane B. Aeroplane B does a quick 'U turn', therefore the wind that aeroplane B is now experiencing completely cancels out the wind that aeroplane A is experiencing and vice versa, so they both fall out of the sky!" You would ask me what planet I came from!

The relative 'wind' that aeroplane B experiences has no effect on the relative 'wind' that aeroplane A experiences (and vice versa); nor does the relative 'wind' experienced by any other 'thing' moving through the air mass effect aircraft A or B, even if that other thing is the planet Earth. Once we are up in the air, the air mass becomes the 'frame of reference' in which we operate, and everything traveling through it experiences a 'relative wind' depending upon its speed and direction of travel through the air. It doesn't matter that the earth is the largest mass in the neighborhood and exerts a gravitational pull on everything; that pull is dead vertical and cannot have any effect on motion that is horizontal: so gravity is not a factor.

To help you visualize this, imagine you and a friend take a swim in a river. The river is wide and it is a foggy day, so that when you swim out to the middle you cannot see either river bank. Your friend has a rubber flotation device and just floats stationary in the water whilst you swim in a circle around her. The only motion you feel through the water is the speed of your swimming. Then out of the fog a wooden pylon, the remains of an old jetty, appears and moves toward you both making a small wake in the water. Your friend grabs the pylon and moves off through the water with it. Now you have difficulty swimming around her because of her movement. Then the fog suddenly clears and you see that you are nowhere near your start point because you have both been drifting downstream with the river all of this time and were unaware of it. Your frame of reference was the water and all of the forces required to keep you afloat and propel you through it were relative to this frame of reference, not the river bank. Indeed the pylon which your friend grabbed was attached to the river bed, and was, in your frame of reference, a moving object, but its motion did not affect your swimming in any way.

Now imagine this: you are flying along one day above a layer of fog; you can't see the Earth so have no idea which way it is moving through the air today. You encounter a hot air balloon just hanging there in the air; it looks so pretty that you decide to circle around it for a few minutes and wave to its occupants. You quickly adjust your bank and power and rudder balance so that the balloon is at the centre of your turn (your centripetal force is pointing straight at it), and you are going around and around it. You wave at the balloonists and they wave back. Suddenly the cloud beneath you evaporates, and there is the Earth traveling through the air at 20kts on a heading of 250 degrees. Does this realization effect your turn in any way? No!

Now you spy a beautiful church building on a hill coming your way, so you give the balloonists one last wave and head toward the building. As you approach you notice some people standing nearby and their clothing is being blown about and the trees are bending. "It must be windy down there" you think to yourself, "but my wind is still coming over the nose at 120kts". When you get there you decide to circle the church spire a few times, but it soon becomes apparent that this is trickier than circling the balloon. You find you have to vary your bank angle and radius of turn such that it is less when you are traveling in the same direction as the church and more when you are traveling in the opposite direction. Why should this be? Well the balloon was stationary within the air mass but the church is moving through the air mass at 20kts, and since your aeroplane derives all of its aerodynamic forces from its interaction with the air mass the balloon was, in your frame of reference, a stationary target whilst the church is a moving target, just like your friend holding the pylon in the river. Circling the church is no different to circling a slow moving aircraft, say a helicopter flying at 20kts airspeed.

This is where part of the confusion of the myth comes from, the confusion of ground speed (church speed) versus airspeed, because whilst circling the church the variation in ground speed is quite noticeable. On one side of the turn when traveling in the same direction as the church we only had a 100kt relative speed to the church (your airspeed <u>minus</u> church speed) but on the other side when traveling in the opposite direction we had a 140kt relative speed (your airspeed plus church speed). But aeroplanes don't care about groundspeed at all; so the aeroplane's 'wind' just kept coming over the nose at 120kts.

So why do the myth believers claim they lose airspeed? Well, note that they say that you have to make a "quick" 'U turn'. What is a "quick" 'U turn'? Is it a 1.4 or 2 G turn? And how much did I say the total drag increased in a 2G turn?? Figured out where the myth falls down yet??

A typical scenario where accidents have been attributed to this myth is the turn to 'downwind' after take-off. It is usually accompanied by a heavy aeroplane on a hot day taking off into a strong wind and then turning 'downwind' at low level. The aeroplane is struggling to gain altitude in the conditions and is probably encountering some turbulence or wind shear close to the ground too. It is already operating at or very close to minimum drag speed so this is the last place the pilot should be increasing the induced drag and causing the total drag to move to the 'backside' of the 'curve' by commencing an early turn. The end result is a loss of airspeed and altitude and, possibly, impact with the ground.

I once challenged a myth believer to come fly with me. I suggested that we would climb up above the cloud and do a number of 'quick' turns from various headings and I would get him to tell me from the behavior of the airspeed indicator which way the wind was blowing. He never took up the challenge.

The only time that the movement of the ground through the air mass is of interest to an aviator is during take-off and landing, that is, when the aeroplane is changing its frame of reference from land vehicle to airborne vehicle and vice versa. Flying from one location to another location on the ground (and, if you are a Bomber pilot, dropping a bomb on something on the ground) does not influence the handling of the aeroplane in any way (or the flight of the bomb during its fall). In these cases the aeroplane has to be aimed as if it is 'attacking' a moving target. There are specific navigational techniques for doing this which are the subject of Book Three, so I won't go into them any further here.

The air mass in which an aeroplane operates and its interaction with that air mass is the aeroplane's frame of reference; it is not influenced by the motion of any other thing moving within that air mass or the interaction the other thing may have with the air mass. (Unless you run into each other!!)

For those of you who can remember your high school physics, consider this. In 1687 Isaac Newton, in addition to proclaiming his three 'laws' of motion also proclaimed that there is no absolute 'frame of reference', he said: "the laws of physics hold good in all frames of reference regardless of their motion relative to one another". There is no 'favored' frame of reference either; each has equal 'right' to their point of view.

This ‘principle of relativity’ is why you and a friend can toss a ball to one another in an aeroplane doing 500kts (your frame of reference) without one of you being killed by the sudden 500kt impact of the ball and why the people tossing a ball back and forth in another aeroplane doing 500kts in the other direction (their frame of reference) have no influence on you or the flight of your ball.

During the 19th century, experiments in electrodynamics threw Newton’s principle of ‘relativity’ into doubt for a while when it seemed that light didn’t quite behave in accordance with it; but then, in 1905, a guy named Albert Einstein came along and fixed the problem and reinstated Newton’s principle to its rightful place. The principle of relativity has been unassailable ever since.

I understand the difficulty that many ‘low time’ pilots have with this myth. They spend most of their waking hours using the earth as their frame of reference as they go about their daily routine. When they get airborne they are unable to shift their ‘point of view’, that is, their ‘mental’ frame of reference, from earthling to aviator. Physically they are moving in the air mass, but mentally they are stuck on the ground. In the introduction to this book I said that an aviator “becomes one with the aeroplane and the air”, and uses the sky as a “playground”. These are not euphemisms; this is in fact what happens when you ‘slip the mental bonds of Earth’.

Annex D.

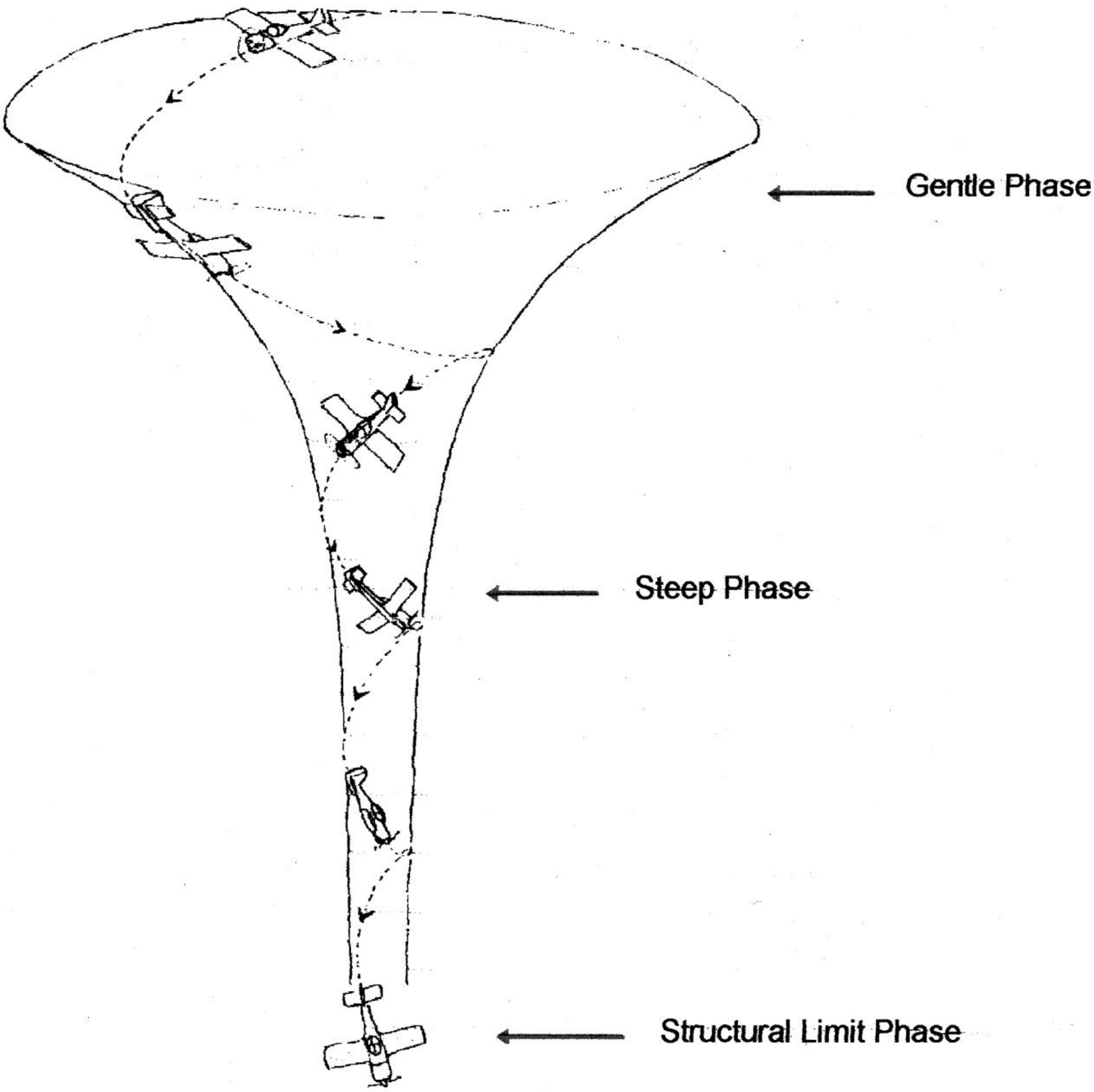
The Spiral Dive

Spiral instability is a consequence of the interaction of an aeroplane's directional and lateral stability. If the directional stability is more pronounced than the lateral stability the aeroplane will be prone to spiral instability (refer to the lesson on Stability and Control). If the controls of a spirally unstable aeroplane are released, that is, if the pilot removes his or her hands and feet from the controls in cruising flight, the aeroplane will be totally dependent upon its stability characteristics to maintain a straight and level flight path. If, under these circumstances, the flight path of the aeroplane is disturbed, even slightly, in such a way that it rolls a few degrees, the aeroplane will commence a spiral dive.

In its early stages the spiral will resemble a gentle descending balanced turn of wide radius (the gentle phase) but as it develops, the bank angle will progressively increase, the descent attitude will steepen into a dive and the radius of the spiral will decrease (the steep phase). By now the airspeed will be increasing and the 'G forces' will be building. Eventually the bank angle will approach 90º, the dive angle will be very steep, the airspeed will be very high (probably beyond the aeroplane's maximum permitted dive speed), the radius of the spiral will be small and the 'G forces' will be so high that in-flight structural failure is possible (the structural limit phase). Throughout this spiral the balance ball will remain close to centre.

The simplest analogy of this type of spiral is the path a small piece of flotsam follows upon entering the whirlpool that is formed when the plug is pulled from the plughole in a bath full of water. At the surface the spiral path of the flotsam is wide and gentle, but near the plughole it is steep, tight and rapid.

A spiral dive commenced from straight and level flight as a consequence of the controls being released will consume many thousands of feet of altitude. Depending upon its proximity to the ground the aeroplane will impact the ground at various points in the developing spiral. If the spiral is commenced near the ground an outside observer would see the aeroplane flying a wide gentle descending turn prior to impacting the ground. If the spiral commenced further from the ground an observer would see the aeroplane's flight path developing into a very steep, fast, tight spiral prior to impact. If the spiral commenced even further from the ground an observer may witness the in-flight breakup of the aeroplane for reason that will be detailed in the lesson on Aircraft Structural Limits. The following diagram shows the aeroplane's flight path as the spiral dive progresses through these three phases:



Recovery from the ‘gentle phase’ of a spiral dive is the same as flying out of a normal descending turn, but as the spiral enters the ‘steep phase’ a more positive procedure is required. The standard recovery from the ‘steep phase’ of a spiral dive is:

1. Reduce power to idle (to control airspeed).
2. Relax elevator control to neutral (to control ‘G force’ build up)
3. Roll the aeroplane to ‘wings level’ with the ailerons.
4. Smoothly pull out of the dive.

Note that it is important to roll the wings level **before** pulling out of the dive. If the ‘stick’ is pulled back before rolling wings level the increased horizontal component of the lift will be greater than the increased vertical component causing an even tighter spiral!

Spiral dives are usually caused by the pilot, either by losing control of the aircraft or, mishandling its controls. Prior to the development of ‘blind flying’ instruments back in the 1930’s, many aircraft were lost when attempting to fly in cloud as a result of entering a spiral dive without the pilot having a horizontal reference to aid recovery. Often the wreckage was scattered over a large area as a result of the in-flight breakup of the aeroplane. Those early pilots called this the “grave yard spiral!” This sort of ‘accident’ still happens occasionally today, when untrained pilots attempt to fly in conditions of poor visibility.

Another form of mishandling which can result in a spiral dive is the gross abuse of the rudder. If, whilst in any normal flight attitude, the rudder is applied positively, the aeroplane will yaw excessively and will, as a result of its lateral stability, roll rapidly to a high bank angle accompanied by an excessive nose drop. The resulting spiral dive will not start with a gentle phase; this will be bypassed and the aircraft will enter the spiral at the steep phase. This manoeuvre is often called an ‘accelerated spiral’ and any aeroplane, regardless of whether it is prone to spiral instability or not, can be forced into an accelerated spiral dive in this way. Throughout this type of spiral the balance ball will be at its extreme left or right limit, opposite to the direction of the initial rudder application.

Certain advanced flight manoeuvres can, if mishandled, result in this rapid entry into the steep phase of a spiral dive. I will be discussing these situations in later lessons.

Lesson Eight

CLIMBING

During a climb an aeroplane is gaining potential energy; that is, gaining altitude. This can be achieved by two possible methods.

The first method is the conversion of the aeroplane's kinetic energy (speed) into potential energy (altitude) by 'zooming'! Zooming is a great 'buzzword' which simply means 'trading speed for altitude'. Zooming is a transient method of climbing and can only be sustained until the aeroplane's speed runs out. Now a light aeroplane at cruising speed does not have a great amount of kinetic energy to start with so its zoom potential is not great either. A light aeroplane doing 120Kts can only zoom a few hundred feet and still have flying speed at the top of the zoom. Still, this may be enough to 'hop' over an obstacle at low level if the need should arise, so we shouldn't discount it completely. As the aeroplane gets heavier and/or faster its kinetic energy, and therefore its zoom potential, increases significantly, and can be quite useful. I was once able to extricate myself from a hazardous situation when I experienced an engine failure at very low level. The aeroplane weighed about 16,000 lbs and was traveling at 420Kts at the time so I was able to convert this into a 10,000ft altitude gain, which enabled me to glide to a suitable landing site.

The second method, which is a more sustainable method, is the conversion of the chemical energy, contained in the fuel in the tanks, into potential energy. That is, using the power output of the engine to steadily 'pull' the aeroplane 'uphill'. This is the method that I will be discussing for the rest of this lesson.

Anyone who has ridden a bicycle is familiar with the 'problem' of riding uphill. The effort to pedal uphill increases significantly as the hill gets steeper or if we try to maintain 'cruising speed' up the hill. Indeed, most cyclists will slow down and change to a lower gear to better utilize the 'muscular energy' they have in reserve. An aeroplane has a similar problem; the gradient of hill which it can climb also depends upon how much kinetic energy it has in reserve (for 'zooming') and how quickly it can convert its reserve of chemical energy into power.

When we are riding our bicycle on flat level ground the total weight (W) is being supported by the ground, and the energy available can be used exclusively to overcome the 'zero lift drag'. But as we start uphill we feel what seems to be an additional drag force, and as the gradient of the hill increases this force gets greater and greater! This force is of course the force of gravity, or at least a component of it. It is the 'downhill component of gravity' which feels like extra drag.

Study the following diagram (Figure One) and you will see what I mean by the 'downhill component of gravity'.

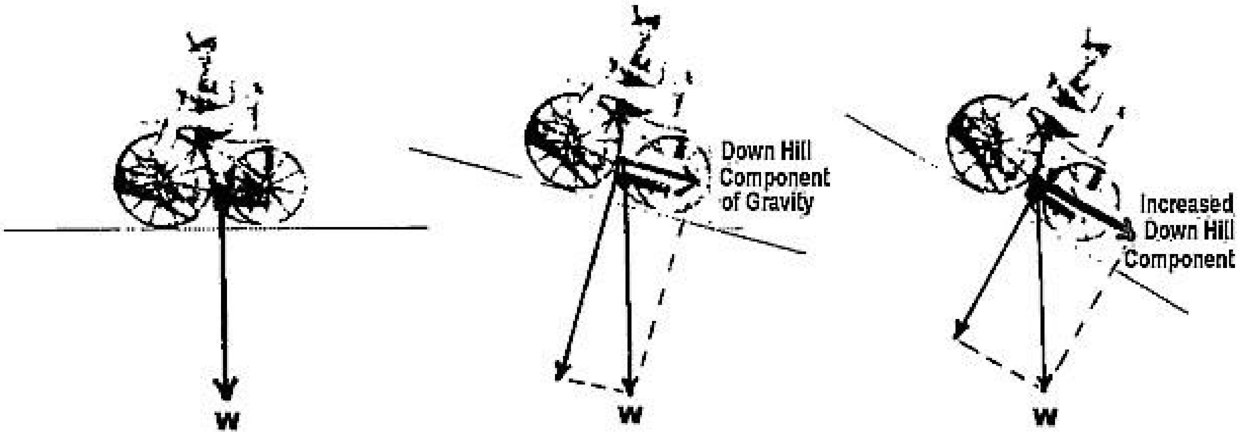


Figure One – Downhill Component of Gravity

Gravity is always vertical, and the road only supports the component of it which is at 90º to the road. The other component is parallel to the road, and is trying to pull the bike back down the hill. (Indeed it is this component which makes rolling downhill so easy.) So in order to go up the hill we must be able to overcome this downhill component of gravity **as well as** overcome the zero lift drag. As the hill gets steeper the downhill component we have to overcome increases. (For the mathematicians, it increases as the Sine of the gradient angle.) Overcoming this increasing downhill component requires an increasing rate of expenditure of energy, that is, more power. (More people peddling.) See Figure Two.

Figure Two – Steep Hills Require More Power

Obviously there is going to be a limit to how much energy a single rider has in reserve and how quickly he/she can convert it into power (how ‘fit’ the rider is), which means that there is going to be a limit on the ‘steepness’ of the hill that can be climbed. If the hill gets too steep the rider can always slow down to reduce the zero lift drag and therefore divert more energy into overcoming the ‘downhill’ component of gravity. Ultimately, she can always stop and walk! Stopping and walking is not an option available to an aeroplane, indeed even slowing down too much can be detrimental, because if it gets too slow it will get too far onto the ‘backside’ of the drag curve and make the situation worse!

A light aeroplane in level flight is being supported by the ‘lift’ from the wings, and at cruising speed it requires an amount of thrust to balance the **total** drag which absorbs about 75% of the total possible power output of the engine. This means the remaining ‘reserve’ of power, which when converted to thrust by the propeller, is only able to pull the aeroplane up a ‘slight’ hill at that speed. However, if the aeroplane is allowed to slow the thrust increases and the drag decreases, (refer back to the lessons on Drag and Thrust if you have forgotten why this is so), so it can go up a steeper hill, or to put it in aeronautical terms, the climb gradient (angle of climb) increases as the speed decreases. (Up to a point.) The following diagram (Figure Three) shows all of the forces acting on an aeroplane during a climb at its ‘best’ climb speed. (I will expand on the word ‘best’ in just a moment.)

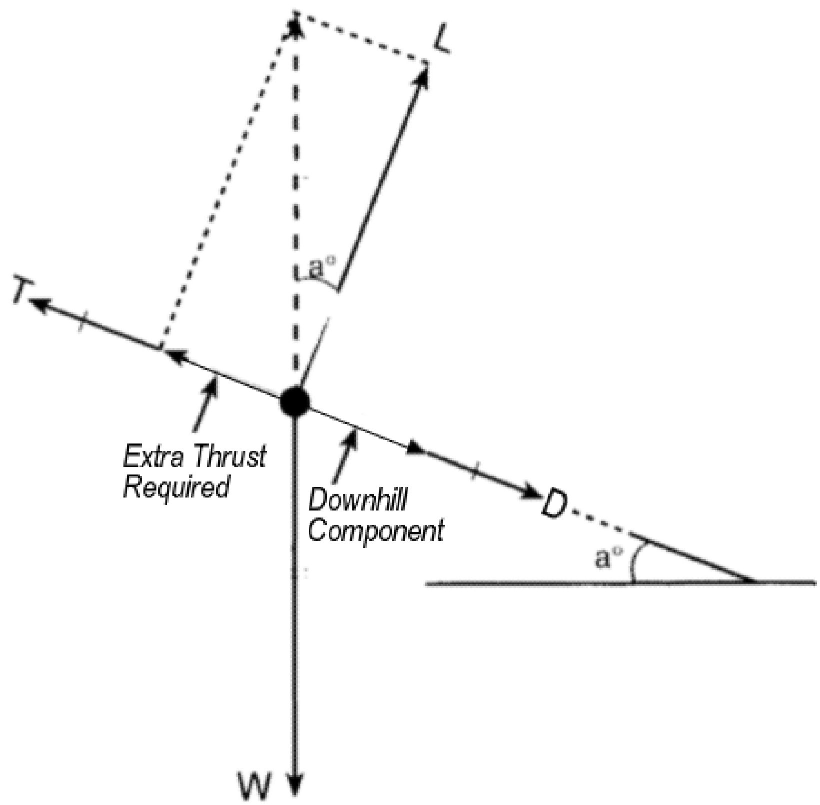


Figure Three – Forces acting in a Climb

The thrust required to overcome the total drag is now only absorbing about 50% of the power available, leaving a much greater reserve of power to overcome the 'downhill' component of gravity. As you can see from Figure Three, it is the thrust in excess of that required to overcome the total drag which determines the climb gradient possible. Note that the 'lift' from the wings is now a little less than the weight too, as it is now the resultant of lift and thrust which balances the weight. This means that the angle of attack is slightly less than it would be in level flight at that speed, which in turn reduces the induced drag slightly, which is helpful. (Once again the angles are exaggerated for clarity.)

So how slow should we fly to achieve a maximum gradient climb? (Bearing in mind that we don't want to get too far onto the 'backside' of the drag curve!) Take a look at the following graph (Figure Four) of thrust required versus thrust available (from a fixed pitch propeller); you will note that the point on the graph where there is the greatest **excess thrust** over total drag is at a speed less than the minimum drag speed! It is a speed as slow as is safe above the aeroplanes take-off speed. (After all, we do have to be airborne before we can climb!)

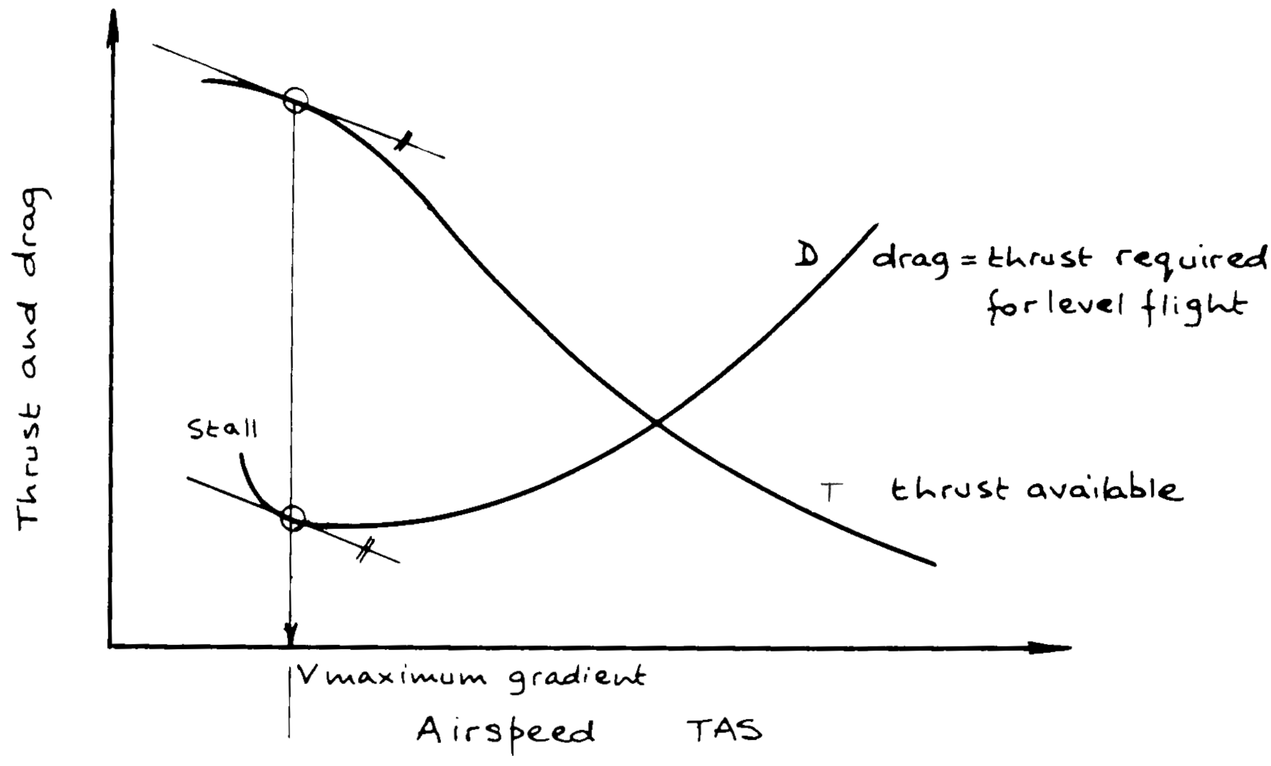


Figure Four – Speed for Best Angle of Climb

The 'pilot's notes' of most light aeroplanes will declare a speed to attain the maximum gradient (angle) of climb as something a little faster than the theoretical 'best' in order to give a safe margin of speed above the aeroplane's stalling speed (Vs). This is usually about 1.2Vs, which coincidentally, is very close to the minimum power speed. (Is this another 'rule of thumb' in the making?)

Climbing steeply is a good way to avoid obstacles which may otherwise impede your progress, especially just after take-off, but climbing at this angle continuously does not guarantee the maximum altitude gain in a given time (rate of climb). Climbing a bit flatter and a bit faster will, because even though we are not going uphill quite as steeply, we are going up the hill faster and therefore gaining altitude more efficiently. Check out the following diagram which shows the difference between 'best rate' and 'steepest gradient' climbs (Figure Five).

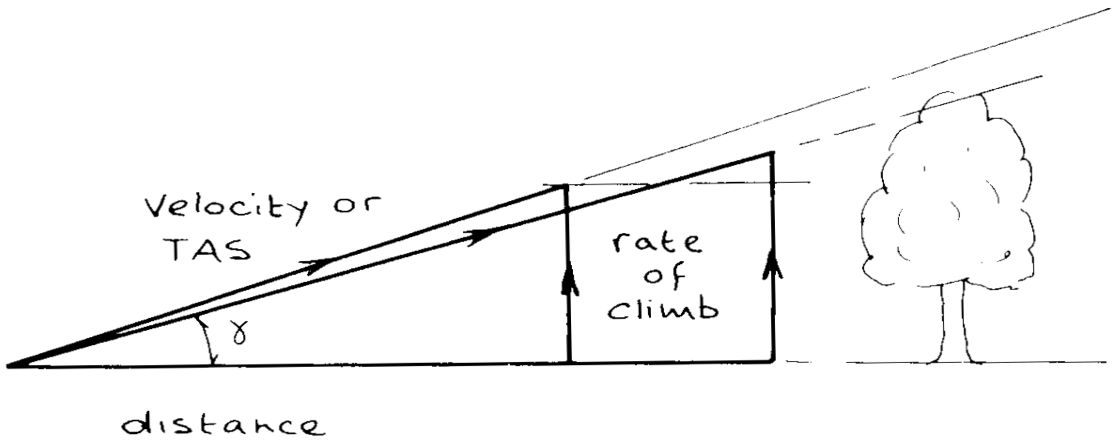


Figure Five – Rate of Climb versus Angle of Climb

So what speed should we use to climb at maximum rate? Once again I have to introduce the concept of power into our discussion because we are talking about applying a force to move the aeroplane **up** a certain distance in a certain time. The 'best rate' of climb speed therefore, is that at which the excess power is at a maximum. How do we determine this speed?

As we learned in the lesson on Power the process of determining 'power available' is similar to that which we used to determine 'power required' from the drag curve. You will remember that we use the thrust curve, and plot the areas given by the product of thrust and speed at each point on the curve. Remember also, that as speed increases the thrust decreases, so the product of the two has a unique shape which cannot be confused with the thrust curve. In Figure Six (below) I have reproduced this 'power available' curve shown on the same axis as the 'power required' curve.

This 'power available' versus 'power required' graph shows the speed where the difference in the values represented by the two 'curves' is at a maximum. This is the maximum **excess power speed,** and therefore is the speed for the 'best rate' of climb. It should come as no surprise to you to learn that this speed is in the vicinity of the minimum drag speed. For comparison the speed for maximum gradient is also shown and you can see that the 'best rate' speed is faster.

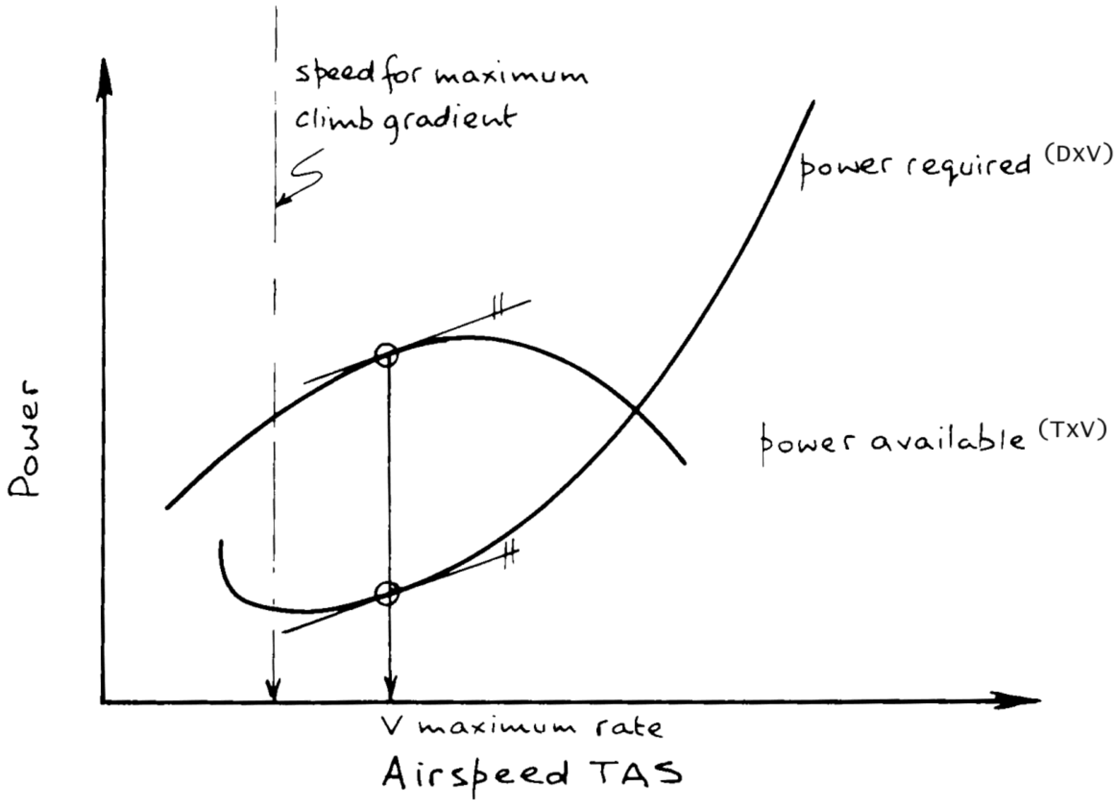


Figure Six – Speed for Best Rate of Climb

Again the aeroplane's 'pilot's notes' will declare a speed a little faster than this optimum speed (about 1.4Vs), not so much for safety but for engine cooling considerations, after all we will be using full power and flying slowly, so an air cooled engine can begin to suffer from a reduced cooling airflow just when it needs it the most.

In the absence of advisory pilot's notes, or thrust, power and speed graphs, a simple rule of thumb for best angle and best rate of climb for a light aeroplane is 1.2Vs and 1.4Vs respectively, but keep an eye on the engine temperature.

Of course an aviator does not always choose to climb at best angle or best rate. Once clear of obstacles any speed where there is an excess power available can be used as the climb speed. Often, for ease of navigation (or engine cooling), a speed somewhat faster than best rate speed will be flown so that the aeroplane will cover a greater distance over the ground in a particular time and, as a consequence, the aviator accepts a reduced rate of climb. Climbing in this way is generally called 'cruise climbing'.

As an aeroplane gains altitude the engine loses power because the air density decreases, and any speed used for a cruise climb will have to be progressively reduced toward the best rate speed for the climb to continue. Eventually it will arrive at an altitude where the power has diminished to the point where all reserve is gone. This means that the aeroplane has reached its 'ceiling'. (The term 'service ceiling' is used to define the altitude at which the rate of climb at best rate speed, is down to 100 ft/min.)

Many high performance piston engines have a means of feeding pre-compressed air into the combustion chambers to offset the problem of power loss as altitude is gained. This is called 'supercharging'. To put it very simply, the supercharger 'tricks' the engine into 'thinking' it is lower and, therefore, it can 'put out' more power at a particular altitude than it could if it were un-supercharged (normally aspirated). I am not aware of any civilian basic training aeroplanes that are fitted with superchargers so we won't discuss them any further here.

So far we have been considering the aeroplane's performance when climbing in a straight line, however quite often it becomes necessary to turn whilst climbing.

Does turning affect climb performance? It certainly does.

What happens to the total drag in a turn? It increases significantly as the bank angle increases, so increasing bank angle and turn rate too much will effectively 'absorb' all of the excess power and kill the climb! If you are having trouble remembering why this is so, re-read the lesson on Manoeuvring.

Remember, the total drag curve is also the 'thrust required curve' and in any turn the drag increases in proportion to the 'G' (remember my 'rule of thumb'?) So even in a turn of only 30º bank angle, the total drag has increased by about 20%, requiring a 20% trade off from the thrust (and power) available to climb. What all this means is that aeroplanes can either turn quickly or climb efficiently, but they cannot do both at the same time. So in order to maintain a reasonable rate of climb in a light training aeroplane, it is common practice to limit the bank angle to about 20º-30º.

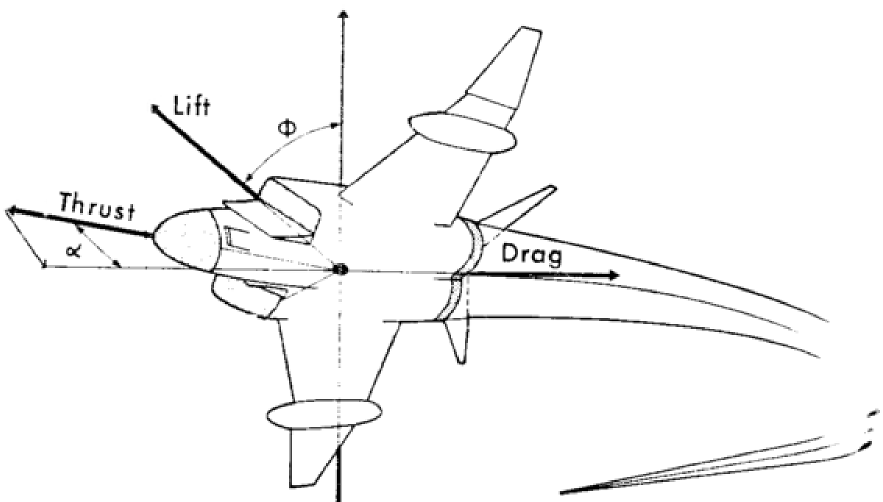


Figure Seven – Climbing and Turning

During WW2 the designers of fighter aircraft were under continual pressure to fit more and more powerful engines into existing ‘airframes’, not so much for more speed (although they were a bit quicker) but to enable their fighter to ‘out turn’ and ‘out climb’ its opponent. Nothing much has changed. A modern jet fighter is no quicker than those produced 50 years ago, but boy, can they climb and turn better! (Figure Seven.)

I opened this lesson by talking about ‘Zooming’ and I would like to close with a final word about it too. When the attitude of an aircraft is raised from level flight to its normal climb attitude, the aircraft’s kinetic energy at cruise is progressively converted as it travels ‘up the hill’ until the speed reduces to the best rate of climb speed and, assuming the correct attitude was set in the first place, the aeroplane will then continue climbing at this speed. The initial rate of climb will be greater than the sustained rate of climb until the excess kinetic energy has been converted. So there is a zoom component present at the beginning of every transition into a climb.

If an aviator wishes to convert this excess kinetic energy into a more positive initial climb rate, then an attitude in excess of the sustained climb attitude can be set until the speed reduces to best rate of climb speed, whereupon the attitude has to be adjusted to the sustained climb attitude. This technique can give an initial altitude ‘boost’ when commencing a climb, but, as I said in the opening, since light aeroplanes don’t have much kinetic energy to start with, the boost will be small. One of the pitfalls which accompany this technique occurs when the pilot holds the excessive attitude for too long and allows the speed to drop below the best climb angle speed. Now the aeroplane can not only stop climbing but can start descending! This happens because the airspeed slips too far onto the back side of the drag curve and all of the power is absorbed by drag. Figure Eight below shows the aeroplanes flight path in this situation. (Once again the angles have been exaggerated for clarity.)

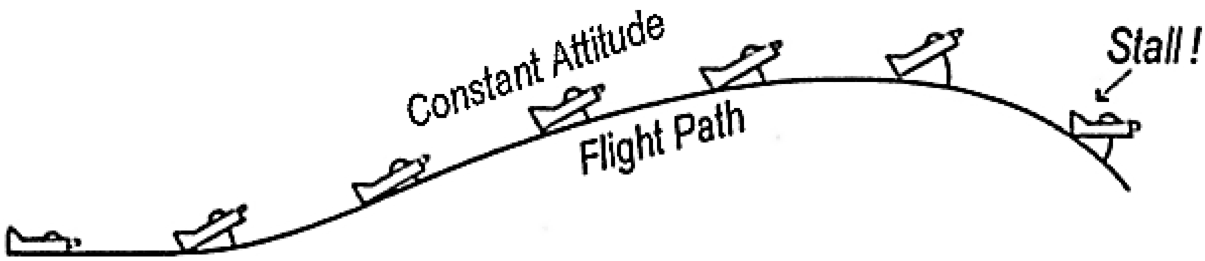


Figure Eight – Holding the Zoom Attitude for too long

Note also, that in order to hold this excessive attitude the A/A must be continually increased as the aeroplane slows. In this case it is the attitude that is constant and the flight path which is changing and, as we have already learned, it is the difference between them which defines angle of attack, (plus wing incidence). Ultimately, as the aeroplane's flight path curves over the top of its trajectory, the A/A will become critical and the wing will stall!

Flying Instructors regularly use the phrase, "Attitude plus Power equals Performance". This is a useful teaching device, but it has its limits. The forgoing is one such limit, because here we have a high nose attitude and full power, which initially gave a climb but is now giving a descent followed by a stall!!

Lesson Nine

GLIDING

Gliding is a sport enjoyed by hundreds of thousands of aviators worldwide. It is usually done in purpose built ‘sailplanes’. For the rest of us, gliding is usually done in the event of a power failure or practicing for the inevitable power failure.

In the lecture on climbing I used the analogy of a bicycle being peddled uphill to explain the concept of the ‘downhill component of gravity’. This downhill component is still there when we are bicycling down the hill; indeed it makes our job very easy, all we have to do is take our feet off the pedals and let gravity do all the work. The downhill component will cause the bicycle to accelerate unassisted by the cyclist until the ever increasing zero lift drag builds up to the point where it equals the downhill component. At this point the speed stabilizes. If the hill gets steeper the downhill component increases and the bicycle will accelerate some more until, once again, the drag builds up to balance it. If the hill gets flatter, the reverse will occur, and the bicycle will be slowed by the drag until it again balances the downhill component. So you can see that the gradient of the hill will determine the speed at which a particular bicycle will stabilize (Figure One).

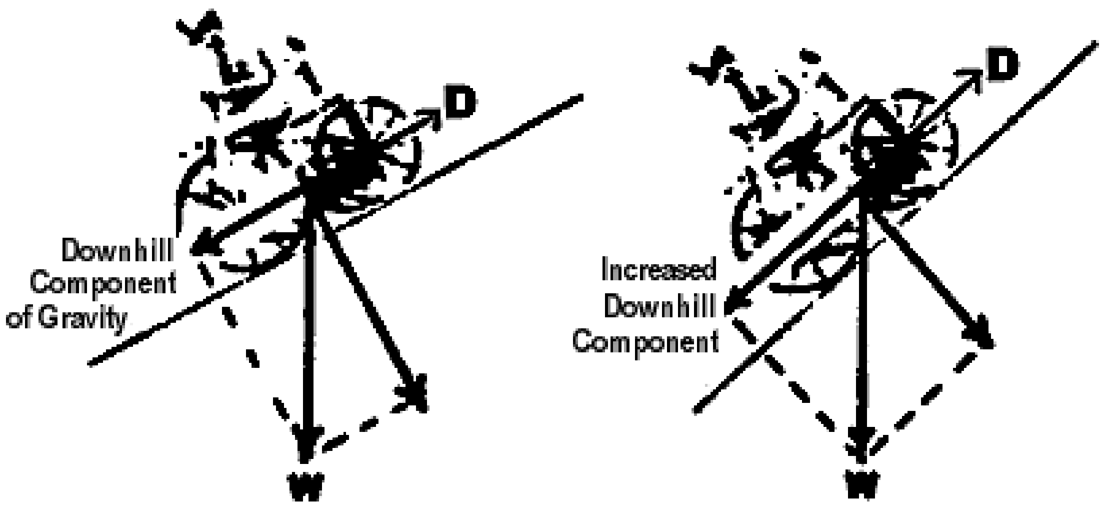


Figure One – Downhill Components of Gravity

If the cyclist applies the wheel brake, thereby increasing the rolling resistance, which is a form of increased drag, the bicycle will slow or require a steeper hill in order to maintain speed. It is the drag which determines the gradient of hill required to roll at a particular speed. If the drag is too much or the gradient too little and the bicycle slows too much, the cyclist can, once again, get off and walk.

A similar situation confronts the aviator. If the engine of the aeroplane fails, energy must still be expended to produce the thrust to overcome the **total** drag in order to maintain airspeed. That is, energy must be expended to produce the power required. Since the engine is no longer producing power the source of energy can only be the potential energy of the aircraft, that is, its altitude. To put that a simpler way, in order to maintain flying speed, an aeroplane must glide ‘downhill’ through the air.

When gliding an aeroplane, the ‘downhill’ component of gravity replaces the thrust and is the only force balancing the total drag. If the aeroplane is very ‘draggy’, like a wire braced biplane, the ‘hill’ will have to be moderately steep to create a component sufficient to balance the drag. But if the aeroplane is very ‘slippery’, like a modern sailplane, only a very slight ‘hill’ will be needed.

Obviously if we wish to maintain flying speed and come down the ‘flattest’ hill possible, the speed at which drag is at a minimum is the speed to fly, and, as we have seen in the lecture on ‘Drag’, this will be the speed represented by the bottom of the Total Drag Curve, that is, the ‘Minimum Drag Speed’. Unlike the cyclist, the aviator can control the gradient of the ‘hill’ to achieve the minimum drag speed, by adjusting the aircraft’s attitude.

For a steady glide with the engine delivering no thrust, the remaining forces of lift, drag and the components of weight (gravity) must be in equilibrium. The following diagram (Figure Two) shows the total drag balanced by the downhill weight component, whilst the weight is balanced by the resultant of the lift and the drag.

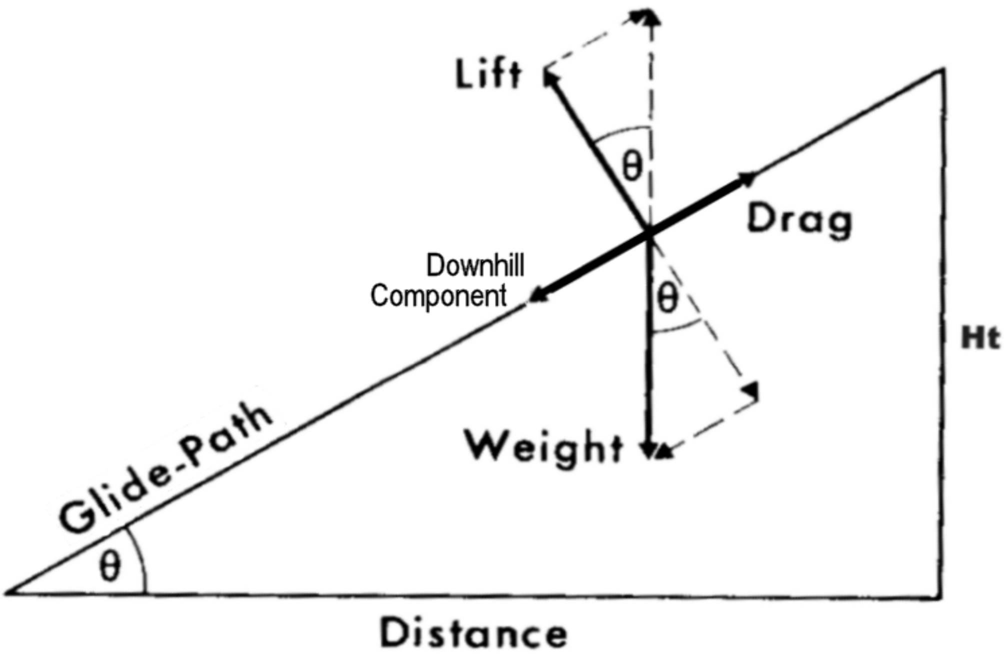


Figure Two – Equilibrium of Forces in a Glide

Now an aeroplane can be set up to either glide for its minimum rate of descent (endurance) or its minimum angle of descent (range). The speed for each is different. Note that, in the preceding diagram (Figure Two), the triangle formed by the lift and drag, and their resultant (which balances the weight), is geometrically similar to the triangle formed by the distance, height and glide path. So if the gliding distance is to be the maximum (from a particular height) the gliding angle must be the minimum possible. This means that the angle of attack must be that which gives the best lift/total drag ratio. As we have also seen from the lesson on Drag, this is obtained at the minimum drag speed. So we can simply state here, that the speed to glide at for **maximum range** is the **minimum <u>drag</u> speed,**

It is not usual for aircraft, other than sailplanes, to need to glide for endurance. However, if the end point of the glide is not important, but the time in the air prior to touch down is - such as ditching in the ocean and needing time to prepare - then the speed for 'minimum sink' is the one to glide at. The same considerations for flying for endurance with engine power, as previously discussed in Annex A to the lesson on Power, apply to this situation too, so we can simply state here that the speed to glide at for **maximum endurance** is the **minimum <u>power</u> speed**. These two speeds are shown at Figure Three below.

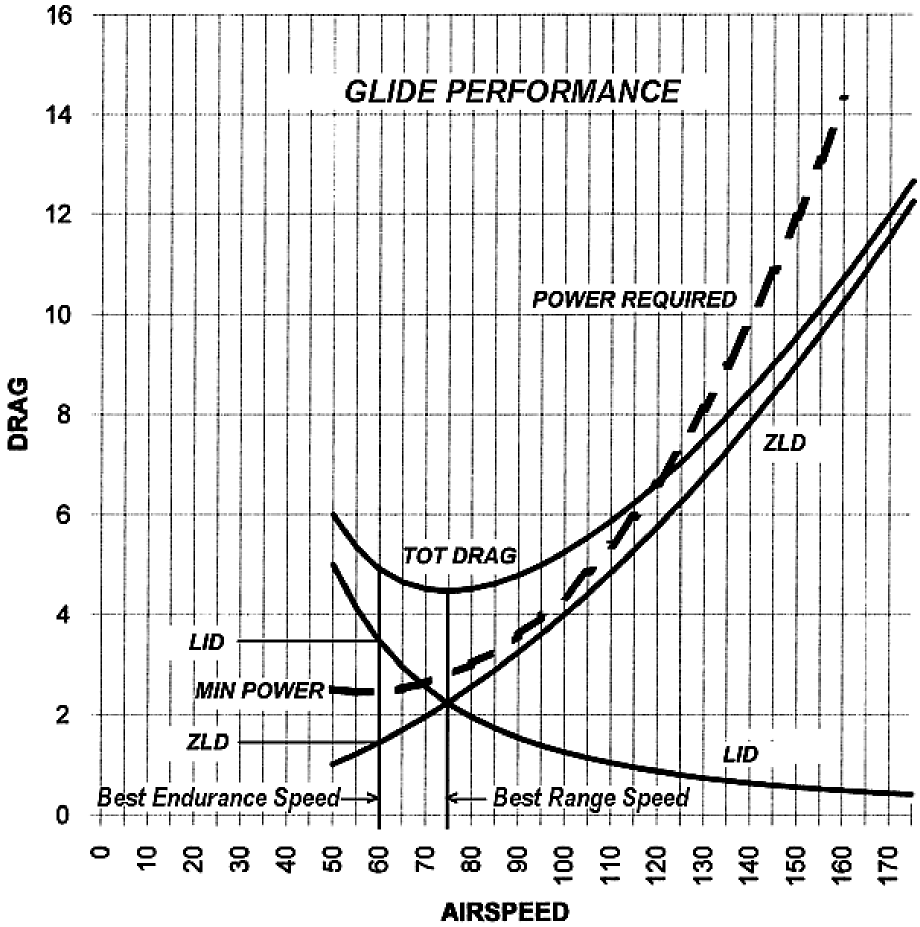


Figure Three – Glide Performance Speeds

The forgoing graph is a repeat of the graph which shows the derivation of total drag from the lesson on Drag, onto which I have superimposed the 'power required' curve and indicated the two key glide speeds. It is interesting to note the proportions of ZLD and LID at minimum power speed. At the minimum power speed (60kts) the Lift Induced Drag is the dominant drag component and is about twice the Zero Lift Drag. I have mentioned this to emphasize how significant LID is in a gliding situation. A fact that most sailplane pilots understand but most powered pilots are completely ignorant of.

Now many pilots will refer to the Vertical Speed Instrument in the cockpit when trying to determine the best glide range performance and incorrectly equate the minimum vertical speed (best endurance) with the best glide range. This misunderstanding could have disastrous consequences. The following diagram (Figure Four) shows the difference in the two types of glide.

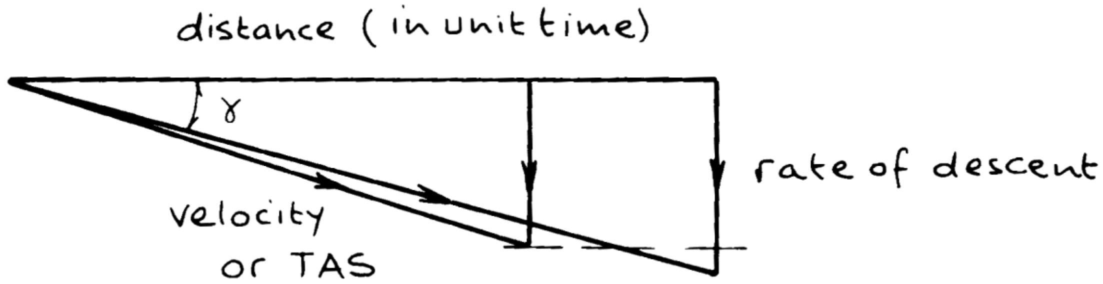


Figure Four – The Two Types of Glide

Note that the faster **vertical** speed (rate of descent) occurs at the higher speed, but the descent **gradient** is 'flatter' so the aeroplane glides further.

Now I remind you that the 'best L/D ratio' I am talking about here is the ratio of **lift to total drag** and the A/A at which this is attained is much greater than the best L/D A/A for the wing alone, (I refer you back to Annex C of the lesson on Drag where this difference and the current confusion about L/D ratio is discussed). This greater A/A, less the wing incidence, is the glide angle of the aeroplane. For example, remember that I told you that an approximate definition of A/A is the angle between where the aircraft is pointing and where it is going? Well, if the glide attitude is the straight and level cruise attitude (where it is pointing) and the relative airflow (RAF) is the reciprocal of the glide path (where it is going) then that defines the glide angle and the A/A (Figure Five).

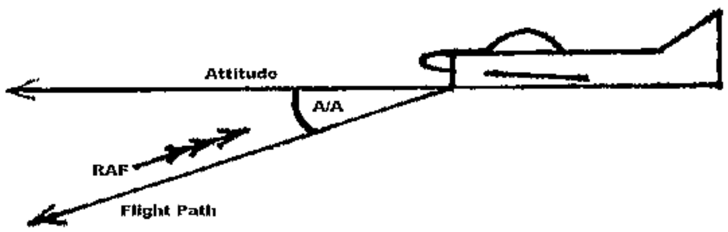


Figure Five – Angle of Attack in a Glide

Fortunately most light aeroplanes have a glide attitude similar to the straight and level cruise attitude, even though the aeroplane in a glide is not flying level but is descending. So if you are unsure what attitude to set to glide your aeroplane, just set and hold the straight and level attitude and the aeroplane will settle into a reasonably efficient glide.

Will this technique give you the best L/D ratio and the best glide? Not necessarily, but I have to ask the question, "best for what?" Covering the greatest distance through the air may not necessarily be the same as covering the greatest distance over the ground! Consider what happens when the air in which we are gliding, is itself moving.

If the air mass in which we are gliding happens to be moving in the same direction that we are going then the glide angle relative to the ground will be flatter and we will glide further over the ground. Conversely, if the air mass is going in the opposite direction, the glide angle relative to the ground will be steeper and we will not glide as far. This movement of the air mass is felt by someone standing on the ground as 'wind' and they would say that the aeroplane has a 'tail wind' or a 'head wind' affecting the glide. An aeroplane doesn't feel this 'wind'; it feels only its airspeed. From the aeroplane's 'point of view' it is the ground that is moving through the air mass because the air mass is the aeroplanes 'frame of reference'. The following diagram (Figure Six) shows the effect a moving air mass has on an aeroplane gliding within it, with respect to its range over the ground.

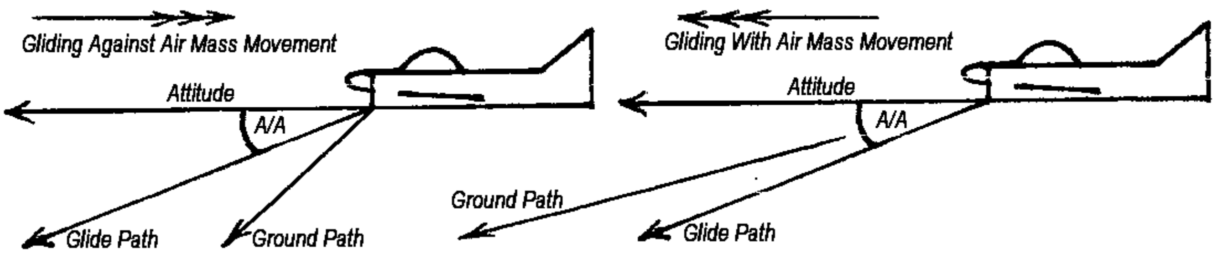


Figure Six – Gliding in a Moving Air Mass

You can see that the relative motion of the air mass and the ground affects the aeroplane's range over the ground. Can altering the airspeed also affect the range over the ground in this moving air mass situation? At 'first glance' it would appear not, as the best glide range speed though the air mass is as good as it gets....isn't it? But consider this. Let's assume that the published 'best glide range speed' (in the aircraft's 'Flight Manual') for the aeroplane is 75 knots and you are gliding in an air mass going 75 knots in the opposite direction! (A bit extreme I know, but it illustrates what I am talking about). How far over the ground will the aeroplane travel in the time it continues to be airborne? The answer is obvious.....zero! But what if you lower the attitude and let the aeroplane accelerate to, say, 95 knots? Sure, it won't be in the air for as long, but for as long as it is; it will cover some ground at a rate of 20 knots. As I said, this example is a bit extreme but it illustrates the principle that the 'best glide range speed' to attain the greatest distance over the ground depends upon the velocity of the air mass (speed and direction) and will always be a little greater than the published speed when gliding 'against' the motion of the air mass and a little less when gliding 'with' it.

At normal 'wind' speeds, the speed adjustments involved are not great, but they may make the difference between successfully attaining a suitable landing site or not. A simple 'rule of thumb' to determine this airspeed adjustment is to increase or decrease airspeed (the appropriate way) by 25% of the speed of motion of the air mass, but never slower than 'minimum sink speed'. (Remember, the speed of motion of the air mass is the same as the wind speed experienced by someone on the ground.) So, for example, if you are gliding a 75kt aeroplane 'with' an air mass moving at 20kts (a 20kt 'Tailwind'), glide 5kts slower at 70kts, and if you are gliding against it (a 20kt 'Headwind'), glide 5kts faster at 80kts. The following diagram (Figure Seven) illustrates the effect of 'adjusting' the glide speed in these circumstances.

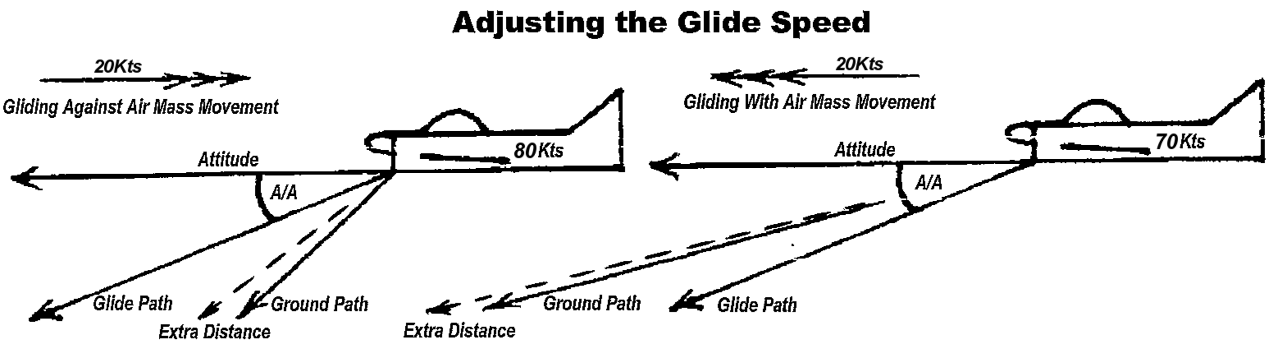


Figure Seven – Adjusting Glide Speed for 'Wind' Effect

Sailplane pilots call the speed for maximum ground coverage in a moving air mass, 'penetration speed', and most powered pilots are completely ignorant of the concept! (But you can read more about it in the 'Sailplane Supplement' to this book.)

Another factor which affects glide performance is the aircraft's weight, but not in the way that we might first think. The weight of an aeroplane does not affect the L/D ratio and therefore does not affect the distance that can be flown from a particular height; however it does affect the speed that the aeroplane must be flown at to achieve the A/A for the best L/D. The following diagram (Figure Eight) shows the balance of forces at two different weights, W1 and W2, the two corresponding speeds, S1 and S2, the lift in each case, L1 and L2 and the drag which results, D1 and D2. Note that the ratio of each of these sets of forces is the same, showing that the glide angle **'a'** doesn't change, but that the speed 'down the hill' does.

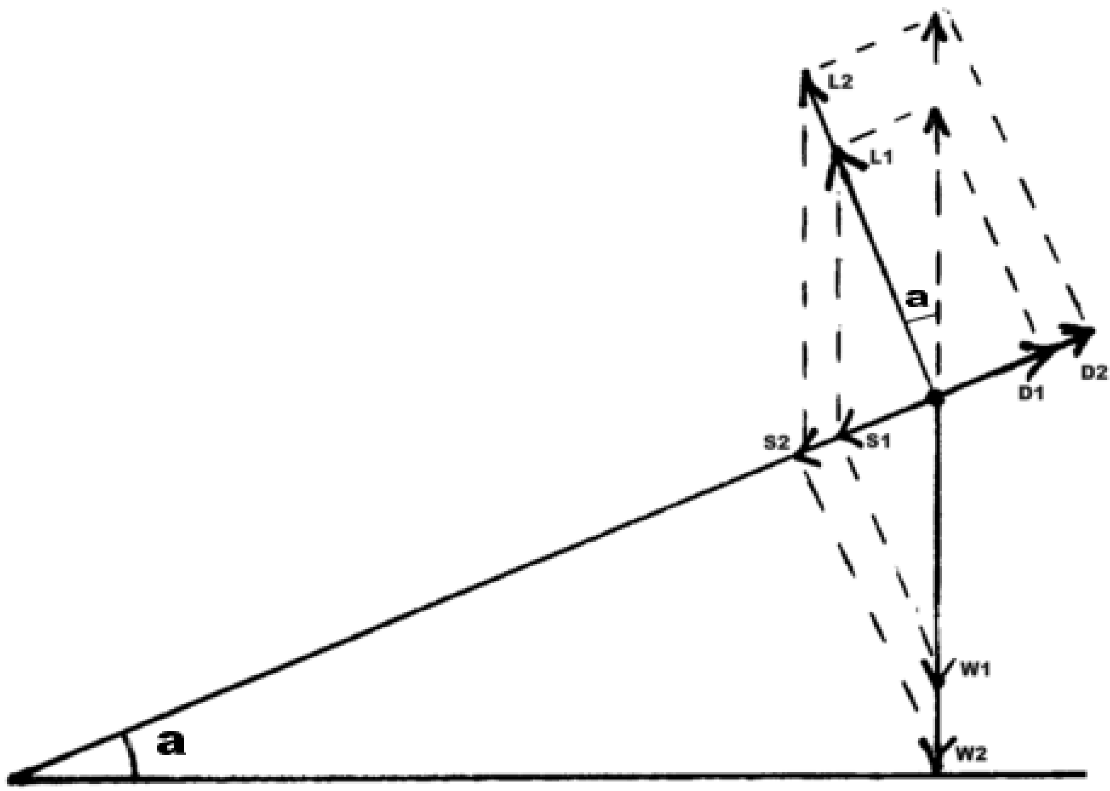


Figure Eight – The Effect of Weight on 'Best' Glide Speed.

A simple 'rule of thumb' to estimate the change required in the airspeed to compensate for changes in weight is to adjust the airspeed by a percentage equal to **half** the percentage change in the weight. That is, if the weight is increased by 10% the glide speed should be increased by 5%. Therefore a heavier aircraft must be flown faster than a lighter aircraft. It will come down the 'hill' faster and be in the air for less time so it follows that **weight does affect the endurance of a glide,** so if you have to ditch and you have the capability, jettison as much weight as possible. (The aeroplane might float better too!)

The glide performance figures stated in the aircraft's Flight Manual assume the aeroplane is being operated at maximum weight, so as an example of this 'rule of thumb', assume our 75kt aeroplane has a maximum weight of 1000Kg, therefore flying it 100Kg (10%) lighter would mean the best range glide speed would be 71.25kts (5% slower), whilst 200Kg (20%) lighter equates to 67.5kts (10% slower).

Does turning affect the aircraft's glide performance? Yes it does. As detailed in the lessons on manoeuvring and climbing, any turn involves an increase in the Lift Induced Drag and hence the Total Drag. So, if you are aiming for maximum glide **endurance,** and you have to turn, keep the angle of bank **low**. If however you are gliding for maximum **range** the situation is more complex, and involves balancing the requirements for both glide performance, rate of turn and radius of turn.

First we should address the question: "If we want maximum range from our glide, why are we turning at all?" Well, depending upon the circumstances of the engine failure, it may be necessary to turn toward the most suitable landing site and then turn again to align the aeroplane with the best landing path. Consider the following. Let us assume that our aeroplane when gliding for maximum range has a rate of descent of 700 ft/min and we need to make a 180º turn. If the turn is done at 'Rate One', which is 180º per minute and which needs only about 20º of bank, and only effects the descent rate slightly (about 2%), the aeroplane will lose 715 feet during the turn. However, if we roll to 60º of bank and execute a 'Rate Four' turn, the turn will be completed in 15 seconds. Obviously the drag will have increased significantly (2.0G = 2 x Total Drag) as will our rate of descent, (approximately 40% greater) to about 1000 ft/min, but this increased rate of descent has to be sustained for only 15 seconds, which would result in an altitude loss of only 250 feet!

What speed should we execute this 2G turn at? Well 2G is a 100% increase in apparent weight, suggesting a 50% speed increase; however, we don't need best range speed when we are not pointing in the direction we want to go, so we should do the 'sum' based upon the best endurance speed, which for the aeroplane in this example, is 60kts. So, in this case, turning at 90kts will achieve our objective most efficiently.

Not only does the rate of turn versus the rate of descent influence the choice of bank angle, but as you can see from the following diagram (Figure Nine), the turn radius can also be a factor when aligning the aeroplane with the desired landing path. The aircraft in this example will have, in a rate one turn at 75kts, a 1200ft turn radius; but in a rate four turn at 90kts, a 400 ft turn radius.

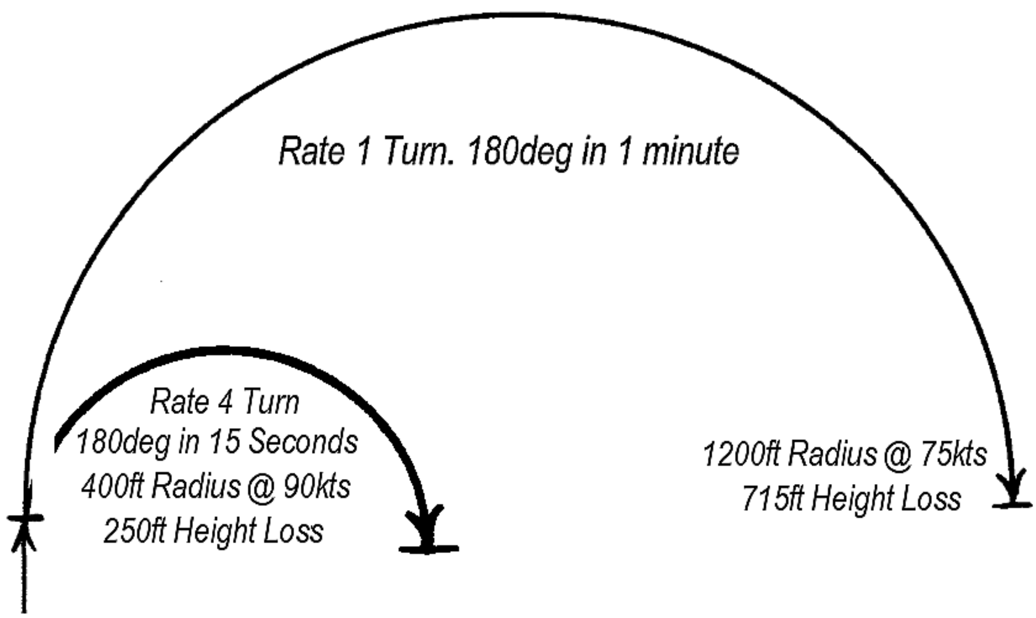


Figure Nine – Rate of Descent versus Rate of Turn

In general terms it can be said that, “As the bank angle increases the rate of turn increases much faster than the rate of descent”. So with due regard for the increased stall speed which results from a ‘tight’ turn, you don’t have to “pussy foot” around when turning toward a safe landing site. Indeed it is better if you don’t. (The effect of bank angle on the stall will be covered in the lesson on Stalling.)

I would now like to remind you of the ‘spiral staircase’ effect that I spoke of in the lesson on Manoeuvring. When turning during a glide you can expect to ‘hold on’ bank throughout the turn; if you find that you are not, or worse, ‘holding off’ bank then you are doing a ‘skidding turn’. Check your balance ball and adjust your rudder to bring it back to centre. A skidding turn during a glide can have disastrous consequences for reasons I will discuss fully during the lesson on Spinning. Interestingly, this ‘spiral staircase’ effect decreases as the bank angle increases and the likelihood of inadvertently skidding during the turn is diminished.

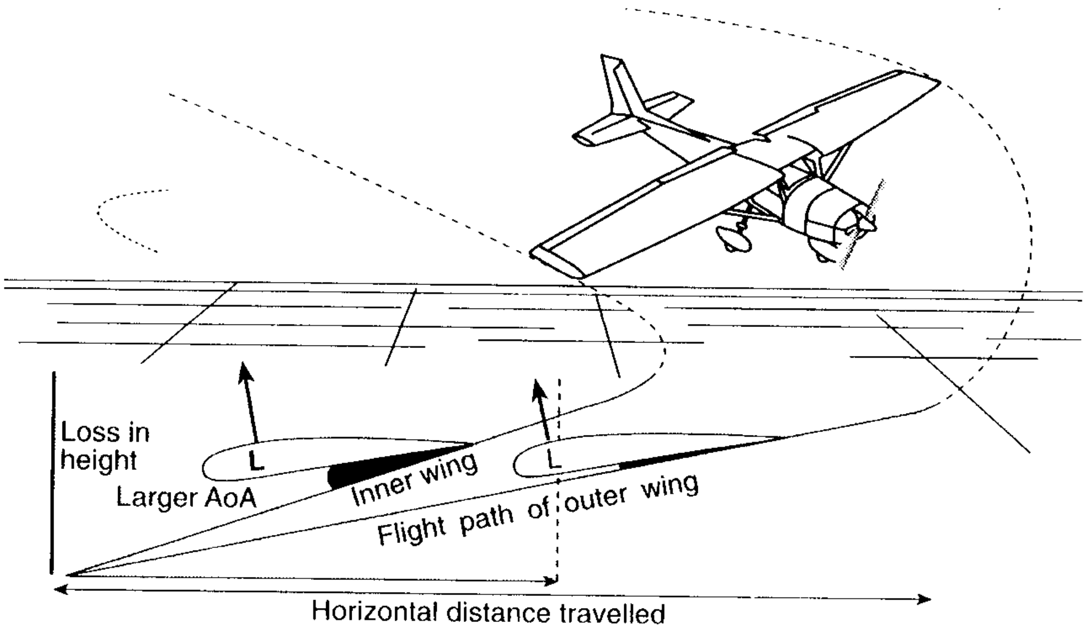


Figure Ten – Holding <u>On</u> Bank during a Gliding Turn

That is as much of the aerodynamics of gliding that I am going to discuss at this time; however, later in this book I revisit them in respect of modern Sailplanes and explain where all of those “Rules of Thumb” come from. In Book Two in the lesson on ‘Forced Landings’, I discuss how best to employ your knowledge of gliding when confronted with an engine failure and I have detailed my personal thoughts on ‘Forced Landing Philosophy’; however, before concluding this lesson I would like to briefly discuss ‘Descending’ an aeroplane.

I have often been surprised by student and private pilots who believe that gliding is the only way of losing altitude in an aeroplane with a perfectly serviceable engine! This, of course, is not so. There are any number of possible power and attitude combinations that can achieve a controlled descent at either high speed, whilst enroute to somewhere, or low speed, whilst making an approach to land. Imagine you are driving a car along a flat road at the speed limit when the road suddenly ‘tips’ downhill. As the car starts down the hill the ‘downhill component of gravity’ adds to the thrust and will, if unchecked, cause the car to increase speed. In order to not exceed the speed limit you must lift your foot off the ‘gas pedal’ a little to compensate. The steeper the hill the more you have to ‘lift’ your foot, and if the hill is very steep you may even have to ‘ride’ the brakes a little.

A similar situation confronts an aviator; however, an aviator can choose the steepness of the hill to fly the aeroplane down. This can be achieved with an appropriate attitude adjustment and, if the cruising speed is to be maintained, a corresponding power reduction. A ‘cruise speed descent’ is often the most useful way of descending as it does not require the elevator to be re-trimmed and it doesn’t alter the ground speed, so the navigation ‘problem’ is simplified. Those aeroplanes fitted with ‘turbo-charged’ engines are also limited in the rate that the power can be reduced, so a gentle cruise speed descent suits them best.

There is literally an infinite range of attitude and power combinations available to achieve a controlled descent in an aeroplane, and remember there are no speed limits in the sky so letting the speed increase downhill is quite acceptable (although some people on the ground may be upset by the sonic ‘boom’ if you happen to be flying an aeroplane capable of such speeds). Some will say that this is not a descent but a dive! Okay, so what? There is no clear definition of the difference between descending and diving. One man’s dive is another man’s descent; however, I have ‘coined’ my own definition which I present here for your consideration:

“A dive is a downhill flight path in which an aeroplane attains a speed it is not capable of attaining in level flight.”

So, by my definition, any descent at, or less than the speed which an aeroplane can achieve in ‘flat out’ level flight is not a dive. I will leave you to decide if this definition works for you or not.

Obviously a low speed descent in order to land an aeroplane has certain speed limits associated with it and is usually achieved with the use of additional drag from flaps or side slip. Often a small amount of power is also used to afford the aviator the greatest flexibility in achieving a good approach and landing. How to do this in your aeroplane will be covered in Book Two.

Lesson Ten

GROUND EFFECT

In the late 1950's a new type of 'craft' came upon the aviation 'scene'. It was written about extensively in all the flying magazines and popular science magazines of the time. It was called an 'Air Cushion Vehicle' or ACV, but quickly became known as a 'Hovercraft'. Hovercraft were supposed to be able to 'fly' at very low level and high speed over all types of flat surfaces including land, water, ice, snow and swamps. Development of these craft was swift, and during the 1960's large Hovercraft were in military and civilian commercial use worldwide. Some simple commercial offshoots were also produced, namely the Hoover 'Hover' vacuum cleaner and the 'Flymow' lawn mower! Unfortunately none of these craft quite lived up to the initial 'hype' which accompanied their introduction, so they didn't 'take over the transport world' as suggested, but within their operational limitations many are still in use in specialized applications today. (Including the table game, 'Air Hockey'.)

A Hovercraft's basic operational principle is quite simple: an engine(s) driving a fan, forces air into a 'plenum chamber' (like an upturned soup bowl). The air pressure in the plenum chamber increases, creating a pressure 'bubble' which lifts the craft a small distance clear of the surface upon which it is resting. The air immediately escapes through the gap created, but is replaced by more air being pumped in by the fan (Figure One).Obviously the height at which the Hovercraft can 'hover', depends upon how powerful the engine is, and how efficiently the pressure in the chamber can be maintained. The Hovercraft was said to be sitting on a cushion of air, hence the original name. This whole phenomenon was also called 'Ground Effect'.

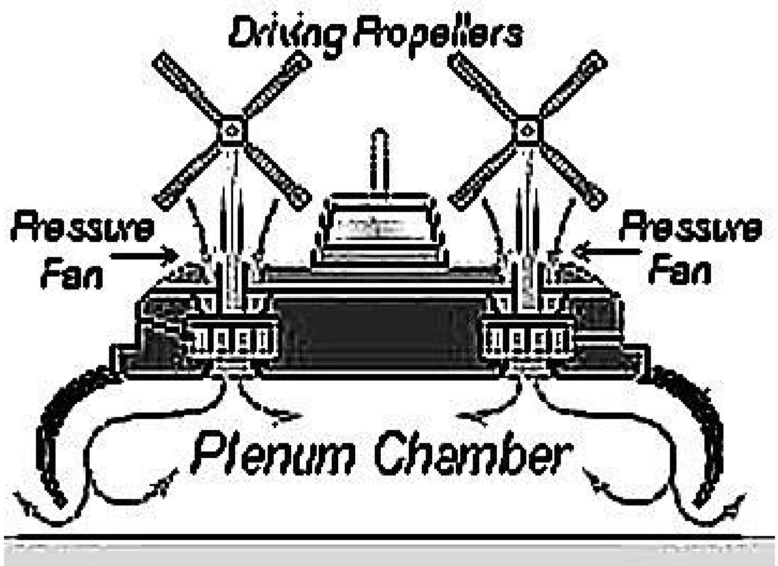


Figure One – 'Plenum Chamber' Hovercraft

A further development at the time was the ‘Ram Wing Hovercraft’, which did away with the direct ducting of air into a plenum chamber, and instead relied upon a build up of air pressure beneath a low aspect ratio ‘wing’ being propelled forward by an normal aircraft engine. This craft was, in effect, a low flying aeroplane, but it was incapable of flying above the ‘ground effect’ created by its wings (Figure Two). The formal name given to these craft was ‘Ground Effect Vehicles’ or GEVs. The Russian military, during the ‘cold war’, expended a lot of effort developing GEVs as high speed transport vehicles, but once again they never attained the operational capability promised for them.

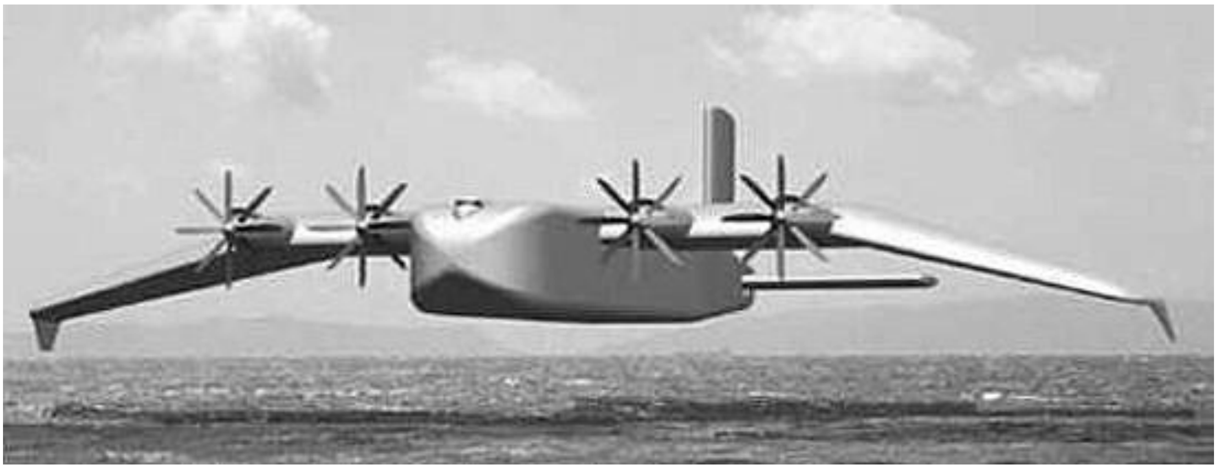


Figure Two – ‘Ram Wing’ Hovercraft (GEV)

Now ‘Ground Effect’ was a phenomenon familiar to aviators long before Hovercraft or GEVs became fashionable. It is experienced by an aeroplane when operating, as its name suggests, very close to the ground. This is usually during take-off and landing, but is also experienced by agricultural fliers when going about their daily business. It is the phenomenon which causes an aeroplane to ‘float’ during landing. It can also allow an overloaded aeroplane to get airborne and climb a few feet before crashing into the trees at the end of the runway!

So what is going on near the ground? An aeroplane on a landing approach will start to experience ground effect at an altitude equivalent to about one wingspan above the ground or water. This effect will increase as the descent continues and becomes noticeable at a height of about half a wingspan. During this phase of the landing the aeroplane is becoming, in effect, a ‘Ram Wing Hovercraft’, for a short time. The airflow under the wing is constrained from flowing downwards by the surface beneath it, thus increasing its static pressure further but reducing the downwash. Now a reduction of downwash will, as we have learned previously, reduce the ‘total reaction’, and hence, reduce both the lift and the induced drag. But the loss of lift is offset by the static pressure build up due to the ‘ram wing’ effect. The net result is that there is a reduction of induced drag without a corresponding loss of effective lift, causing the aeroplane to ‘float’ a short distance beyond the planned touch down point before settling onto the ground (or water).

The following diagram (Figure Three) shows the airflow around the wing of a low wing aeroplane just before 'touch down', and the resulting 'old' and 'new' total reaction vectors.

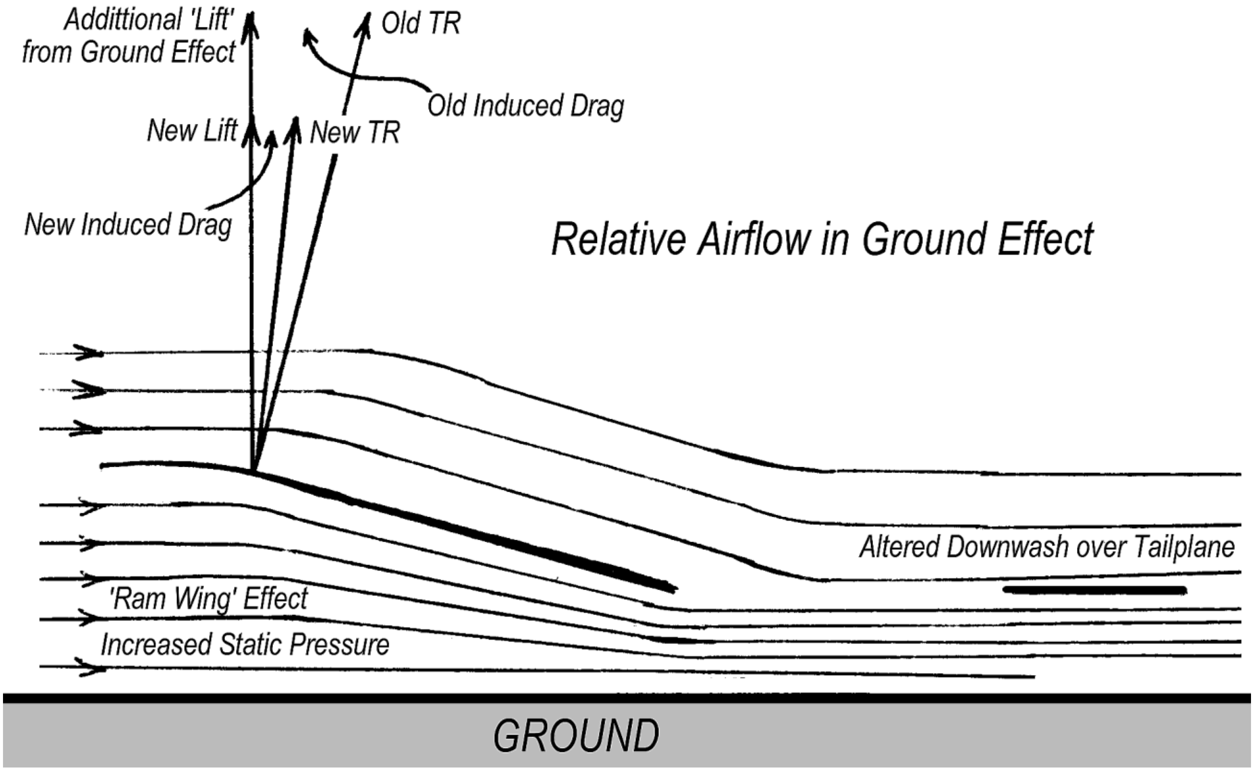


Figure Three – Airflow around a wing in 'Ground Effect'.

In the preceding diagram (Figure Three), the old and new induced drag vectors have not been draw for clarity, but can be interpolated from the length and angle of the 'Old TR' and 'New TR' vectors. Note that the 'Old' TR vector, due to the original downwash, has been reduced because the proximity of the ground has reduced the down wash. This has caused a reduction in both the induced drag and the lift. Also, the 'New' TR vector angles forward slightly, because of the changed downwash angle, causing a further reduction in induced drag. However, whilst the 'old' lift vector has been reduced, the 'air cushion', which results from the 'Ram Wing' static pressure build up, compensates for this loss. The end result is, as I have said, a reduction of induced drag without a corresponding loss of effective lift.

Ground Effect can also alter the airflow around the tailplane (depending upon its location). This usually takes the form of an altered negative angle of attack due to the altered downwash angle from the wing. This will alter the stick position versus angle of attack relationship a little during the landing, often necessitating slightly more 'back stick' to hold the landing attitude.

The following graph (Figure Four) shows the actual percentage reduction of induced drag as a function of the wing's height above the ground, expressed as a percentage of its span.

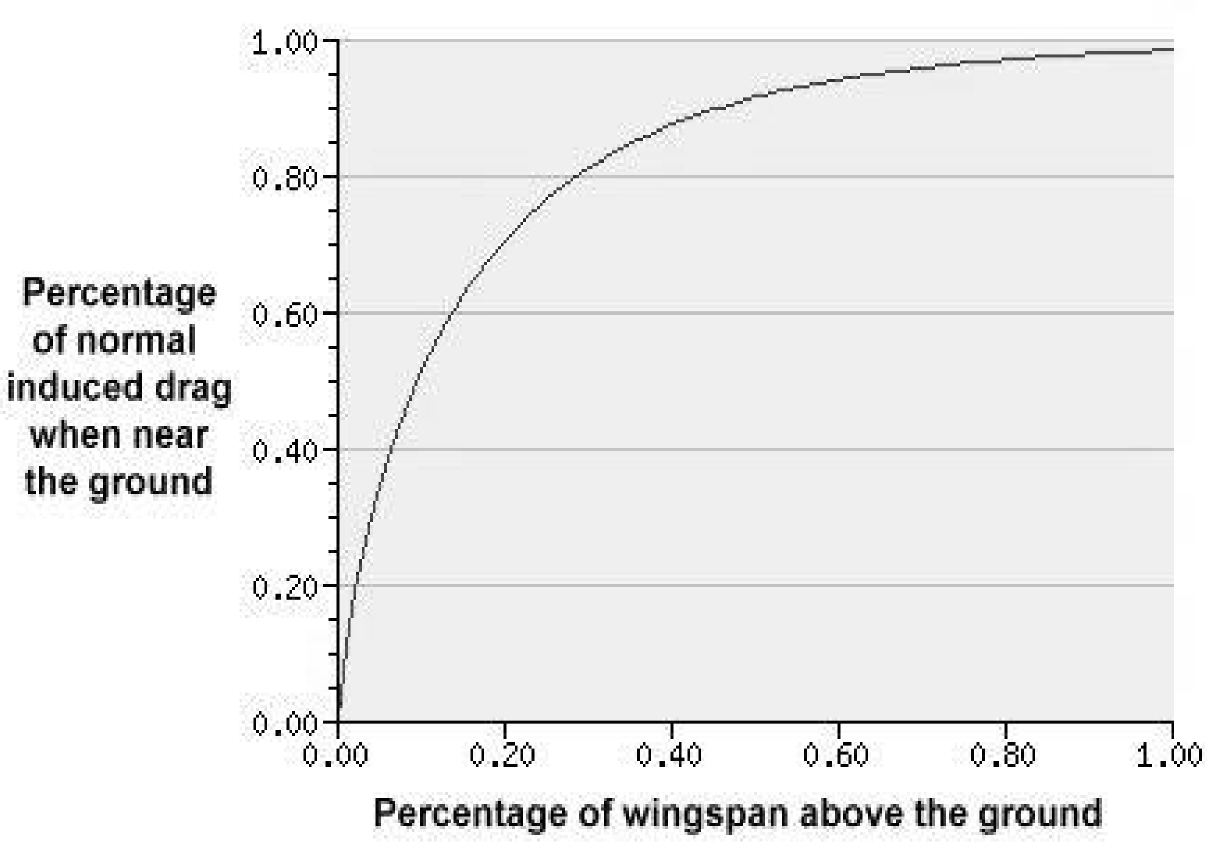


Figure Four – Reduction of Induced Drag with reducing height.

The amount of Ground Effect experienced by an aeroplane is influenced by the position of the wings, that is, a low wing aeroplane experiences it more than a high wing aeroplane. From the forgoing graph you can see that a low wing aeroplane's wing, which is about 20% of its span above the ground at touchdown, is experiencing about a 40% reduction in induced drag, whilst a high wing aeroplane's wing, which is about 40% of its span above the ground at touchdown, is only experiencing about a 15% reduction.

The position of the flaps will also influence the ground effect experienced. An aeroplane landing with flaps lowered will produce a greater ground effect 'bubble' than it would if landing 'flapless'. The exact amount will depend upon the degree of flap set. In an emergency, this 'float in ground effect' can be reduced by raising the flaps as the aircraft starts to float. This can be done, if necessary, from a height of a 'half wingspan' and will significantly reduce the ground effect prior to touchdown.

I will talk a little more about Ground Effect in the lesson on landing technique in Book Two.

Lesson Eleven

STALLING

In the lessons on Lift and Drag I mentioned the 'Critical' angle of attack several times, and briefly described what happens if this angle is exceeded. First let me reiterate. If the angle of attack of a wing exceeds its critical angle the 'Coanda Effect' over the top surface is disrupted, and the airflow no longer 'sticks' to the wing or follows the curve. The airflow separates from the wing surface, and turns back on itself as depicted in the diagram below (Figure One).

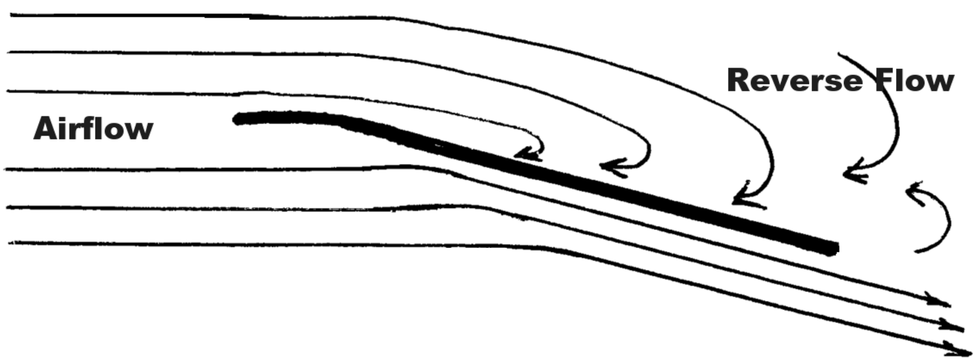


Figure One – Airflow Separation at Critical Angle of Attack

This turning back causes a sharp increase in zero lift drag. Not induced drag, but drag caused by trying to push an inclined plane at too great an angle through the air, and 'sucking' that mass of air along too. It can't be induced drag because, once the airflow detaches from the top of the wing it ceases to be deflected down. This means that the part of 'total reaction' which is generated by the top surface vanishes, and the associated induced drag vanishes too.

This sudden decrease in total reaction (and therefore loss of lift), accompanied by the sudden increase in zero lift drag, is called an 'aerodynamic stall', nowadays shortened to just 'stall'. (Not to be confused with stalling the engine of your car by dropping the clutch without stepping on the gas.) Now stalling the wing is not a very efficient way to fly, but it is still flying. We are still flying because the bottom of the wing is still deflecting the airflow, but the loss of energy as the wing stalls and the process of un-stalling it can involve an altitude loss which, in certain circumstances, we may not have in reserve. If we have a powerful engine at our command this height loss can be reduced considerably.

So what causes a stall? Well, to put it very simply, the pilot does! The pilot may not mean to do it, but by either ignorance or poor flying he or she does. Indeed they each may exclaim loudly, "It stalled on me!" But aeroplanes don't stall 'on pilots', pilots stall aeroplanes. You would never hear someone say "my finger jammed itself in the door", would you? We control where our fingers are and what they are doing, and in the same way we can also control 'our' angle of attack and not 'jam it in the door'. Okay, but that doesn't really explain the phenomenon does it? So let me explain how the pilot can stall and un-stall the wings at will, so that, if you do it, at least you won't be able to claim ignorance as an excuse.

I refer you back to the lesson on 'Stability and Control', where I explained the relationship between the tail and the wing, or more precisely, between the elevator deflection and the angle of attack of the wing. Let me restate the pertinent point here:

The angle of attack of the wing is caused by the angle of deflection of the elevator, independent of the airspeed. If we pull the stick back too far and deflect the elevator too far we will increase the angle of attack of the wing beyond the critical angle and stall it.

It's that simple. Now note that I said "pull the stick back too far". The control stick (or control wheel) has a direct mechanical link to the elevators by either push rods or cables, so that if you move the stick a certain amount the elevator will move a corresponding amount, and each time you move the stick that amount the elevator will move the same corresponding amount. This is true today, tomorrow, next week, on the ground or in the air at 70kts or at 170kts! Take a look at Figure Two below.

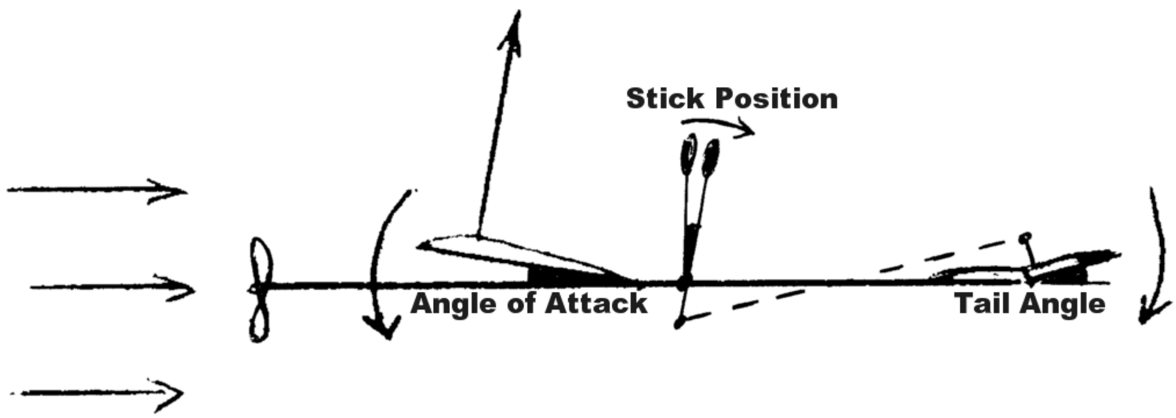


Figure Two – Stick position controls elevator angle which controls A/A

It follows then that if the stick controls the elevators and the elevators control the angle of attack of the wing, there must be a stick position which corresponds to the critical angle of attack. Not only that, but there must be **a range of stick positions which correspond to every other angle of attack too!** This is also true in the air at 70kts or at 170kts, today, tomorrow, next week! And don't you have control of the stick position? Figured it out yet?

***YOU** have direct control of the angle of attack of the wings of the aeroplane you are flying, at all speeds, and in all attitudes, in the air!*

Go back and read that last sentence again. This 'Gem' of information indicates how you can begin to forge the neural links in your brain which will allow the wing to become an extension of you, just like your fingers.

The actual angles that the stick and the elevators move through to produce a particular angle of attack are different for different aeroplanes. The stick angle to elevator angle ratio depends upon the 'gearing' of the mechanism, and the tail angle to wing angle ratio depends upon the 'tail volume' and elevator area. Tail volume and elevator area are set by the designer so that the angular movement of the elevator is always less than the corresponding angular movement of the wing, thereby ensuring that the wing reaches its critical angle first. If this was not so, the pilot could lose control of the aeroplane by stalling the tailplane before the wing!

On a particular aeroplane, the 'Reynolds Number' and the position of the Centre of Gravity do vary this A/A / stick position relationship a little, but not much in a low speed light aeroplane as they are always at low Reynolds Numbers, and normally have a limited Centre of Gravity range. (To review 'Reynolds Number', go back to Annex A in the lesson on 'Lift' and take a look at the different stall angles of attack at different Reynolds Numbers, you will see that even over a large range of Reynolds Numbers the critical angle of attack does not change much.)

So what causes a stall? The pilot does, by moving the stick to or beyond the stall stick position. If you have inadvertently stalled the wing how do you un-stall it? Simple; move the stick to a position corresponding to an A/A less than the critical A/A.

Try this simple exercise. Close your eyes and move your hand around, touch your nose, touch your ear. Your brain knows where your hand is and where your nose is, so bringing them together is easy. Pick up your pen and close your eyes again. Now touch your nose with the pen. Same deal, your brain knows where your pen is. Put the control stick of an aeroplane in your hand and move it backwards and forwards.....now doesn't your brain know what the angle of attack of your wing is? Or at least, can you see how it can be taught?

Infant children take about two years for their brains to 'hard wire' their control of the 'motor skills' required for walking and running etc. It takes musicians about two years to be able to unconsciously 'find' the appropriate notes on their keyboard or strings, and it will take you about the same length of time to 'know', and to 'feel' the angle attack of your wing, without conscious thought, using this technique. To achieve this 'hard wiring' you must do three things. The first is to understand the principles involved in this angle of attack control technique (which is the underlying purpose of this lecture). The second is to go out and fly, and explore the stick position and angle of attack relationship of your aeroplane in various attitudes and at various airspeeds (a good flying instructor can help with this, and I discuss some simple flying exercises to achieve it in Book Two). The third thing is practice, practice, practice.

I do not believe in the old adage "practice makes perfect". Practice makes permanent; that is, 'hard wired'. So you had better be practicing the right thing from the start. My version of that old adage is that "good instruction makes perfect and practice makes permanent". This is why I found teaching my techniques to 'experienced' pilots more difficult than teaching them to beginners, as the experienced pilots had already hard wired poor techniques which had to be 'unwired' first.

Now am I saying that it will take about two years of practice before you can realize the benefits of this technique? No, but it will take time to achieve the final hard wiring so that the wing becomes an extension of your brain, (just like your fingers). During your practice you are going to have a lot of fun and gain so much confidence in your ability to control the aeroplane that you will rapidly become very 'comfortable' in the sky.

Have I digressed from the subject of stalling? Not really, stalling is a function of angle of attack and I have been talking about angle of attack control. Earlier I said that to un-stall a wing all you have to do is move the stick to an A/A less than the critical A/A. This begs the question "to what A/A?" Well since we now know that we can set any angle of attack we like by simply moving the stick to the appropriate position, what angle of attack should we set? How about the angle of attack that gives the best lift to total drag ratio so that the aeroplane can regain lost energy most efficiently? How do we determine this stick position? Easy! Establish a glide at the correct speed and note the stick position which maintains it. (This should be the 'best glide speed' through the air without concern for wind or survival factors). You will find that this stick position is not very far forward of the stall stick position because the best 'lift to total drag ratio' angle of attack is about ¾ of the way back to the critical angle of attack. It will equate to one or two 'knob widths' forward of the stall position (depending upon how fat your stick grip is, and what the range of travel of the stick is).

If you inadvertently stall the aeroplane with power on, say in an aerobatic manoeuvre, resetting the stick position to the best lift/total drag ratio stick position will un-stall the wing and allow the manoeuvre to continue. I used to regularly have my students deliberately stall and un-stall the wing once or twice during the course of a loop by simply moving the stick back and forward between the two positions. This would accelerate their understanding of this direct angle of attack control technique and help them realize that total control is in their hands.......literally.

If you have inadvertently stalled the aeroplane with the power off, say whilst gliding, then as you un-stall the wings apply full power (and set the flap up to the take-off position if they are down, if not don't touch them). Hold the angle of attack until the aeroplane pitches to the climb attitude, and then reduce the angle of attack further (ease the stick forward) to hold the climb attitude as the aeroplane gains airspeed. Using this technique you will regain the lost energy (altitude and speed) most efficiently. In many aeroplanes the nose attitude will hardly dip below the level attitude during this process, and will then pitch up to the climb attitude quite rapidly. Fear not, it will not re-stall, because you are holding the stick at the most efficient angle of attack position. It pitches up rapidly because as soon as the aeroplane starts to accelerate the lift builds as the square of the airspeed and, as we learned in the lesson on 'Manoeuvring', the excess lift causes the pitch up. The more powerful the engine, the quicker this will happen.

If you inadvertently stall during a real forced landing, and have no power to accelerate the aircraft, then re-setting the correct glide angle of attack stick position will at least return the aeroplane to the glide quickly.

I must emphasize one more important thing here and that is that everything I have said so far relates to **stick position *not* stick pressure.** The pressure or force you will need to exert on the stick will differ depending upon the airspeed and the elevator trim setting.

The stick force does not matter: the ***stick position*** *does.*

In the previously mentioned aerobatic scenario the elevator trim will be set for high speed flight (low A/A) whilst in the gliding scenario it will be set for low speed flight (high A/A), so upon recovery from the inadvertent stalls in each case the stick forces will be quite different. The elevator trim control is there to make it more comfortable to fly at particular stick positions for extended lengths of time and that is all. Try this exercise in the air. Trim your aeroplane for straight and level flight then grasp the stick with two hands and lock your elbows into your ribs to prevent the stick from moving. Now have your instructor or a well briefed friend (preferably another pilot) wind the elevator trim back and forward through a reasonable range whilst you prevent the stick from moving. The force you will need to hold the stick where it is will vary, and become quite large toward the limits of travel of the trim control. Note what the aeroplane is doing; it is flying along quite happily straight and level, blissfully unaware of the 'arm wrestling' match being conducted between you and the elevator trim, it is responding only to the **stick position**. (Have the trim reset to mid-range before you release the stick at the end of this exercise.)

So what is the point of this exercise? It is to illustrate that if you inadvertently stall an aeroplane at any time the trim could be set anywhere, so the stick force (pressure) may be quite different to that which you experienced during your early stall recovery practice, so it will feel ‘different’, but the **stick position** you should set to recover is **always the same**. This is where musicians have some advantages over aviators as the feedback forces of their instruments are always the same. I can imagine it would be considerably more difficult to learn to play a slide trombone if the forces required to position the slide for each note varied. But I am only guessing as I can’t play a trombone.

All I have described so far has assumed an aeroplane with a conventional configuration, that is low wing and mid tailplane, so that the position of the flaps does not change the elevator to wing angle of attack relationship much, if at all. If your favored aeroplane has a high wing or a high set tailplane you may have to establish the stick position for ‘stall’ and ‘glide’ in the flapped configuration too, because the changed downwash with flap extended could affect the elevator/wing relationship. (See the lesson on ‘Stability and Control’).

Are there any other ‘symptoms’ that can warn us of an impending stall? Yes, a few. The most common is a degree of airframe buffeting from the turbulent airflow caused by its separation from the top of the wing. Often this turbulent airflow will flow back over the tail and cause shaking of the elevators, which of course will feed back to your hand through the stick, and ultimately to your brain. This buffeting happens at or just before the critical angle of attack so it doesn’t give you much warning (assuming for a moment that you are ignorant of where you have just positioned the stick). Each aeroplane exhibits different ‘buffet’ characteristics depending upon wing shape and tailplane position. Some aeroplanes have a short sharp cornered ‘wedge’ attached to the inboard leading edge of each wing to cause a local airflow separation at a few degrees less than the critical angle of attack, and cause a very sharp distinctive buffet through both the airframe and the stick. I did my initial flying training in an aeroplane with these wedges; they worked very well as a stall warning device. I also flew the Vampire jet trainer in which one of the warnings of impending stall was a ‘buzzing’ noise caused by the airflow ‘breaking away’ over the canopy. On the Tiger Moth, the slats pop out with a ‘bang’ as the critical angle is approached. Each type of aeroplane is different when it comes to the secondary indicators of an impending stall, **but in all cases the primary indicator is the stick position.**

Because of the differences in secondary indicators and the almost universal ignorance of the primary one, most regulatory authorities now require all modern light aeroplanes to be fitted with an electric ‘stall warning’ device. It is usually a small metal ‘blade’ protruding from the leading edge of the wing which is ‘flipped’ up by the airflow, a few degrees prior to the critical angle of attack being reached. The movement of this blade activates a micro switch which in turn activates a light and/or horn in the cockpit. These devices are quite handy for the pilot who is unaware of the primary indicator of the stall, provided electrical power is available; which it may not be during the latter stages of a real forced landing.

What can we expect to happen 'post stall' if we do not recover immediately? Well as previously stated, the aeroplane loses a significant amount of lift and gains a significant amount of drag, and since it is lift that is keeping the aeroplane up there, or the excess of lift that is enabling it to manoeuvre, we will stop manoeuvring and/or descend quite rapidly. For instance, if we are turning, the turn will stop, if we are flying level, the 'levelness' will stop, and if we are looping, the loop will stop. Now most pilots who stall the wing in a loop do so in the second half of the loop where gravity can cause the illusion that the aeroplane is continuing to loop. Indeed it may continue 'looping' to a near vertical dive where, if it is still being held in a stall, the pitching will definitely stop! Obviously, in all of these examples, this 'departure' from the intended flight path cannot go on for too long, especially if the ground happens to be nearby. However, 'popping' the stick forward to the best L/D ratio angle of attack position will instantly solve the problem.

If you fly an aeroplane with a conventional configuration, (low wing and mid tailplane), there is an interesting exercise you can fly. Remember I mentioned in the lesson on 'Stability and Control' the effect of the downwash over the tail? I said that it can cause the tailplane to have a negative angle of attack even though its incidence is zero? Well at the point of stall lock the stick position and observe what happens. The downwash from the top of the wing is reduced so the mean downwash from top and bottom is also reduced, thereby reducing the negative angle of attack of the tailplane, and reducing its counter moment. The pitching moment of the wing now dominates, and pitches the wing to a reduced angle of attack which automatically un-stalls the wing and re-establishes the downwash. If we don't move the stick, the re-established downwash over the tail drives it down again, thereby increasing the wing angle of attack again, to the point where it stalls again! (The force on the stick will vary during this cycle of activity so hold onto that stick position.) The end result of this exercise is that by holding the stick precisely at the stall angle of attack position the aeroplane will rock in and out of the stall all by itself. This is a good demonstration of the effect of downwash over the tail and the angle of attack control technique.

When we look at wings from above (planform) it is obvious that they come in all shapes and sizes. These various shapes are attempts by the designers to achieve the best compromise between the competing variables of aerodynamic efficiency, structural strength, cost, ease of manufacture and aircraft handling. Long wings with small chord lengths (high aspect ratio) are very efficient but not very strong, whilst short stubby wings (low aspect ratio) can be made very strong but are not so efficient. Elliptical wings have good handling characteristics but are difficult to manufacture and highly tapered wings are both easy to make and are reasonably efficient, but have some ‘dodgy’ handling characteristics near the critical angle of attack.

Highly tapered wings are prone to what is called ‘tip stalling’, that is, they are prone, when at high angle of attack, to have the outer region of the wing toward the tip, stall at a lesser angle than the inboard region, thus causing a loss of lateral control and possibly inducing a spin. The wings of most modern aeroplanes are only slightly tapered, and have the whole wing twisted slightly such that the angle of incidence at the tip is a couple of degrees less than at the root. This arrangement retains reasonable efficiency and eliminates the tendency to tip stall. This twisting is called ‘washout’ and is very common on light touring aeroplanes giving them quite benign stalling characteristics. Most good training aeroplanes don’t have this feature so that the student pilot can learn about lateral control at the stall, and spinning. Unfortunately most flying schools use touring aeroplanes as trainers, thereby denying the student the opportunity of receiving thorough training in this most important aspect of flying.

By now I can hear many pilots howling, “but what about the stall speed, you haven’t mentioned the stall speed yet!?” Okay, what about ‘stall speed’? Stall speed is largely irrelevant; but since so many flying instructors and test officers dwell upon it, let’s discuss it for a while. Let me start by saying that an aeroplane can be stalled at any speed and in any attitude, or not stalled at any speed or attitude! It all depends on where you put the stick.

In order for an aeroplane to maintain straight and level flight whilst slowing down, the angle of attack must be progressively increased. Eventually it will slow to a speed where the angle of attack is critical. This is the published ‘Stall Speed’ (**Vs**). Now straight and level flight is only one of an infinite number of possible flight paths the aeroplane could be flying, so **‘Vs’** is unique. The stall speed will also depend upon whether the wing has flaps extended or slats deployed, and what the aircraft’s weight is and how much power is applied. So the definition of **‘Vs’** is further refined as the speed an aircraft with clean wings (literally, and with no lift augmentation) and at maximum weight, with idle power set, will reach the critical angle of attack whilst maintaining straight and level flight. Pretty stringent definition huh? Vary any of these criteria and the speed at the stall changes.

Not having lift augmentation devices extended is pretty clear, but what about weight? How does that affect the straight and level stall speed? Imagine two identical aeroplanes flying abeam each other in formation, one is light and the other is at its maximum all up weight. The heavier aeroplane will have to generate more lift to keep it in level flight, and since it is flying at the same speed as its lighter companion, it will have to be flying at a greater angle of attack. Now as the formation starts to slow down, but maintain straight and level flight, the angle of attack of both aircraft will have to increase; but the heavy aircraft has a few degrees 'head start' on its way to the critical angle, and it arrives there at **'Vs'**. The lighter aircraft can slow a little more before it too reaches critical angle of attack, so its 'stall speed' is a little slower than **'Vs'**.

As a general rule the greater the weight the greater the stall speed (for a particular aeroplane). There is a very simple formula which can be used for calculating the stall speed at various loads, if we express the load as a factor of the maximum all up weight. That is, if the additional load doubles the total weight of the aeroplane its load factor is 2, and so on. Here is the formula:

New stall speed = Vs x √Load Factor (That is, the square root of the load factor)

Or: **Vs (New) = Vs√Load Factor.**

Let's look at an extreme example to illustrate. Let's assume that, somehow, the aeroplane suddenly weighs 4 times its normal maximum weight and that it's **Vs** is 55kts.

Then: **Vs(new) = 55√4**
= 55x2
= 110kts

At this stage you are probably wondering how an aeroplane can weigh 4 times its maximum weight, because in a light aeroplane the weight changes possible are only a small percentage of its total weight. Full fuel or ¼ fuel, and one, two or three passengers is about the normal weight range, right? So the stall speed variation is not going to be great, maybe 4 or 5 knots (and most airspeed indicators only have an accuracy of +/- 2 knots anyway!) But when we manoeuvre the aeroplane, the acceleration causes the apparent weight to increase dramatically, and its effect on the stall speed is significant. In the lesson on 'Manoeuvring' we saw that in a 60º banked turn the aircraft is subjected to 2 'G' which is also the same as saying the load factor is 2. So an aeroplane turning with 60º of bank will behave as if it is twice as heavy and have a **'Vsm'** (the '**m**' stands for manoeuvre) 40% faster.

Vsm = Vs√G
= 55√2
= 55 x 1.4
= 77kts

In a 30º banked turn the aeroplane is subjected to 1.2G, and in a 45º banked turn 1.4G; so if we insert these load factors into the formula we get the following stall speeds:

30° bank, 60kts (10% increase)
45° bank, 66kts (20% increase)
60° bank, 77kts (40% increase)

Or, if you want to avoid the mathematics, just remember 10%, 20%, 40% increase in stall speed for 30°, 45°, and 60° bank respectively, whatever aeroplane you are flying, be it a Cessna or a Jumbo Jet! Oh yes, and in a loop we usually 'pull' about 4G to start the manoeuvre, so at that instant our stall speed has just doubled!

Now with these numbers in your head you can impress your girlfriend at the hangar party or your test officer during your next flight review, but I cannot think of any other use for them.

Imagine that you have applied a small amount of power but not quite enough to sustain your speed. As the aeroplane slows it moves to the 'back side' of the drag curve so the drag increases and it slows some more until it approaches critical angle of attack. The nose is now pointing some 15 degrees above the horizon and so is the thrust line of the engine. There is now a small vertical component of thrust which offsets a small percentage of the aircraft's weight. The wings 'think' the aeroplane is slightly lighter so the stall speed will be slightly slower. So how do we calculate the stall speed now? Who knows?

I illustrated an extreme example of this in the lesson on Climbing wherein I discussed what would happen if an excessive nose high attitude was held after the kinetic energy of a 'zoom' had dissipated. Here is that diagram again (Figure Three).

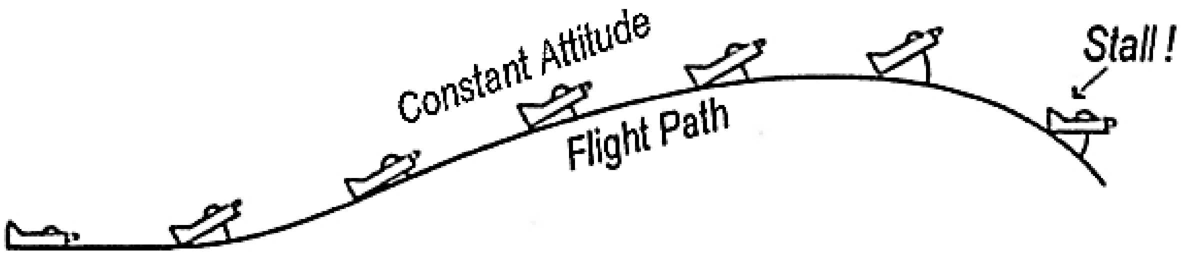


Figure Three – Stalling after a 'Zoom' climb

What I didn't mention in that lesson was that in order to hold the constant attitude as the flight path curved over the top, the stick would have to be moving steadily back, warning the aviator of the impending stall.

Now imagine we are in our aeroplane with a **Vs** of 55kts, doing a descending turn from 'base' to 'finals' with 35° of bank and 1450 RPM power set, and 10 degrees of flap extended at 68kts. We have half full fuel tanks and our wife on board (who won't disclose her weight). What is your stall speed now!? Is your current airspeed a safe margin above the stall!?

Think quickly! Weight, bank, attitude, flap, power, the square root of something, groan! Gasp! Good luck!

But wait! The stick is forward of the critical angle of attack position. So, we're OK.....Phew!

The stall recognition and recovery techniques taught at most flying schools, and which are based upon hopelessly inadequate flying training syllabuses, do not come close to equipping a pilot with the correct knowledge and skills to cope with an inadvertent stall in the forgoing situation. The standard stall recognition being taught states that a stall is accompanied by a low airspeed, a high nose attitude and 'sloppy' controls, and finally at the stall, the nose drops. Then the recovery involves shoving the stick forward to get the nose below the horizon to increase airspeed before easing out of the ensuing dive many hundreds of feet lower.

Obviously the standard teaching is focused on only low speed, straight and level situations and does not 'cater' for more general (and common) situations. So what are the general symptoms of an approaching stall? I have already detailed them but let's just put them in a 'nut shell' here:

1. Stick position moving toward the stall stick position.
2. Increasing control and airframe buffet.
3. Maybe an electric warning horn.
4. Finally, with the stick at (or beyond) the stall position, the aircraft departs from the desired flight path.

Where the nose is pointing and what the airspeed is, is irrelevant!

And the recovery?

1. Move the stick to the best L/D A/A position.
2. Apply full power.
3. Manoeuvre to avoid obstacles (like the ground!) without moving the stick back to the stall point again.

It's that simple!

Sometimes at or near the critical angle of attack the aeroplane encounters an asymmetric stall, that is, only one wing stalls! This could be caused by the 'tip stalling' characteristics of a highly tapered wing planform, or air turbulence, or rough handling by the pilot. Turbulence and rough handling may introduce a rolling motion which can cause the relative airflow to be slightly different for each wing. At the critical angle of attack this can produce a sharp 'wing drop'.

Whatever the cause, once the 'wing drop' has occurred, and the A/A of the down going wing exceeds the critical angle; it's A/A will continue to increase because all of those things that we learned about lateral stability are reversed. That is, the increased A/A of the down going wing no longer increases lift to correct the situation, but loses more lift and takes the wing deeper into the stall, causing it to lose even more lift and gain a whole lot more drag. Meanwhile the up going wing 'backs off' from the stall and retains its lift. So a significant lift and drag asymmetry is created (see Figure Four) wherein the roll continues and the drag imbalance produces a rapid yawing motion. This whole process is called 'auto rotation' and, if unchecked, could result in a spin! (This process and how it degenerates into a spin will be covered in more detail in the lesson on spinning.)

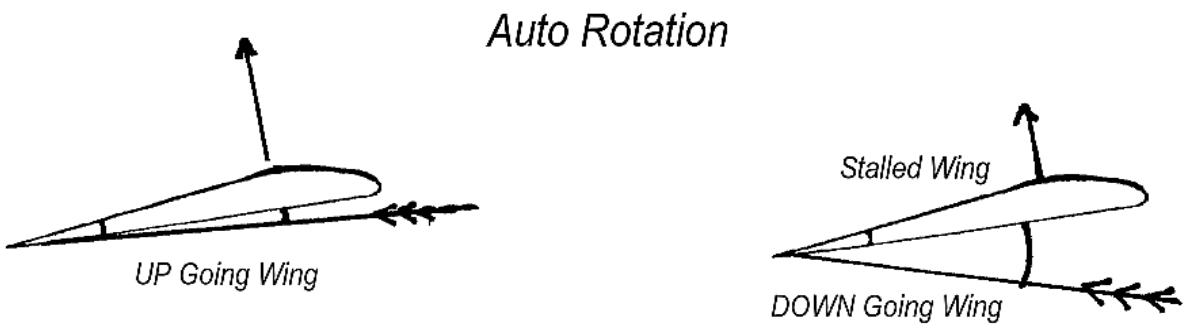


Figure Four – Auto Rotation

Stopping the auto rotation at the 'incipient' stage is quite simple, but initially the process is, unfortunately, not intuitive. An inexperienced or poorly trained pilot's initial instinct, upon encountering a 'wing drop' at the stall, is to move the ailerons to 'pick it up'. This action causes the aileron on the down going wing to increase the A/A of that wing further, thereby exacerbating the situation! The correct action is to simply stop the yaw with opposite rudder whilst simultaneously reducing the A/A to best L/D. Once the wing is un-stalled the ailerons will now work in the correct sense and can be used to 'pick up' the dropped wing.

So, if at the point of stall the aeroplane departs from the desired flight path by both pitching and rolling (and yawing), we have an asymmetric stall 'on our hands'. Returning to the 'stall recovery in a nut shell' steps, we now have to add a few extra actions:

1. Move the stick forward to the best L/D A/A position whilst simultaneously applying rudder to stop further yaw.

2. Apply full power whilst simultaneously rolling the wings back to their initial attitude with aileron and centering the ball with rudder.

3. Manoeuvre to avoid obstacles (like the ground!) without moving the stick back to the stall point again.

Most pilots that I have met are, to some degree, afraid of the stall! It has become a big ‘boogie man’ to them and has robbed them of much of the fun that is to be had in the air. A thorough understanding of the stall, and proper training in how to detect its approach, and control the recovery from it, banishes this boogie man forever. Now I am not saying that one should ever become cavalier about the stall, particularly near the ground, but a healthy respect born out of knowledge and experience with it, will ensure a pilot added longevity and added enjoyment from his or her flying.

In this lesson I have examined ‘Stalling’ from an aviator’s point of view. At Annex A I have given an aerodynamicist’s view of ‘Stalling’.

List of Annexes to the lesson on: Stalling.

Annex A. Aerodynamics of Stalling.

Annex A.

Aerodynamics of Stalling

In the main text of this lesson it was stated that if the critical angle of attack of the wing is exceeded, the Coanda effect ceases to operate, and the airflow separates from the top surface of the wing. Depending upon the type of wing section (particularly the camber) and the aspect ratio of the wing planform this may not be the sharp separation implied by that opening statement, so I should modify the statement and say that as the critical angle of attack is approached the Coanda effect becomes progressively less and less. This means that separation can start to occur over a range of about 2º- 4º of A/A prior to the critical A/A being reached. At the beginning the airflow separation is toward the trailing edge (back edge) of the wing and this separation point moves progressively forward as the A/A increases further.

The following diagram (Figure One) is a repeat of the NACA 23015 'wing section characteristics' chart from Annex A to the lesson on Lift. You can see that the lift graph starts to curve down beyond about 12º A/A whilst the final 'Stall' occurs just beyond 16º. This downward trending curve represents the reduced rate of increase of lift with A/A, as the airflow separation point moves forward from the trailing edge.

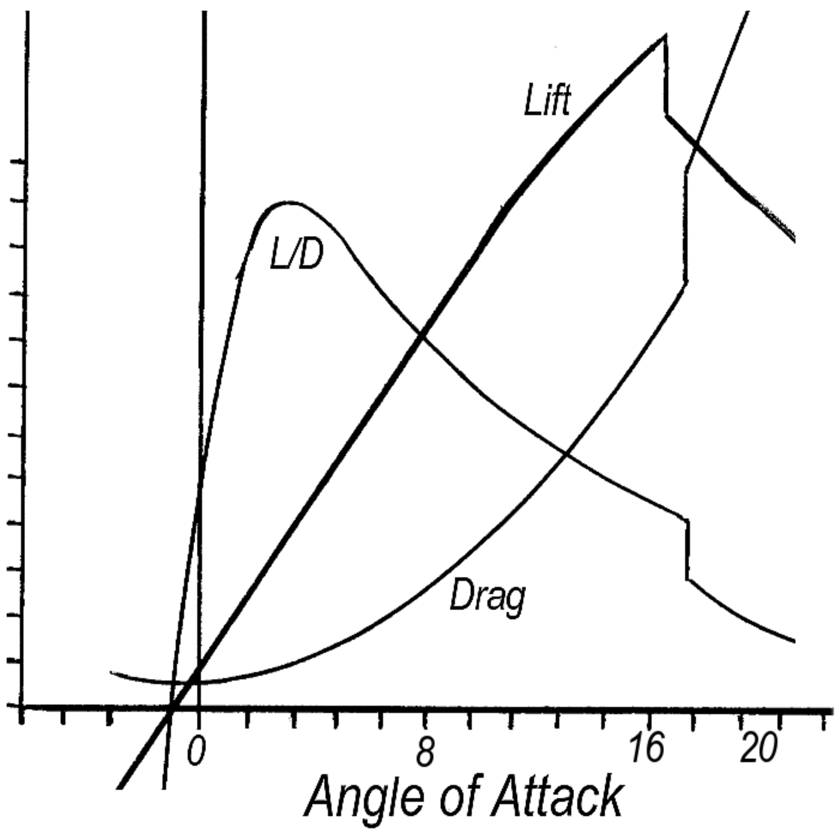


Figure One – NACA 23015 Wing section characteristics chart

Figure Two (following) is a series of pictures of the airflow around a wing section at different A/A, in which you can see this progressive airflow separation. The left hand column shows airflow around the wing section at angles of attack up to 10º. Note the smooth passage of the air. The right hand column shows the airflow as the A/A approaches the critical angle, through to a 'fully stalled', then 'deep stalled' wing.

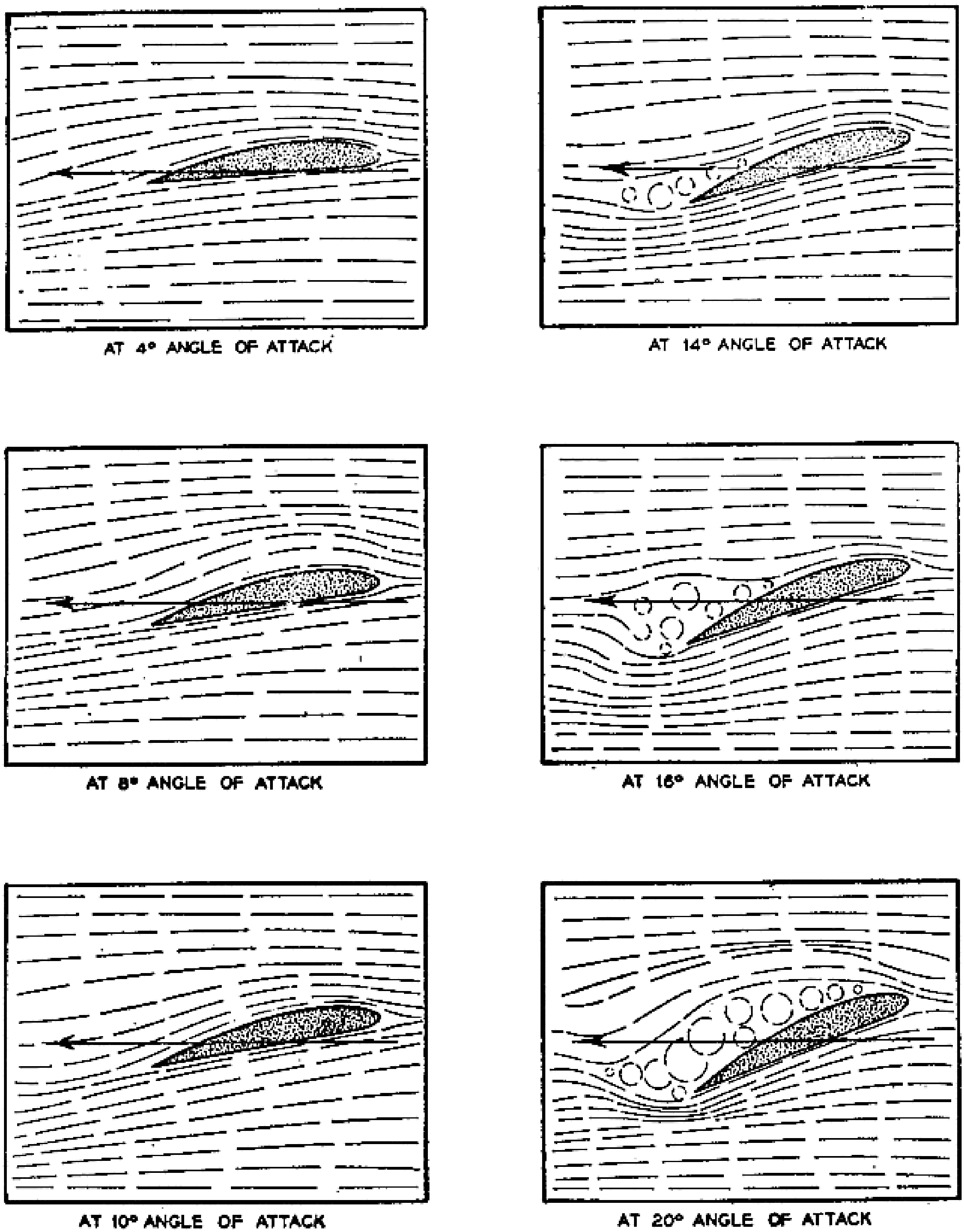


Figure Two – Progressive airflow separation with increasing A/A

During an asymmetric stall, only one wing is stalled due to a difference in the A/A of each wing as the critical angle was approached. The following (Figure Three) is a 'blow up' of the top end of the Lift and Drag graphs showing the differences in lift and drag on each wing caused by this situation. These differences cause the aircraft to both roll and yaw further, and this motion is called 'Auto Rotation'.

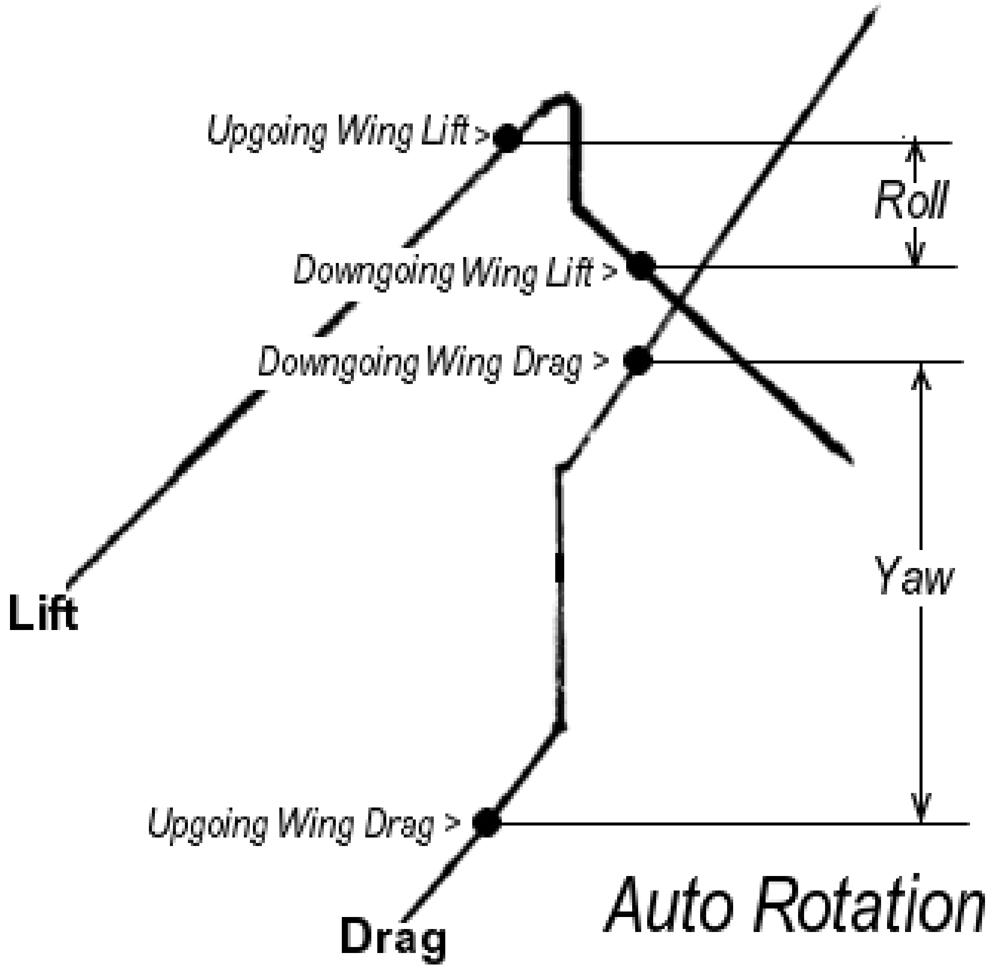


Figure Three – Asymmetric lift and drag causing Auto Rotation

Note the large difference in drag created. The yaw caused by this asymmetric drag can cause the Auto Rotation to develop into an incipient spin. (See the lesson on Spinning.)

Lesson Twelve

SIDE SLIPPING

The description of how an aeroplane turns contained in the lesson on Manoeuvring forms the basis of this lesson. If you have forgotten it, go back and review it before continuing.

Side slipping occurs when the sideways force we create by banking an aeroplane is prevented from becoming a centripetal force. When we do this the aeroplane simply moves sideways through the air, like the car in the (Manoeuvring, Figure Three) example moved sideways across the road when it encountered the cross wind.

Of what use is it? Well it has two primary uses; the first is, as I have just said, to move sideways through the air, which is very handy when the air is moving sideways across your intended landing path. That is, when landing in what is called a ‘crosswind’. You will recall I spent a whole annex at the end of the lesson on Manoeuvring, discounting the effect of ‘wind’ on the aeroplane’s performance in the air mass, but when landing, we are trying to come out of the air and become a land vehicle again, so the situation is a little different when making this transition. The second use is to create a lot of zero lift drag, to either steepen a glide approach, or ‘wash off’ excess speed before touchdown (or both).

There is another use for sideslip, and that is to enable the pilots of long nose ‘tail draggers’ to see where they are going on final approach to land, by ‘swinging’ the nose out of the way. In this case extra power has to be used to offset the extra drag created when the approach angle and speed are already okay.

Let’s now look, in a bit more detail, at how to sideslip an aeroplane.

As explained in the lesson on Manoeuvring, the sideways force created by the inclined lift vector, when the aeroplane is banked, starts a sideslip, but the directional stability immediately starts to yaw the nose into the new relative airflow, converting the sideways force into a centripetal force, and the aeroplane turns. We use the rudder to augment the directional stability as required to ‘balance’ the forces; but what if we did the opposite? That is, what if we applied rudder opposite to the direction we are banked such that we cancel out the effect of the directional stability? We would prevent the aeroplane from turning, and it would just move sideways through the air. That is a sideslip.

The more we bank an aeroplane the greater is the sideways force and sideways movement, and the more positive is the tendency to yaw into the new relative airflow, so the more opposite rudder we have to apply to stop this tendency. Most light aeroplanes have reasonably positive directional stability and a relatively small rudder, so the amount of sideslip that can be generated is limited by the rudder 'authority'. This means that the angle of bank has to be limited accordingly, otherwise excess bank 'overpowers' the opposing rudder and the aeroplane does a 'side slipping turn'. About 20º of bank is the limit of most non-aerobatic aeroplanes, but most aerobatic aeroplanes have more rudder authority and less directional stability, so more pronounced sideslips can be achieved.

The following diagram (Figure One) shows the forces and their effect in a sideslip. The difference between where the aeroplane is pointing and where it is going (through the air mass), in the horizontal plane, is the sideslip angle. Also, this sideways movement through the air generates a lot of zero lift drag because aeroplanes are not so 'streamlined' when going sideways!

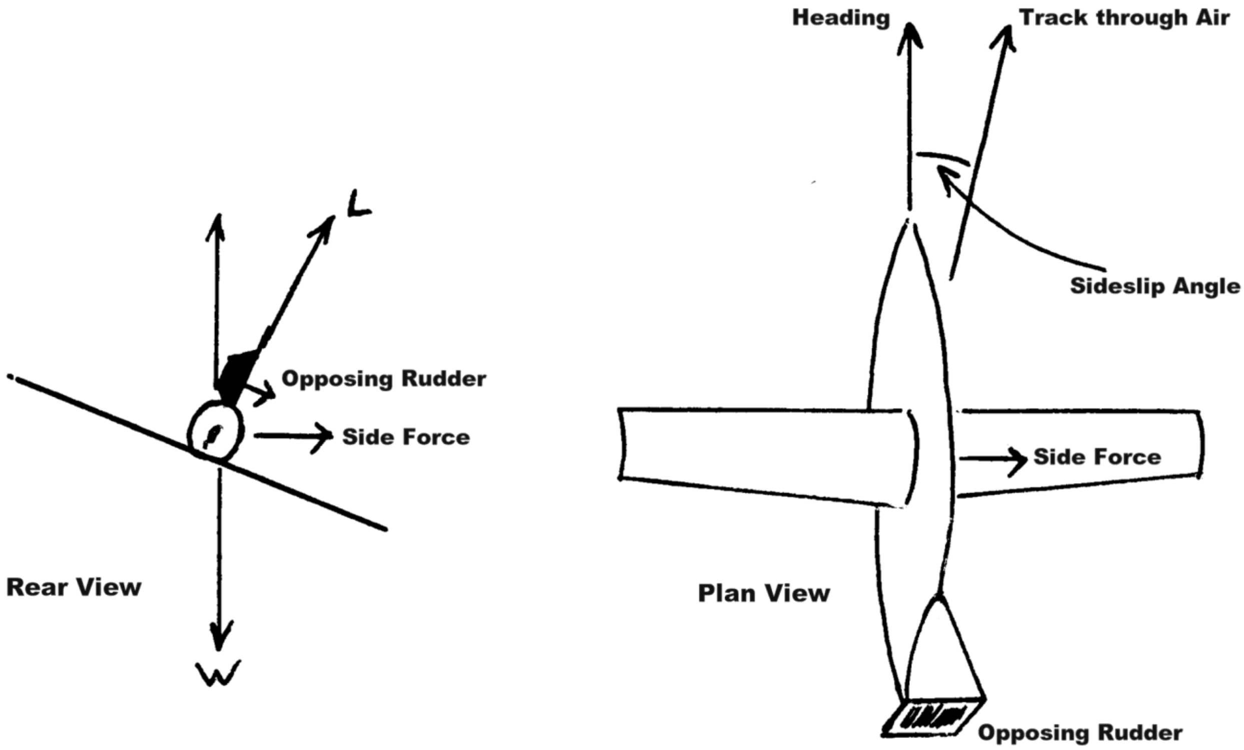


Figure One – Forces in a Side Slip

Now an aeroplane approaching to land in a 'crosswind' will have a drift angle over the ground which is the resultant of the aircraft's airspeed and the wind speed, so if the aviator can generate a sideslip angle equal to, but opposite to the drift angle, the effect of the crosswind during the landing can be eliminated. The following diagram (Figure Two) shows this side slipping approach technique. You can see that the sideslip angle cancels the drift angle, and the aeroplane continues to 'head' and 'track' down the runway centerline.

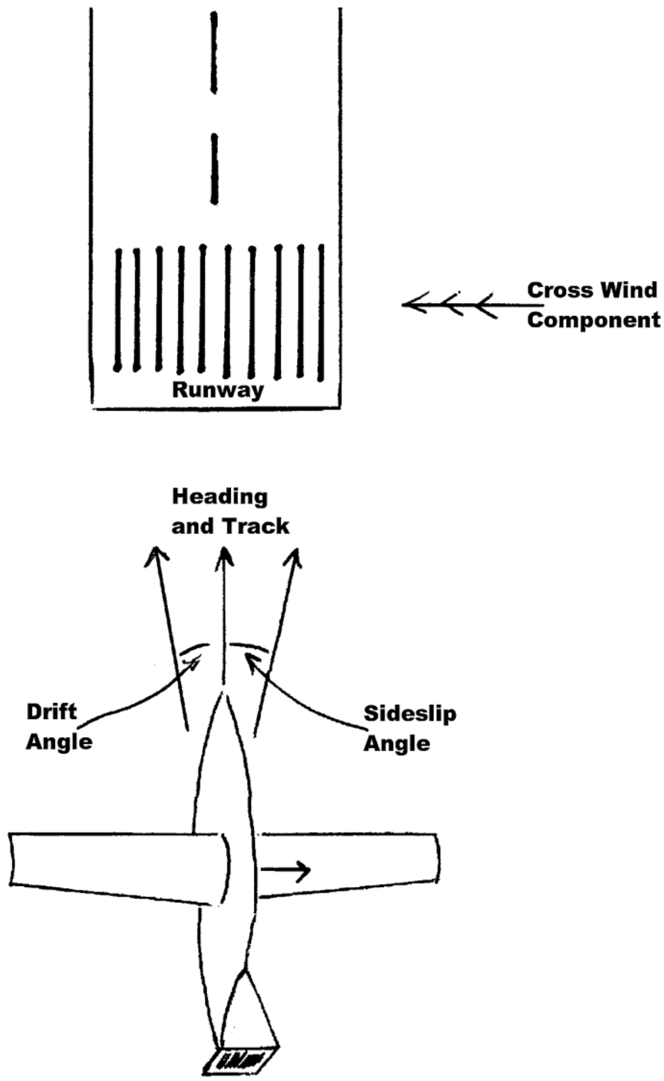


Figure Two – Side slipping to counter a 'Crosswind'

A sideslip can be set up at any point on the final approach, but to avoid 'knee trembles' from holding on rudder for too long, most aviators will set up the sideslip just prior to arriving at the landing threshold, having 'crabbed' down the final approach to that point. ('Crabbing', in this context, is simply adjusting the aircraft's heading so that it tracks down the runway centerline.)

Now many flying instructors try to teach their students to set up the sideslip during the 'flare' and 'hold-off' phase of the landing. This is a heck of a co-ordination exercise for a new student and often results in a most 'spectacular' arrival! This of course does nothing for the aeroplane's structure or the student's confidence. Why do they delay setting it up till so late in the approach? Well many instructors believe that a sideslip is a precursor to a spin (!) because the speed is low and the controls are in a similar 'out of balance' position. This is a misconception brought about by their lack of understanding of spinning. Let me put it simply; you can no more spin off a properly 'set up' side slipping approach than you can off a properly set up 'straight' approach. There is a whole lesson on spinning to come where this will be explained in more detail.

So how do we set up a sideslip on, say, mid finals? Assuming that we are at the correct approach angle and are tracking the extended runway centre line with a ‘crab angle’, we apply a moderate amount of rudder to yaw the aeroplane into line with the runway centre line (removing the crab angle) and the instant it gets there, bank into the crosswind sufficient to stop further yaw **without releasing the rudder**. If you subsequently note that the aeroplane is drifting ‘downwind’ of the extended centre line, increase the bank angle (to increase the sideways component of the lift) and apply a little more rudder to keep the aeroplane on runway heading. The aeroplane will now move back to the extended centre line and when it gets there, ease off the sideslip (bank and rudder) a little to hold it there. Obviously if you have used too much sideslip at the initial set up the aeroplane will move into the crosswind so the reverse procedure should be adopted. Of course there will also be a drag increase when the sideslip is established which, if you are making a constant speed approach, will necessitate a power increase to maintain airspeed; or will assist the speed reduction if you are making a variable speed approach. (I define these two different types of approach techniques in Book Two.)

As the crosswind effect can vary as you proceed down the approach so the sideslip will have to be varied accordingly, all of the way down final approach and through the flare and hold off till the aeroplane touches down on the ‘into wind’ wheel. That’s right; we land whilst still side slipping and we land on one wheel. We then hold the sideslip until the aeroplane settles onto its other wheels as it loses speed, then we move the aileron control fully ‘into’ the crosswind to compensate for the extra lift on that wing due to its dihedral angle. Finally, keep straight with rudder and nose wheel steering and go easy on the brakes.

I have often been asked “why not just land with the aeroplane still ‘crabbing’?” We could, but this would put unreasonable side loads on the undercarriage and tyres, which at best would increase the wear and tear on the aeroplane and at worst, damage it. So it is best to align the wheels with the landing direction at touch down.

To align the wheels with the landing direction, Jumbo jet pilots try to 'kick' it straight just before touchdown. They cannot sideslip as they will 'wipe off' the out board, ‘into wind’ engine on landing each time, which would cause the price of a ticket to increase somewhat. The 'kick it straight just before touchdown’ technique works on any aeroplane; the problem is determining when the wheels are going to touch. If you kick too soon the aeroplane will start drifting off the runway during the float. This is why you then have to "lower the wing into the crosswind" (sideslip), hence the co-ordination problem for student pilots. When I flew the Sabre, the 'kick it straight’ technique was all that I used because its 135kt touchdown speed made any drift angle, even in strong crosswinds, minimal, and the Sabre didn’t float.

A few of the biggest jets have ‘adjustable’ main gear which is automatically aligned with the runway via a Doppler tracking system, so they just crab down final approach and land without ‘kicking it straight’ or side slipping! Many years ago I had the opportunity to fly an Auster J5 with a ‘crosswind undercarriage’, which was supposed to enable the pilot to do the same thing (without Doppler). The main wheels were able to swivel up to about 15º either side of straight ahead independently of each other. It had small hydraulic dampers to smooth out their motion. It worked well in a crosswind landing but caused chaos when doing everything else on the ground!

The maximum sideslip angle which can be generated will determine the maximum drift angle which can be accepted, which means the maximum crosswind component in which the aeroplane can be safely landed using the normal threshold speed. When the crosswind component is greater than about 2/3 of the published maximum, it may be prudent to reduce the drift angle by increasing the threshold speed a little, say 10%, which will assist the aviator by requiring a corresponding reduction in the sideslip angle, thereby making the aeroplane more ‘manageable’. This, of course, will mean that we will cross the landing threshold faster, but we don’t want to ‘float’ as the drift angle may become unmanageable as the aeroplane slows during the ‘hold off’ phase, so we should use less flap to ensure a quick clean touch down at the higher speed. Remember, if we have increased speed by 10% the lift has increased by 20%, so we don’t need the lift augmentation provided by lowering all the flap. Reducing the flap setting to ‘the first notch’ would be more appropriate in this situation. Indeed, many aeroplanes handle better in a ‘flapless’ configuration at these speeds in a cross wind.

Now many flying instructors will say that you should always land as slow as possible to avoid overrunning the runway; however, most crosswinds are only a component of the total wind, the other components is headwind. So if the strength of the crosswind component demands an increased threshold speed it is probable that the strength of the headwind component will correspondingly keep the ground speed reasonable for the runway length available. If the wind is all crosswind and strong, and the runway is so short as to require the slowest touchdown speed, then it may be prudent not to land there that day. Come back when the wind has abated.

I once landed my aeroplane at an airfield where the wind strength was a gusty 35kts with 20kts of crosswind, which was the published maximum for the aeroplane. By increasing my threshold speed by 15% and landing flapless I had no difficulty in overcoming both the crosswind and the turbulence associated with such a strong gusty wind. Shortly after I landed I watched another aeroplane making an approach to the same runway with full flap extended and quite slow. The pilot was obviously having difficulty controlling the situation as he ‘aborted’ two approaches, but on the third attempt he persevered and finally touched down, but very heavily, and the undercarriage collapsed! Later I spoke to him and asked why he had used that landing configuration in such conditions. He said that his instructor had taught him to always use ‘land flap’ for landing!! The runway was 3000ft long; his aeroplane came to rest less than 500 ft down the runway from the landing threshold. He had a very nice aeroplane up until then.

Without the drag of full flap how does the aviator control the approach angle and speed on final? Remember that I said that there were two uses of sideslip, and that the second was to increase zero lift drag? As the crosswind increases and the flap setting reduces, the sideslip angle must increase and so must the drag. So speed control is not a problem; indeed in light crosswinds where full flap can still be used, it may be necessary to increase power a little to overcome the increased drag resulting from the sideslip.

During a glide approach to a practice or real forced landing when there is no crosswind, side slipping can be used flexibly to control the drag and hence the speed and/or angle of approach as required. Sideslip can be applied and removed and applied again as many times as required to control the approach without the detrimental side effects of raising flap (loss of lift). The following diagram (Figure Three) shows an aircraft tracking the runway centerline (without a crosswind), and using sideslip to generate extra drag.

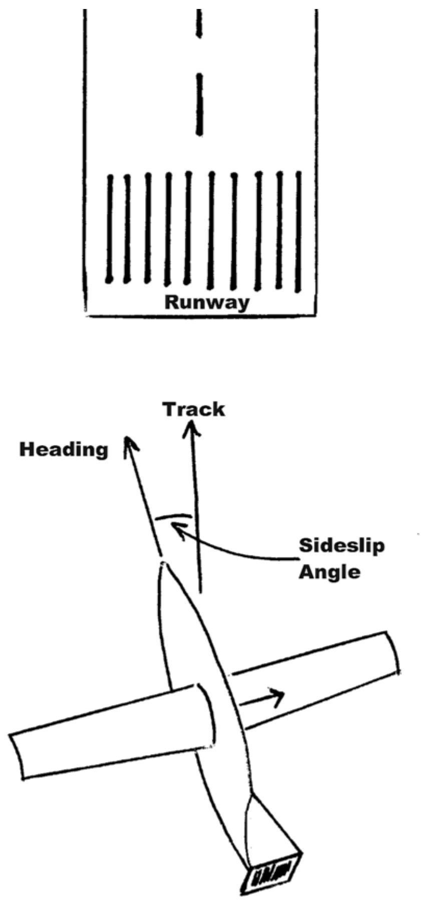


Figure Three – Side Slipping to control Drag

Some flight instructors call this a ‘forward slip’ because the aeroplane continues to track along the original flight path through the air rather than move sideways across it, but I think this term causes unnecessary confusion.

The technique used to apply sideslip when there is no crosswind is similar to that previously described except that we start with the nose pointing down the ‘runway’ (no crab angle). So first yaw the nose offline about 10º with positive rudder application, then roll on bank to stop further yaw without releasing the rudder. This establishes the sideslip. From this point on the amount of rudder used will determine the amount of sideslip and drag (like a foot brake) and small bank adjustments will control the track.

During the approach the amount of sideslip and therefore the amount of drag can be varied as required to adjust the angle of approach, or if you are happy with the angle, it can be used to control the speed of approach. It is similar to rolling downhill in a car and varying the amount of brake used to regulate the car’s speed. At any time during the approach, but certainly just before touchdown, the sideslip can be removed by simply taking your foot off the rudder pedal and, once the directional stability has caused the nose to yaw back in line with the runway, rolling the wings ‘level’.

At the beginning of this lesson I mentioned that it was possible to ‘overpower’ the effect of the rudder by increasing the bank angle beyond that required for a maximum straight sideslip. This will result in a ‘side slipping turn’. Side slipping turns can be useful when a lot of altitude has to be lost (without the normal associated speed increase) during a forced landing situation, but I must emphasize that you must know the difference between side slipping turn and a skidding turn. Side slipping turns involve increasing bank in order to turn (just like a normal turn) and are safe and useful, whilst skidding turns involve reducing bank and letting the applied rudder skid the nose around, which can be lethal! (The reasons for this will be covered in detail during the lesson on spinning.) I strongly recommend that the use of side slipping turns and the dangers of skidding turns, be demonstrated by a competent flying instructor.

Side slipping is a vital skill in an aviator’s repertoire, either to land in a crosswind, or ensure a successful forced landing. Unfortunately a large percentage of student pilots are no longer taught this vital skill. Usually this is because of their instructor’s misconceptions about spinning and often because the type of aeroplane used was never designed for training, so its structure may be too weak to handle the repeated side loads on the wings and flaps and rudder encountered in sideslip training. Flight training is best done in aeroplanes strong enough to handle the rigors of the task and should only be done by instructors who know how to fly.

Does this mean that, having learned to fly and use sideslip properly, you can’t use it in non-training types of aeroplanes if required? Absolutely not! It simply means that in the course of ensuring that you and your family walk away from the engine failure you have just experienced, you may overstress the flaps. So what! In an emergency situation the flaps are the least of your worries.

Lesson Thirteen

AIRCRAFT STUCTURAL LIMITS

One of the primary instruments in the cockpit of any aeroplane is the Air Speed Indicator (ASI) which, as the name suggests informs the aviator of the speed the aeroplane 'thinks' it is going through the air (IAS). The dial of the ASI usually has colour coding throughout the speed range of the indicator. It has a green arc which extends from **Vs** to some much higher figure where it suddenly becomes a yellow (caution) arc, which then continues on to a red radial line situated toward the top of the instruments range. Inside of these two coloured arcs is a further white arc which usually extends from a speed a little below **Vs** to a somewhat higher speed. These different coloured arcs and radial lines represent some of the aeroplane's structurally significant speeds and speed ranges.

An aeroplane in flight is continually being subjected to various air loads, vibrations, gusts and manoeuvre loads. Part of the job of the designer is to design it to be strong enough to withstand these loads over and over again for many thousands of flying hours without critical parts of the structure failing. Obviously there are limits to the maximum load that any structure can withstand and these limits are clearly laid down for an aeroplane in its 'Flight Manual'. Some of them are displayed on the face of the ASI by way of the coloured arcs. Unfortunately most pilots do not fully understand these limits, nor do they understand their part in using these ASI colour codes to protect the aeroplane's structure from being 'overstressed', that is, 'Bent'! In saying this I mean no criticism of these pilots or their instructors because the definitions and the meaning of many of these limits have, over the years, become quite confusing. This is my attempt to clarify them.

Aeroplane structures are subjected to many loads that the pilot has little direct control over, such as the stress that raising and lowering the undercarriage or flaps can have on the mechanism and the various levers, bearings and bell-cranks associated with this activity. Engine vibration puts continual stress on engine mounts and airframe in addition to the internal wear within the engine. Undercarriage and flap operating speed limits and engine power setting limits are clearly laid down in the aircrafts 'Flight Manual' and should be adhered to. The **white arc** on the ASI is either the flap or the undercarriage operating speed range and the engine tachometer has similar colour coding to inform the aviator of the recommended and limiting power settings for that particular engine. These colour codes are clearly defined in the aeroplane's 'Flight Manual', so I am not going to elaborate on them any more here.

I wish to address the subject of the flight loads that the pilot puts on the aeroplane whenever he or she maneuvers it or flies it into turbulent air, as this is where the pilot's influence on the long term structural integrity of the aeroplane is greatest. The parts of the aeroplane that are most critical under stress when the aeroplane is manoeuvring or experiencing loads due to turbulence are the wings and their attachment to the fuselage. It is the wings that generate the lift and centripetal force which causes the aeroplane to manoeuvre (accelerate), which in turn causes the apparent increase in the weight of the aeroplane via the centrifugal force. As we have discussed in a previous lesson, we express this acceleration in multiples of 'G'. It is the wings and the 'G loads' they are subjected to that I wish to focus on. First, let us consider the loads caused by the intentional maneuvers performed by the pilot. I will return to the gust loads caused by turbulent air later.

The following diagram (Figure One) is a 'head on' view of a conventional aeroplane in straight and level flight. By conventional, I mean one fuselage supported by a wing sticking out each side. (There have been many deviations from this convention over the years, but 99% of the aeroplanes flying today are, in this sense, 'conventional'.)

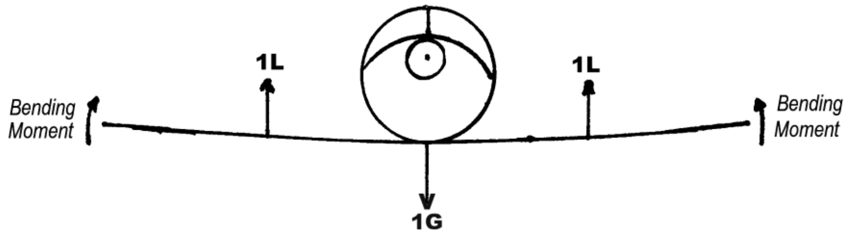


Figure One – Loads in Straight and Level Flight

The majority of the mass of a conventional aeroplane is contained within the fuselage and the 'lift', through each wing's aerodynamic centre, is outboard of the aeroplane's centre of gravity (The location of the aerodynamic centre was described in Annex C to the lesson on Stability and Control).You can see from the diagram that this means that the wings are subject to continual bending 'moments'. Now in the next diagram (Figure Two) I show the same aeroplane in a 60º bank turn, but with 'wings level' and the horizon banked for clarity. As we learned in the lesson on manoeuvring, a 60º bank turn requires twice the lifting force from the wings, and because of this, the fuselage (and everything in it) 'feels' twice as heavy (2G).

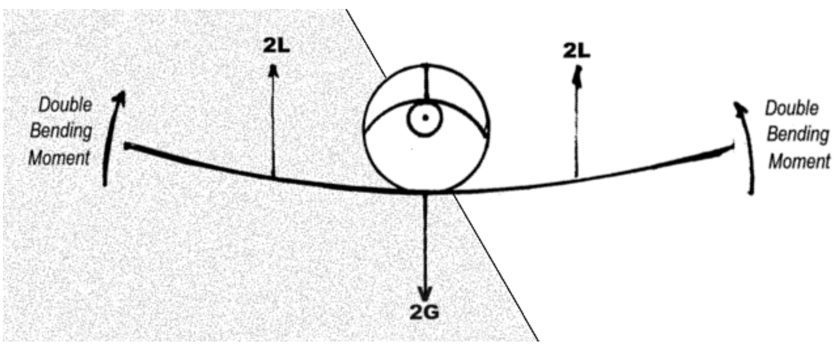


Figure Two – Loads in a 60º banked turn

It should be apparent that the bending moment on the wings is twice what it was in straight and level flight. (I have exaggerated the bending a little for emphasis in these diagrams.) Here is another at 4G, which is about the acceleration an aerobatic aeroplane would experience entering a loop (Figure Three).

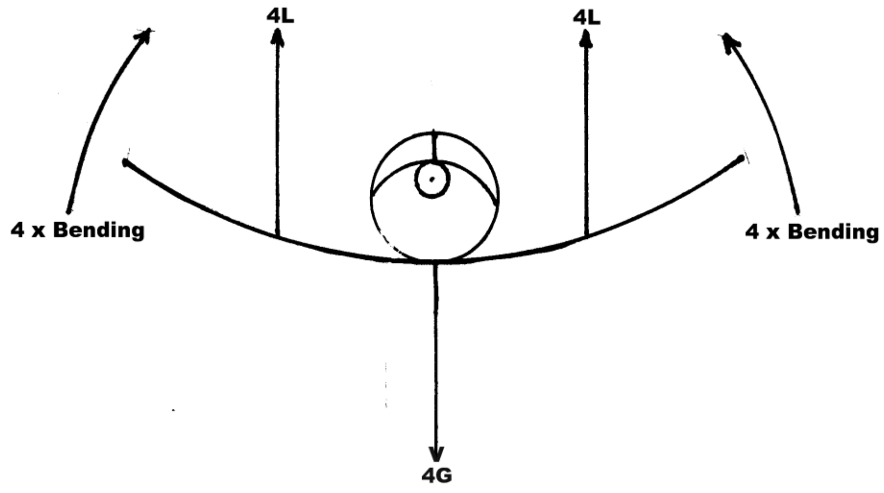


Figure Three – Loads in a 4G entry to a Loop

Since the aviator has immediate and direct control of the lift being developed by the wings, he/she also has immediate and direct control of the acceleration the aeroplane is subject to and consequently the bending moments applied to each wing. The aviator can vary the lift by varying either the aeroplanes airspeed or the angle of attack of the wings, or both. Remember, the simple expression for this is:

$$\mathbf{L \propto A/A \times V^2}$$

This means: lift varies directly with change of angle of attack and also varies with the 'square' of the change in airspeed. (This is a simplification of the standard formula for the calculation of lift, in that only those parts of the formula that the pilot has immediate control over are included. I refer you back to Annex C to the lesson on Lift.) So if we double the A/A we get double the lift, but if we double the airspeed we get **four** times the lift at the same A/A! (If you are a bit 'hazy' on this I again refer you back to the lesson on Lift.)

As I have detailed in previous lessons, the instant, equal and opposite reaction to this variable lift force is a centrifugal force, commonly (although incorrectly) expressed as a 'G force'. Designers and aviation regulatory authorities impose limits to the 'G' a particular aeroplane can be subjected to. They could equally express these limits as limits of allowable lift, because without 'lift' you can't get 'G'.

The amount of lift that can be developed by a particular wing when set at its maximum (critical) A/A will depend upon airspeed. Any attempt to get more lift at a particular airspeed by increasing the A/A further will cause the wing to stall and deliver less lift. So we can say that, in a way, the stall acts as a sort of 'safety valve' or 'safety net', which prevents too much lift and therefore too much 'G' being developed at a particular airspeed.

Remember the formula for calculating the stall speed at a particular 'G'? (From the lesson on Stalling.)

$$\mathbf{Vsm = Vs\sqrt{G}}$$

This means that the velocity of the stall in a manoeuvre (**Vsm**) equals the velocity of the stall at 1G (**Vs**), multiplied by the square root of the manoeuvring 'G', (remembering that **Vs** is the 1G stall speed at maximum 'all up' weight).

We can rearrange this formula to give us the maximum possible 'G' at any airspeed.

$$\mathbf{\sqrt{G} = Vsm \div Vs}$$

Therefore: $\mathbf{G = (Vsm \div Vs)^2}$

For example, if our aeroplane's **Vs** is 55kts and we are flying at 110kts (2Vs), we have the **potential** of 'pulling' 4G. Calculated as follows:

$$\mathbf{G = (110 \div 55)^2}$$
$$\mathbf{G = 2^2}$$
$$\mathbf{G = 4}$$

Now 4G is beyond the allowable limit of most aeroplanes, but those same aeroplanes are quite capable of flying at airspeeds greater than 2Vs. This means it is possible (if we increase the A/A to its maximum) to overstress them at cruising speed. What if we were to dive this same aeroplane to 165kts?

$$\mathbf{G = (165 \div 55)^2}$$
$$\mathbf{G = 3^2}$$
$$\mathbf{G = 9!!}$$

Now 9G is enough to do serious damage to most aeroplanes, but 165kts is only 3Vs and can easily be achieved by most aeroplanes!

Using this formula we can create a graph of the 'G' possible at the maximum angle of attack for every airspeed within the aircrafts airspeed range. Here it is at Figure Four.

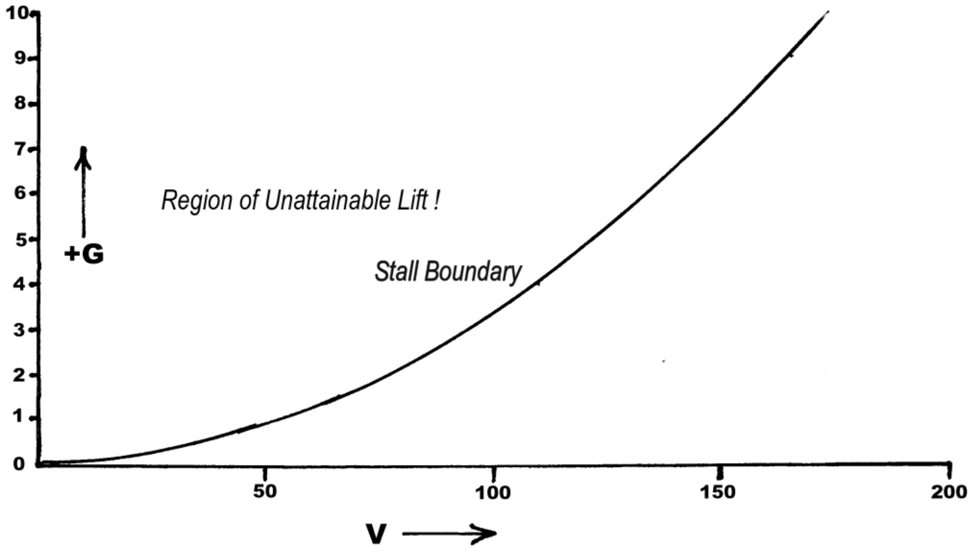


Figure Four – 'G' versus Airspeed at Maximum A/A

Note that the 'G' is increasing as the 'square' of the speed and since this line represents the 'G' which is possible at maximum (critical) angle of attack, it is not possible to 'pull' more 'G' at any particular airspeed because the wing will stall. We call this line the 'stall boundary'. So whilst we can vary the A/A and the lift in the normal way when operating below the stall boundary, we cannot increase lift or 'G', by increasing A/A when we are operating at the boundary. (The region of the chart beyond the stall boundary is often referred to as the 'Region of Unattainable Lift'.)

The designers of the aeroplane will declare a 'Design G limit' at maximum 'all up' weight, and since the aeroplane we are using in this example is an aerobatic aeroplane, its positive 'G' limit is 6. So we can add a further line to our graph showing this 6G limit (Figure Five).

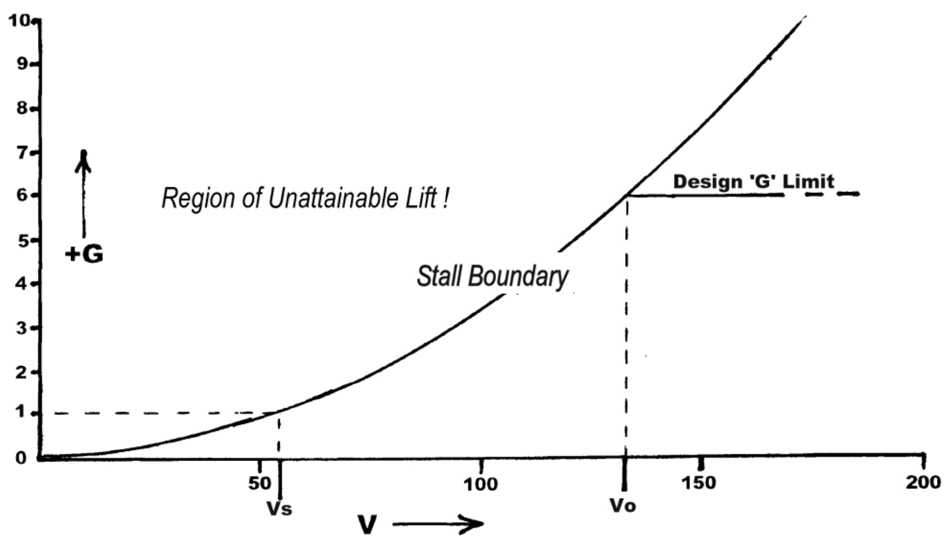


Figure Five – Design 'G' Limit and corresponding Airspeed

I have included **Vs** on this graph too, which you can see occurs at 1G. Also note that the 'Design 'G' Limit' line intersects the Stall Boundary at a particular airspeed which is given the symbol **Vo**, meaning the "**O**perating manoeuvring speed". To put it another way, **Vo** is the stall speed at the 'G' limit. **(Vo = Vsm @ 6G.)** Now, we could calculate **Vo** using the stall speed formula and inserting the limiting G into it as follows:

Vsm = Vs√G
Vo = Vs√G limit
Vo = 55√6
Vo = 55 x 2.45
Vo = 135kts

Or we could simply extract it from the graph. You can see that **Vo** on the graph is 135kts. This graph also shows us that at any speed below 135kts it is not possible to 'pull' 6G because the wing will stall and prevent it. (Here is the stall acting as a safety net.) But at speeds greater than 135kst it is possible, so the pilot has to exercise restraint in the way in which the aeroplane is maneuvered when flying faster than **Vo**.

Vo does not mean that the aeroplane cannot be maneuvered at greater speeds. It simply means that care should be exercised to ensure that the G limit is not exceeded, as the pilot is now 'working without a safety net'.

If this were a 'normal' category aeroplane, which is limited to only +3.8G, its **Vo** would be only 107kts, but the aeroplane would be capable of cruising much faster than this. Which is why all pilots, whether or not they fly aerobatic aeroplanes, **must** understand this **Vo / 'G'** Limit relationship. (Since **Vs** is the 1G stall speed at maximum all up weight, **Vo** must also be the G limit stall speed at Maximum all up weight. See annex B for further discussions on this aspect of **Vo**.)

In addition to calculating **Vo**, the designer also calculates the limit on how fast the aeroplane should be flown. He has many things to consider when determining this speed limit. One is simply the straight structural load on the airframe as a result of the drag caused by pushing it through the air at speed. Another is any control problems which may occur at speed, such as control flutter, and another, which is only applicable to fixed pitch propeller driven aeroplanes, is the speed at which the propeller will 'windmill' at 'red line' RPM with the throttle closed. This figure is given the symbol **Vd**, the 'design **d**ive speed', but you won't find it on the ASI because the regulators have introduced a 'safety buffer' by defining another speed equal to **.9Vd** which is given the symbol **Vne**, which stands for "**V**elocity **n**ever **e**xceed" and this figure is represented on the ASI by the **red radial line** near the top of its speed range. **Vne** can now be added to our graph as a vertical line extending from this speed (Figure Six).

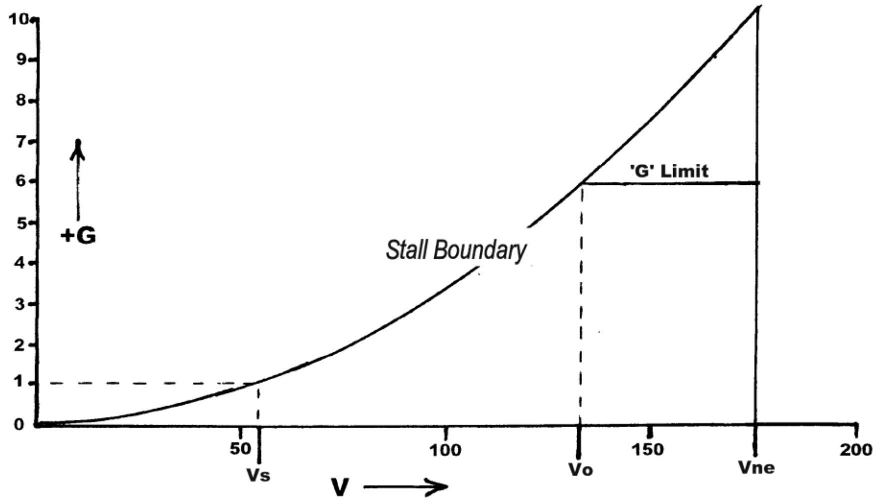


Figure Six – Velocity Never Exceed

The **Vne** in this example has been set at 175kts. You can see that there is an area of the graph at speeds between **Vo** and **Vne,** and above the 'G' limit line, where the pilot has the 'potential' to overstress the aeroplane. Indeed at **Vne** the potential is 10G!

So far we have been assuming that all the accelerations have been positive, that is, positive 'G', but in turbulence and certainly with aerobatic aeroplanes negative accelerations can also be experienced. Most aeroplanes are not designed to be as strong under negative accelerations, so whilst the negative 'G' side of the graph is similar to the positive 'G' side, the negative 'G' Limit and negative **Vo** will be different. Here is the complete graph incorporating both positive and negative 'G' limits for an aerobatic category aeroplane with a +6 and -3 'G' limit (Figure Seven).

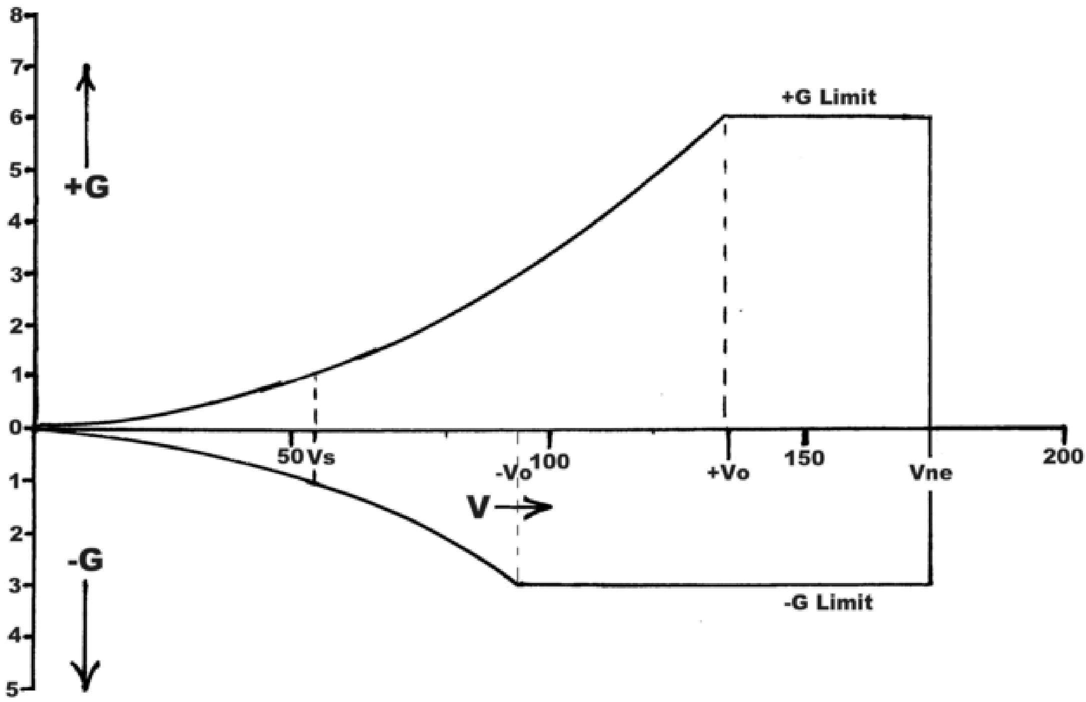


Figure Seven – Negative 'G' Limits

So we now have a graph which defines all of the structural limits of the aeroplane, (well almost). The curved lines represent the ‘stall boundary’ and the ‘G’ beyond this line is ‘unattainable’ because the wings will stall at the boundary, whilst the horizontal lines represent the acceleration limits imposed by the designer (or regulator), on any pitching manoeuvre the aviator might attempt when flying at speeds above **±Vo**, and the vertical line represents the airspeed limit beyond which the aeroplane should not be flown. These lines enclose an area which is called the aeroplane’s ‘Manoeuvre Envelope’. Flight within this envelope is okay but flight outside it is either impossible or damaging to the aeroplane. All aeroplanes, regardless of the purpose for which they are designed, have Manoeuvre Envelopes similar to this, but the +/- acceleration limits and **Vs, Vo** and **Vne** will, of course, vary with each type.

Accelerometers, in those aeroplanes fitted with them, usually have the +/- acceleration limits marked on them with red radial lines to assist the aviator in determining his proximity to his aeroplane’s ‘G’ limit when manoeuvring. These limits will depend upon the category of operation. I cannot emphasize enough how important I believe it is that an aviator understand the Manoeuvre Envelope of his/her aeroplane.

Is there anything more to learn about the Manoeuvre Envelope? Yes there is. Let’s step back and take another look at our aeroplane head on (Figure Eight).

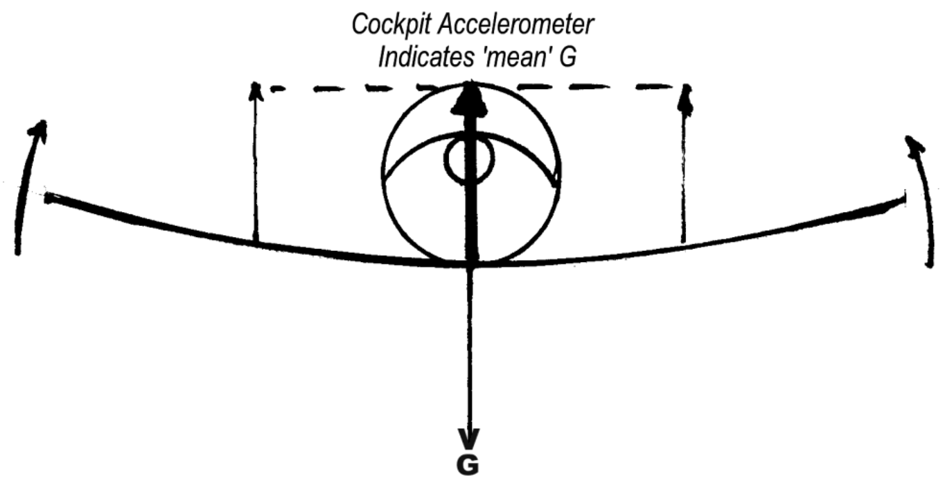


Figure Eight – Cockpit Accelerometer Reading

Each wing produces its ‘share’ of the required lift, and its ‘centre of lift’ vector is located at the aerodynamic centre of the wing, but the accelerometer is mounted in the cockpit and will be indicating the mean lift/G being experienced. If the aeroplane happens to be rolling, then one wing must be developing more lift than the other, but because the accelerometer is in the centre of the aeroplane it will only indicate the mean of these two lift forces, and this could be unchanged from straight and level flight despite the fact that the ‘up going’ wing is obviously being stressed to a greater degree than the ‘down going’ wing (Figure Nine).

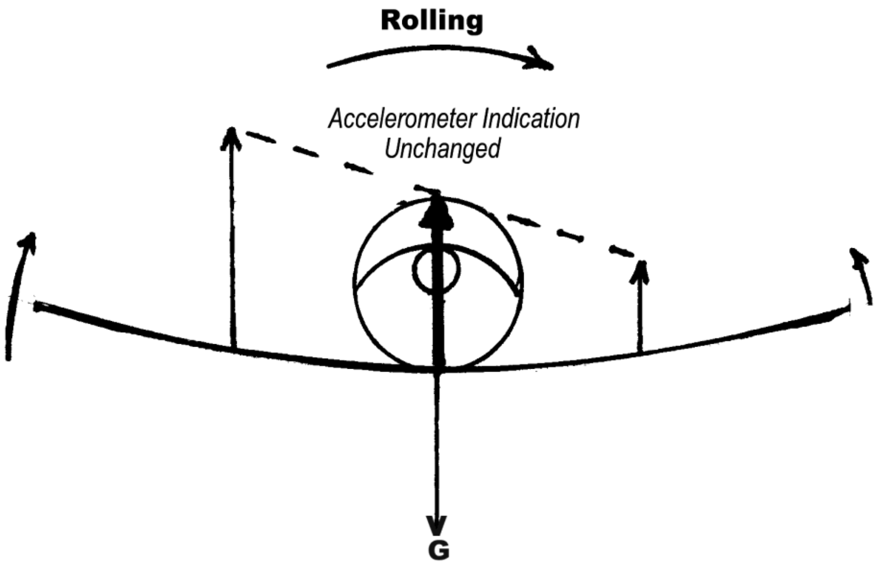


Figure Nine – Cockpit Accelerometer Reading during a Roll

Now the act of rolling the aeroplane in straight and level flight is not going to generate sufficient asymmetric lift to exceed the aircraft's design limits on either wing, but what if the pilot rolls whilst doing a high 'G' manoeuvre? Imagine that the following head on view is of an aeroplane that is just arriving back in level flight after doing a loop. The pilot has not yet relaxed the A/A but at this instant he/she rolls the aeroplane at maximum rate (full aileron deflection). Figure Ten.

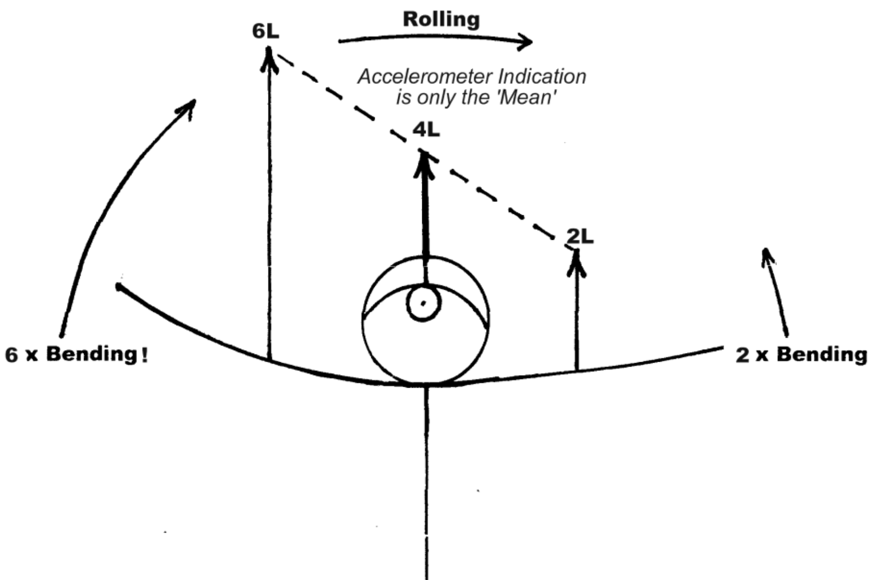


Figure Ten – Rolling whilst 'Pulling' 4G

The symmetrical lift generated toward the conclusion of the loop causes an acceleration of 4G, and is indicated on the accelerometer, but then the rapid roll is caused by an additional asymmetric lift. The 'up going' wing is now generating 6L, whilst on the 'down going' wing only 2L, but the mean indicated

on the accelerometer is still 4L (4G). Here we have a situation where the ‘up going’ wing is at its acceleration limit but the accelerometer is not showing it!
If we view the same situation from the side (Figure Eleven) you can see that the ‘up going’ wingtip is flying along a much tighter curve than the fuselage, and the tighter the curve (at a particular airspeed) the more the ‘G’. Conversely, the ‘down going’ wing is flying along a more ‘relaxed’ curve and is being subjected to less ‘G’.

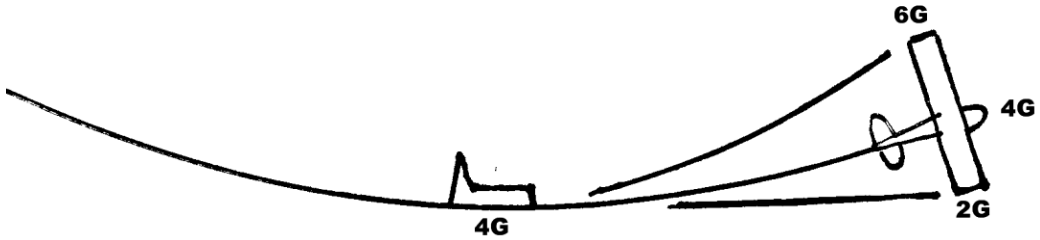


Figure Eleven – Side View of a ‘Rolling G’ Manoeuvre

Now imagine that we are manoeuvring the aeroplane at an indicated 5G and rolling at maximum rate. We have just overstressed the up going wing without the situation being recorded by the accelerometer! (Accelerometers usually have ‘tell-tale’ hands which remain at the maximum and minimum accelerations achieved on a particular flight.) If we could install remote reading accelerometers feeding acceleration data to us from each wingtip in addition to the one already in the cockpit, we could see what was going on, but I don’t know of any production aeroplane that has such an accelerometer set up.

So what can the aviator do to avoid inadvertently over stressing the ‘up going’ wing during a ‘rolling G’ manoeuvre? Obviously if the intention is to roll at maximum rate the ‘G’ being pulled (or pushed) at the time must be limited to something less than the usual limit for that aeroplane. A ‘rule of thumb’ in common use by those aviators that understand the problem (and, now, this includes **you**) is to limit the ‘G’ as seen on the cockpit accelerometer, whilst rolling at maximum rate, to **2/3** of the design limit. That is:

Rolling ‘G’ limit = 2/3 Symmetrical ‘G’ limit.

So an aerobatic aeroplane limited to +6 symmetrical ‘G’, would have a ‘rolling G limit’ of +4, whilst a normal category aeroplane limited to +3.8 symmetrical ‘G’ would have a ‘rolling G limit’ of only +2.5 and both would have a corresponding **Vo(rolling)** calculated as follows:

Rolling ‘G’ = 2/3 x 6 = 4G

So, inserting **4** into the ‘stall boundary’ formula we get:

Vo(rolling) = Vs√4
= 55 x 2
= 110kts.

This means that the aeroplane in our example will stall under +4G at 110kts and this will prevent a 'rolling G' overstress in the same way that a stall at **Vo** will prevent a 'symmetrical G' overstress.

Can the aeroplane be rolled at all above +4G? Yes it can, indeed at +4G it can be rolled at maximum rate but the roll rate must be progressively reduced as the 'G' gets greater until at +6G it should not be rolled at all. If in doubt relax the 'G' to +4 or less before rolling. Now this is not too difficult in an aerobatic aeroplane because we are dealing with high acceleration limits, but in a normal category aeroplane where the 'rolling G' limits are quite low, and the aeroplane is cruising at speeds well in excess of **Vo(rolling)**, caution must be exercised in the manner in which the aeroplane is maneuvered or damage could result.

The following Manoeuvre Envelope diagram (Figure Twelve) includes (+/-) 'rolling G limit' lines and shows the speed at **±Vo(rolling)**, which for brevity I have labeled ±**Vr**. (My use of the symbol **Vr** in this context is not a standard abbreviation.)

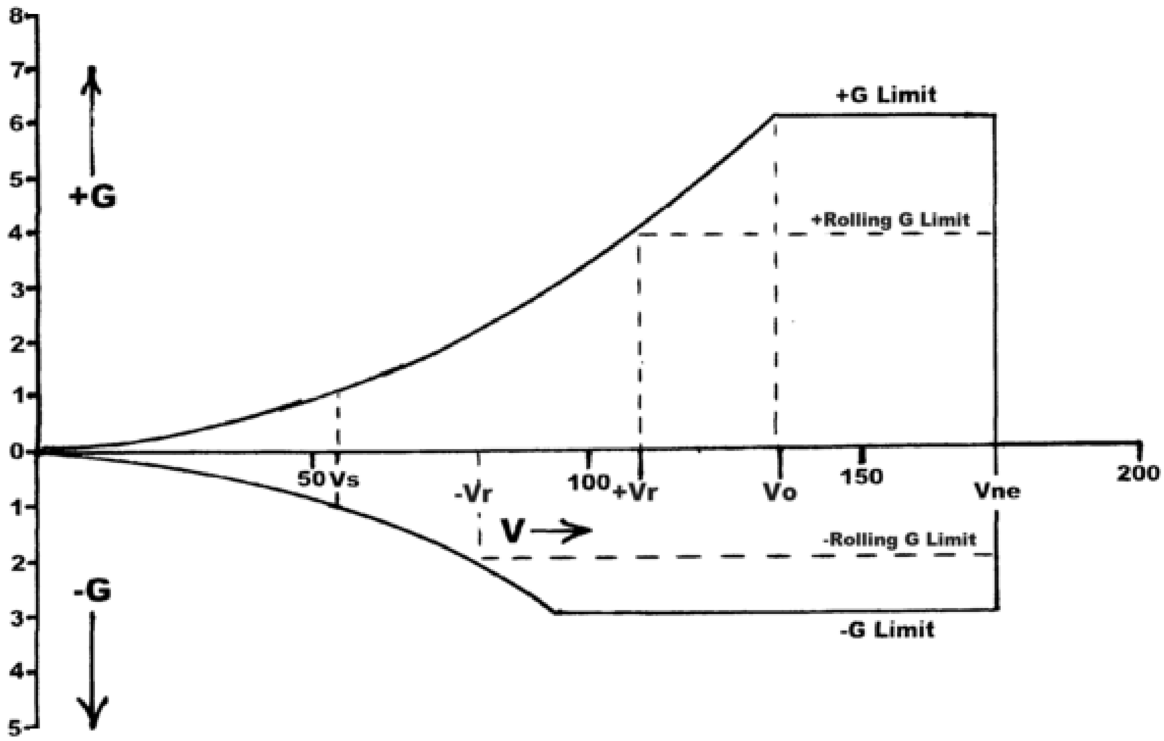


Figure Twelve – Manoeuvre Envelope including Rolling G Limits

'Rolling G' and its limiting effects on an aeroplane's safe manoeuvre envelope is one of the least understood aspects of aircraft structural limits. Many, many aeroplanes have, over the years, been seriously overstressed and damaged as a direct result of this ignorance. But now that you are aware of this, for you, ignorance is no longer an excuse.

In Annex D to the lesson on Manoeuvring I detailed the phases of a spiral dive and labeled the third phase the 'structural limit phase'. The structural limits referred to are the 'rolling G' limits of the aeroplane because in a spiral dive the aeroplane is both rolling and pitching simultaneously and, as the speed builds up, so does the rolling G! The limiting speed in a spiral dive would therefore be **Vo(rolling).**

At Annex C to this lesson I have included a table which shows the symmetrical and rolling 'G' limits for the three standard operational categories of civilian aeroplanes and their associated **±Vo** and **±Vo(rolling)** factors. All you have to do is insert the **Vs** of your aeroplane into the formulas provided, to calculate the corresponding structural airspeed limits for the aeroplane.

Quite often you will find manoeuvre envelope diagrams which have the right hand corners cut off like the one shown in Figure Thirteen. This is because certain gust response criteria have been superimposed onto the manoeuvre envelope.

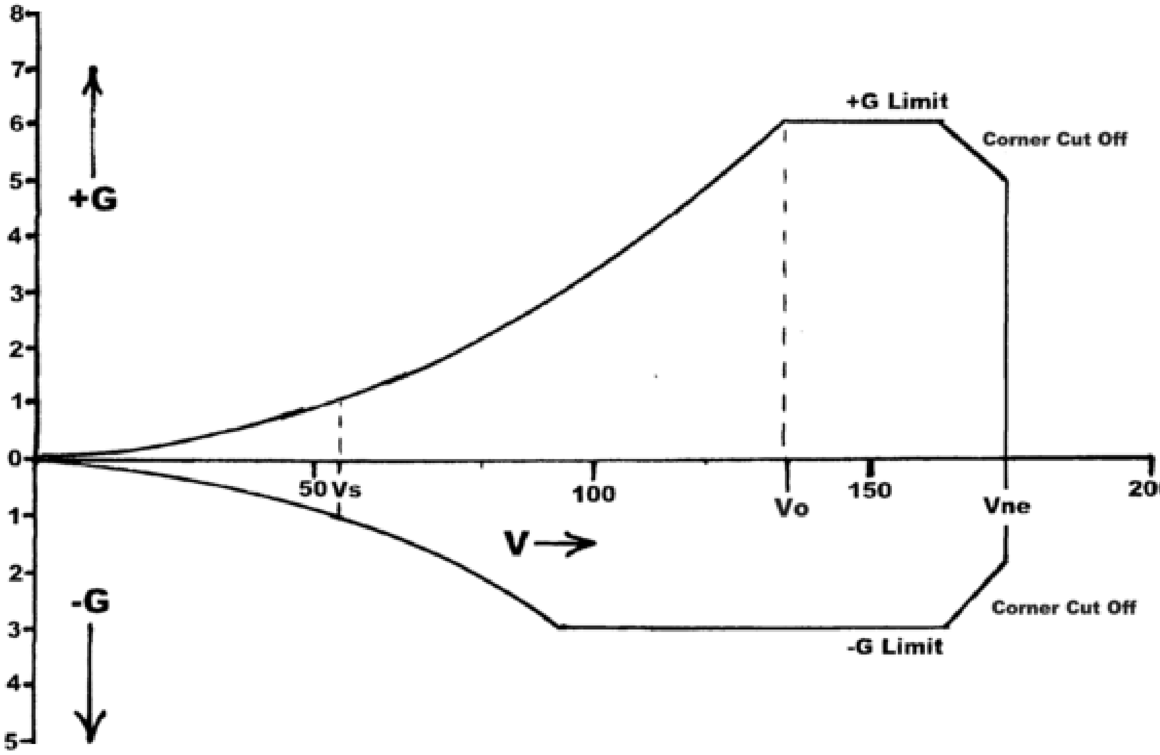


Figure Thirteen – Manoeuvre Envelope minus the corners

These missing corners mean that at speeds approaching **Vne** the G limit reduces progressively. This modification is quite common on the Manoeuvre Envelopes of normal category aeroplanes. Because these diagrams contain not only manoeuvre data but also gust response data, they are called 'Flight Envelopes'. You will find a full explanation for these missing corners in Annex A.

This leads us onto the second part of this lesson which is about flight in turbulent air. Turbulent air currents can be experienced on windy days on the lee side of hills and mountains, in or near cumulus type clouds (especially thunderstorms), at high altitudes near jet-streams, and on hot days with strong 'thermal' activity, or in 'bad weather' in general. Turbulence can consist of horizontal or vertical gusts (or both simultaneously) of varying strength. Horizontal gusts produce momentary changes in the aircrafts airspeed or balance due to its inertia but only small and relatively unimportant changes in the flight load factor, however, vertical gusts can have severe effects on the aircraft's structural integrity and that is what concerns us here.

Vertical gusts can momentarily alter the angle of attack of the wing, which alters the lift being generated by the wing. This excess lift then causes unwanted acceleration. The following diagram shows how this change of angle of attack comes about (Figure Fourteen).

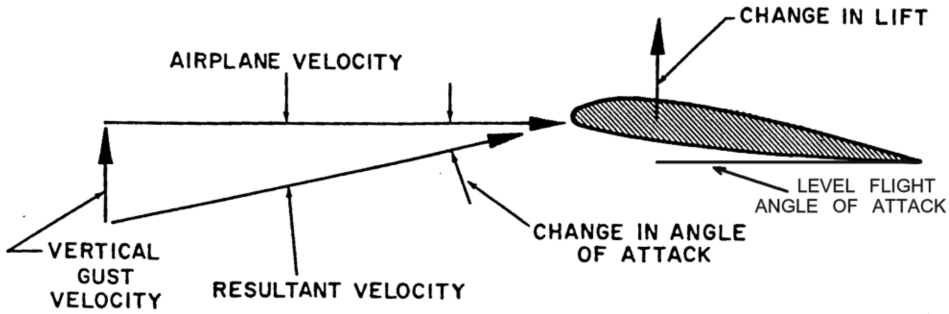


Figure Fourteen – Gust related change of A/A

As you can see, at a given airspeed the angle of attack changes with the strength of the gust. In severe turbulence the increased lift and therefore the acceleration produced, can exceed the design limit. So in severe turbulence the airspeed should be reduced to a figure that prevents the aeroplane from being over stressed by allowing the stall to act as a safety net. This speed is called the 'Turbulence Penetration Speed' and is given the symbol **Vb**. It should come as no surprise to you to learn that **Vb** equals **Vo!**

What size vertical gust would be required to cause the angle of attack to increase to the critical angle at **Vb**? Well, assuming that the critical A/A of the wing of our aerobatic aeroplane is 16º and it is flying level at 2.5º A/A, at 135kts (Vb), the A/A would have to increase a further 13.5º. The following triangle of velocities shows the gust which would be needed (Figure Fifteen).

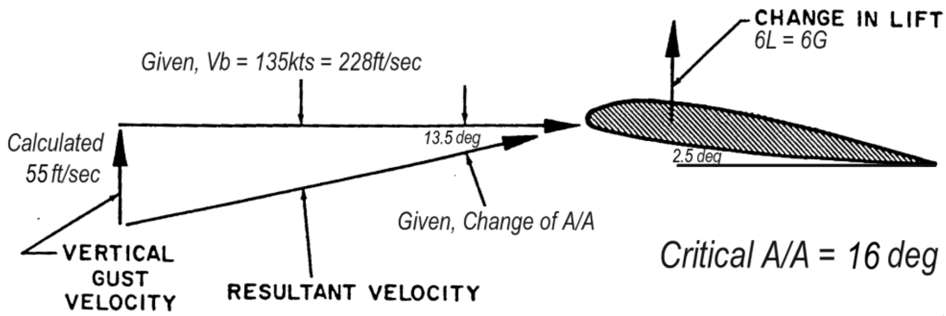


Figure Fifteen – Vertical Gust required to produce Critical A/A

You can see that the vertical gust speed would be 55ft/sec, which is 3300 feet/minute or 32.5kts! Flight in conditions which produce such gusts would be a ‘wild ride’, and can be experienced inside a thunderstorm if you are foolish enough to go there.

What would the acceleration be, at **Vb,** if only a 50ft/sec gust was encountered? It would be 5.45G (6 x 50/55). So the aeroplane could go faster before a 50ft/sec gust would produce 6G. This is because the A/A required to maintain level flight (1G) reduces as the square of the increased airspeed and we only need 6 times that reduced A/A to produce 6G. (If this is a little difficult to grasp refer to Annex A for more detail.)

Regulatory authorities impose ‘gust response’ criteria upon the designs of aeroplanes, which means the designers have to work the problem backwards from the way that we have been looking at it. That is, they start with a particular vertical gust speed that the aeroplane has to be able to withstand and work backward to find the maximum speed at which the aeroplane can be flown in such a gust without the G limit being exceeded. The mathematics for calculating this speed are a bit more complicated as there are a couple of variables involved, so we are not going to go into them in great detail here, (but I have in Annex A if you are interested). However, just to give you a feel of what I am talking about, consider our aeroplane flying level but faster than in the previous example. As a result its A/A has reduced to 2.2º. Ask yourself how much would this A/A have to increase to produce 6G? The answer of course is 6 times, which is an increase of 11º, for a total of 13.2º (2.2º x 6). So if I told you that the gust response criterion was 50ft/sec, some simple trigonometry would give you the corresponding airspeed at which this 11º increase in A/A would occur (Figure Sixteen)

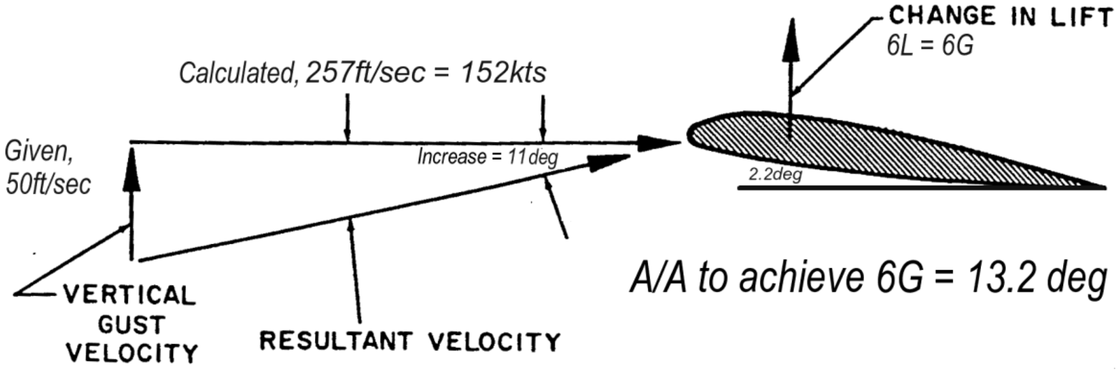


Figure Sixteen – Airspeed Limit for 50ft/sec Vertical Gust

You can see that in this example the answer is 257 ft/sec which is 152kt. Now this speed is above **Vb** so a stronger gust (say 55ft/sec) has the potential to overstress the aeroplane. However, the ‘regulatory authorities’ have concluded that a 50ft/sec gust would only be exceeded in the most extreme circumstances so the associated airspeed is, therefore, safe under all but extreme conditions.

If you are finding this concept difficult to follow lets look at it another way. Imagine the pilot of our aeroplane (working without a safety net) at 152kts pulls 6G. To do that he would have increased the A/A to only 13.2º, which is all that a 50ft/sec gust could produce at that speed. The pilot chooses not to pull more than 6G, whilst the gust is incapable of ‘pulling’ more. It is the designer’s job to figure out at what airspeed the 50ft/sec gust can only ‘pull’ 6G. His mathematics is, as I have said, a little more complex than I have used in this example but the concept is the same. (Once again I refer you to Annex A for a more detailed explanation of gust response calculation for those of you who are mathematically inclined.)

This new ‘acceptable’ gust response speed is called the ‘Maximum Structural Cruise Speed’ and is given the symbol **Vno** (**V**elocity **n**ormal **o**perating) and is the speed indicated on the airspeed indicator by the **‘top’ end of the green arc**. Operations beyond this speed will fall into the **yellow (caution) arc** and should only be conducted in smooth air.

Previously I said that a normal category aeroplane is capable of cruising at speeds above **Vo (Vb),** suggesting that the aeroplane could be easily and unwittingly over stressed, which it can. However, if we accept that the gust factor upon which it is predicated is reasonable and that the pilot is not going to attempt any high G manoeuvres, the concept of **Vno** makes this cruising speed more ‘structurally’ acceptable.

Unfortunately most pilots do not fully understand the meaning of **Vno**. They do not understand that it is a ‘response speed’ to a particular size gust, not a manoeuvring speed, so some may indulge in maneuvers the aeroplane was never designed to do at this speed, thinking “I am in the green arc, so it is OK”!!

We have now established that the standard markings on an Airspeed Indicator are: a green band from **Vs** to **Vno**, a yellow (‘caution’) band from **Vno** to **Vne** and a red radial line at **Vne**. Unfortunately **Vo** and **Vb** are <u>not</u> marked on an ASI.

I do not believe that marking **Vno** on the airspeed indicator is as much use as the ‘authorities’ think it is. I believe that the ‘top of the green arc’ should be **Vo**, as the only sure solution to a close encounter with severe turbulence is to slow down to **Vo** (or even **Vo(rolling),** see Annex B) and it is a much more useful speed to have clearly marked on the ASI when we are doing some ‘serious’ manoeuvring.

From what I have explained to you in this lesson, and given the correct instrumentation (shown in Figure Seventeen which follows), you should now be able to look at the indications of the accelerometer and the ASI at any time during flight and visualize exactly where you are within your aeroplane’s

Manoeuvre Envelope, and fly accordingly. (Note that the accelerometer's 'at rest' indication is +1G in response to the ever present acceleration due to gravity.)

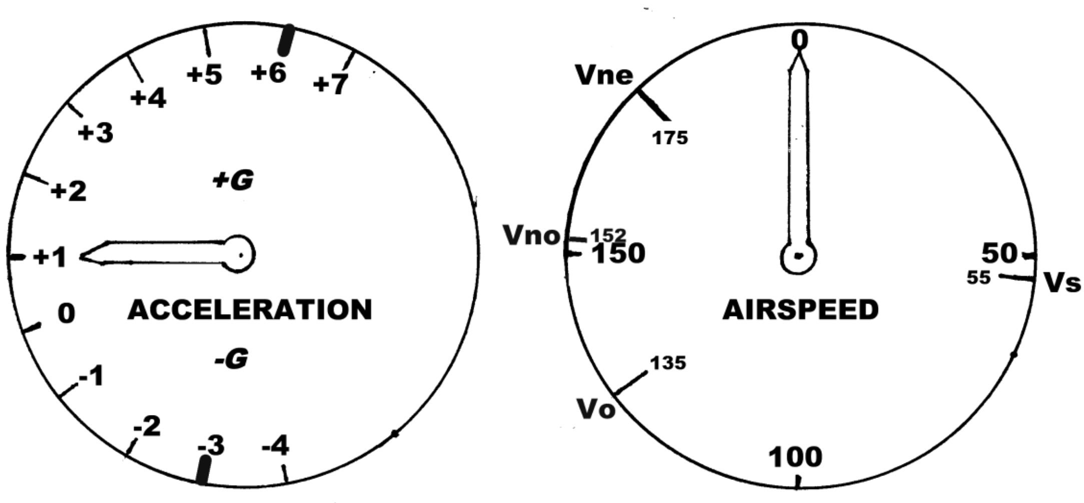


Figure Seventeen – Instrumentation needed in ALL aeroplanes

Unfortunately, you will rarely find an accelerometer in a normal category 'touring' aeroplane (I believe that all aeroplanes should have accelerometers fitted to them) and since **Vo** is not commonly marked on airspeed indicators either, the average pilot is presented with limited information about where the aeroplane is within the manoeuvre envelope when in flight, so be careful and good luck!

List of Annexes to the lesson on: Aircraft Structural Limits

Annex A. The Derivation of Vno

Annex B. More on Vo, Va and Vno

Annex C. Aircraft Structural Limits Tabulation

Annex A

The Derivation of Vno

The calculation of 'gust response speeds' depends upon the change of angle of attack which a particular vertical gust can cause at different airspeeds, and the level flight angle of attack of the wing at these airspeeds, so there are two fundamental variables to consider.

As an aeroplane flies faster and faster, in order to maintain level flight the angle of attack of the wings must progressively decrease to maintain the lift exactly equal to the aeroplane's weight. Since the lift force created by the wings increases as the square of the airspeed, it follows that the angle of attack must decrease as the square of the airspeed to compensate. For example, if the aeroplane has a critical A/A of 16º and a Vs of 55kts then at 55kts it can only just develop enough lift to balance the weight (L = 1), but at twice that speed, 110kts, at the same angle of attack, it would produce four times as much lift (L = 4). So to maintain L = 1, the angle of attack would have to be reduced to one quarter of its critical A/A, that is, to 4º. If the speed were to triple to 165kts the lift would increase 9 times so the A/A would have to reduce to a ninth of the critical angle, which would be 1.8º, and at 220kts, the A/A would be down to 1º. The following diagram (Figure One) illustrates this progressively reducing angle of attack as airspeed increases.

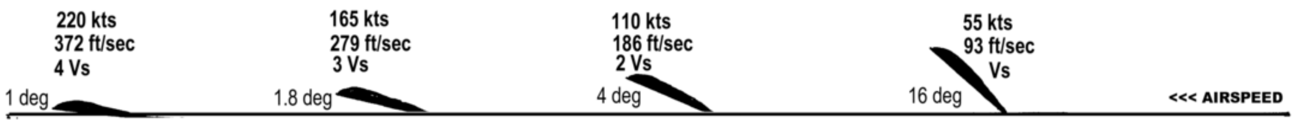


Figure One – Reducing A/A with increasing airspeed

From the above diagram you can see that as the airspeed increases from 55kts to 220kts the angle of attack, in order to maintain level flight (L = 1), decreases from 16º to 1º. (Once again I have exaggerated the angles in the diagram for clarity.)

If a particular vertical gust were to increase the angle of attack to say 6º, then the amount of lift and 'G' produced would depend upon the level flight angle of attack at the time. For example, at 110kts 6º is only 1.5 times the level flight A/A of 4º, and since lift varies directly with A/A, 6º would therefore only cause the lift to increase by a factor of 1.5 and result in an acceleration of only 1.5G, but at 220kts 6º is 6 times the level flight A/A of 1º and would cause a lift increase of 6 and 6G. But this is not the whole story. A particular gust will not cause the same increase in angle of attack at these two different speeds as it too depends upon the airspeed of the aeroplane. The following diagram illustrates what I mean (Figure Two).

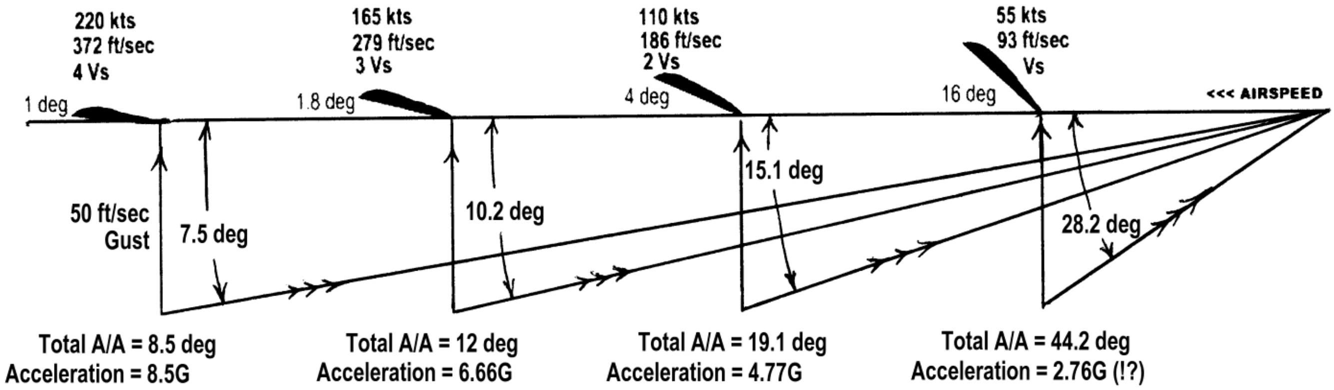


Figure Two – Effect of 50ft/sec gust at increasing airspeed

As you can see, a 50ft/sec gust acting upon the aeroplane flying at 110kts produces about twice the angle of attack change that it would if acting upon the aeroplane traveling at twice that speed. When we add these A/A increases to the level flight A/A's at each airspeed, we can determine the resulting total A/A at those speeds. You will note that some extreme angles result from these calculations, particularly at the low speed end of the diagram, and we know that the stall plays a part in whether the resulting lift from these angles is achievable, but for now let's ignore the stall. We will come back to its implications shortly.

If we now divide the total A/A resulting from the 50 ft/sec gust at each speed by the original level flight A/A at the same speed, we can determine the increased lift factor and therefore the extra G caused by the gust at that speed. The following tabulation results:

50 ft/sec Gust Response Tabulation.

Airspeed	Level A/A	Gust A/A	Total A/A	Total ÷ Level = Lift	'G'
55kts	16°	28.2°	44.2°	44.2 ÷ 16 = 2.76L	**2.76**
110kts	4°	15.1°	19.1°	19.1 ÷ 4 = 4.77L	**4.77**
165kts	1.8°	10.2°	12°	12 ÷ 1.8 = 6.66L	**6.66**
220kts	1°	7.5°	8.5°	8.5 ÷ 1 = 8.5L	**8.5**

If we were to draw a graph of the Airspeed and G figures from this tabulation we would discover that they form a straight line, which is very convenient for our understanding of what these figures represent. We also know that we can't get 2.76 G at 55kts because the wing will stall at 1G, so let's plot this line onto the diagram of the aircraft's manoeuvre envelope and see what we do get (Figure Three).

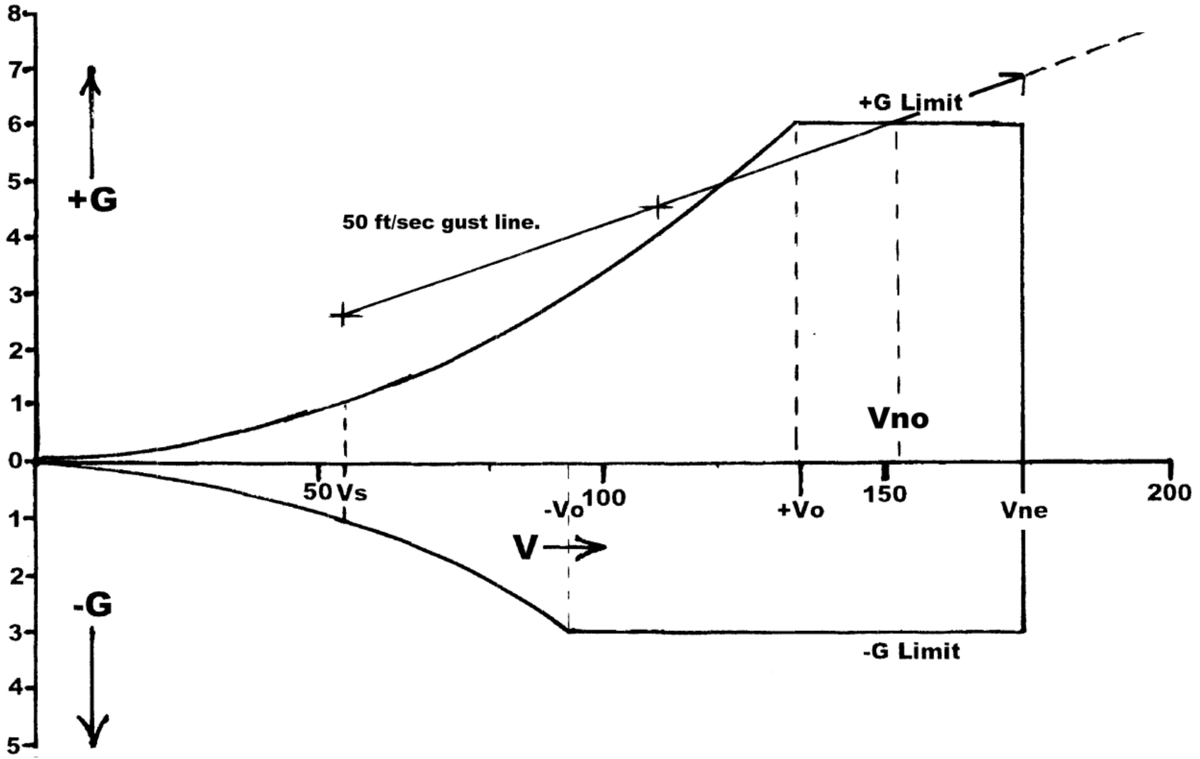


Figure Three – Gust Response line superimposed on Manoeuvre Envelope

Here we see that plotting the airspeed and G from the gust response tabulation onto the manoeuvre envelope diagram, results in a straight line representing the effect of a 50 ft/sec vertical gust on the aeroplane throughout its speed range. You will note that much of this line falls into the 'region of unattainable lift' and is therefore meaningless, but where it crosses the stall boundary and extends into the manoeuvre envelope it is possible to see the effect of this gust on the aeroplane.

At **Vne** this 50 ft/sec gust will cause 7G, a 1G overstress, whilst at **Vo** it will only produce a little over 5G. The speed at which it crosses the 6G limit line is the critical speed, because this is the speed at which the gust will only cause 6G, and beyond which we should not fly the aeroplane in turbulent air capable of producing vertical gusts of 50 ft/sec. In this example it is 152kts. This speed is called the "Maximum Structural Cruising Speed" and is given the symbol **Vno. Vno** is represented on the aircraft's airspeed indicator by the top end of the green arc. Further discussion on the applicability of **Vno** in the 'real world' is contained in Annex B.

In many countries the regulatory authorities also require aircraft designers to calculate gust response figures based upon some lesser vertical gust figure, particularly for normal category aeroplanes. Imagine we go through the whole exercise again for a 25ft/sec gust. This would produce another gust response line similar to that which I have plotted on the manoeuvre envelope shown in the next diagram (Figure Four).

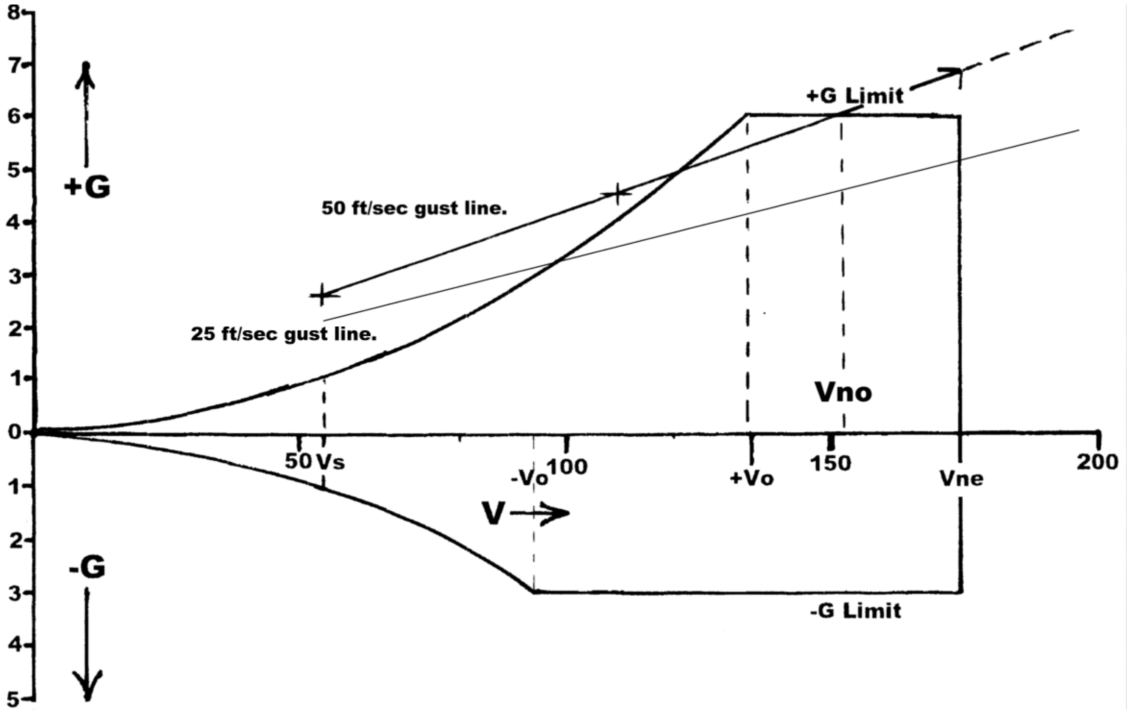


Figure Four – 50 & 25ft/sec lines superimposed on Manoeuvre Envelope

Remember, in the main part of this lesson I briefly mentioned manoeuvre envelopes which had the right hand corners cut off. Well it is these gust response lines which, when superimposed onto the manoeuvre envelope, cause these ‘corner cuts’, and not only on the positive ‘G’ side of the diagram but also the negative side. The actual position of these gust response lines and the associated corner cuts depends upon the gust criteria used in the calculations as required by the regulations in the country of design. (See Annex B.) Here is the complete picture of what is now the aircraft’s ‘Flight Envelope’ (Figure Five).

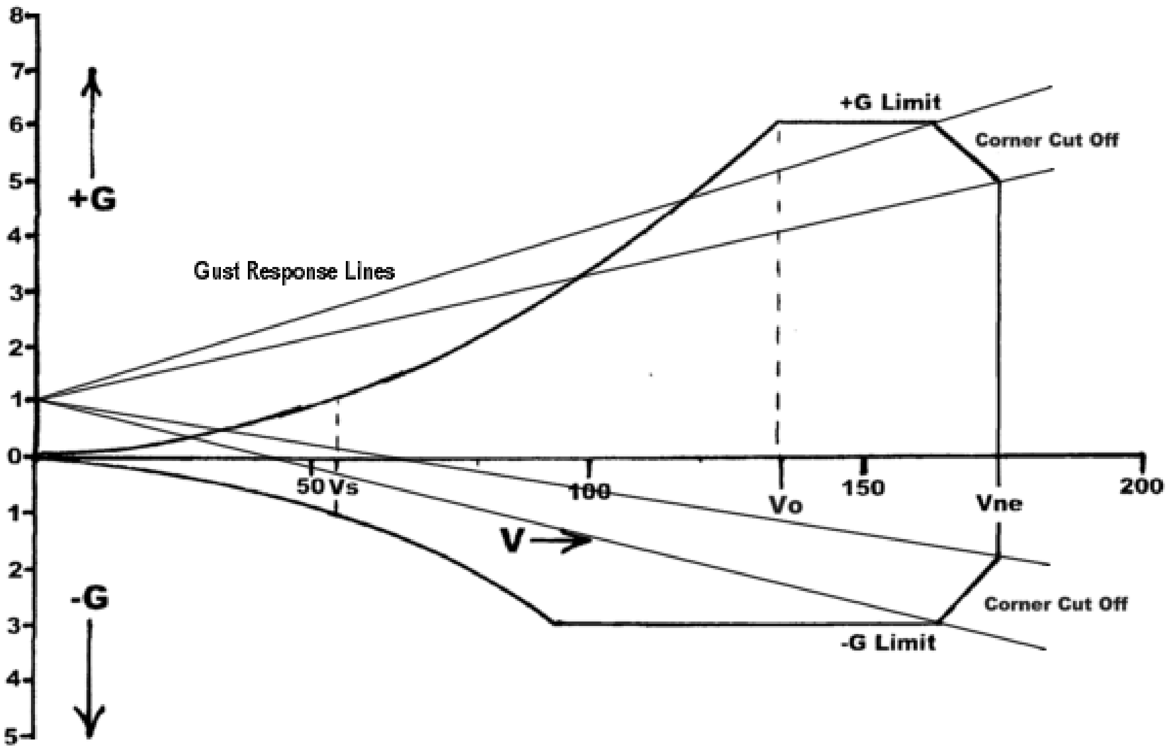


Figure Five – The complete ‘Flight Envelope’

Annex B

More on Vo, Va and Vno

Vo

Vo is a new symbol given to the speed which conforms to the formula **Vs√Glimit.** It was only created by an amendment to the US Federal Aviation Regulation 23 (FAR.23) in 2007. Prior to that date the term **Va** was used, which meant **V**elocity Maximum **A**cceleration, and is the term you will still find in most aircraft flight manuals and instruction manuals. **Vo** was introduced because **Va** came to be called the velocity for 'Maximum Control Deflection' of any control surface. Quote from FAR 23: *"the loads resulting from full control surface deflection at Va are also used to design the empennage (tail) and the ailerons."* So **Va** may equal **Vs√Glimit** when the aircraft is pitched, that is with full elevator deflection, but can be different when the structural loads imposed by full deflection of the ailerons or rudder are considered. So for many aircraft **Vo** and **Va** are the same, but for others they differ.

A simple way to think about this is that **Va** is the slowest of the individual airspeed limits applied to the maximum deflection of each of the three primary control surfaces, whilst **Vo** is the airspeed limit applied to the maximum deflection of the elevator only. This means that **Va** can never exceed **Vo.** (Think about it.)

Here is a further quote from FAR.23 amendment 45: "**Va** *should not be interpreted as a speed that would permit the pilot unrestricted flight control movement without exceeding airplane structural limits!"* This is why 'they' had to create **Vo.**

Vo seems to be a more 'straight forward' figure, but some manufacturers and student texts 'muddy the water' in regard to **Vo**. Some aircraft flight manuals declare different **Vo's** for different aircraft weights because the aeroplane's 1G stall speed varies with these different weights. This can be very confusing for the pilot because whilst the actual stall speed may vary with weight, **Vs**, by definition does not. **Vs** is always measured at the aeroplane's maximum all up weight, therefore **Vo,** by definition, will always be at the aeroplane's maximum all up weight too! If the aeroplane is stalled at **Vo** when it is lighter than its maximum all up weight, the accelerometer will record an acceleration greater than the aeroplane's limit, (the same lift force acting on a reduced mass equals greater acceleration), but this does not mean that the wings have been overstressed! Consider this: An aerobatic category aeroplane which has a maximum all up weight of 800kg and an acceleration limit of 6G, has wings strong enough to safely withstand a maximum load of 4800kg (800 x 6), but if on a particular flight it only weighs 700kg then, if stalled at **Vo,** it will have ‘pulled’ 6.86G! (4800 ÷ 700) So in this case the wings’ attachment to the fuselage has not exceeded their load **limit**; it is only the published load **factor** which has been exceeded. **HOWEVER**, before you go out there and bend your aeroplane and blame me, let me emphasize that there may be other bits of the aeroplane which will break if the published G limit is exceeded. Let me explain.

The aircraft designer, having decided upon the category of operation of the aeroplane is not going to ‘over engineer’ other parts of the aeroplane to be able to exceed the G limit for that category. A good example of this is the engine mount frame. There is no purpose in making this strong enough to withstand say, 8G, when the ‘red line’ is set at 6G because this would mean the aeroplane is carrying a weight penalty which would degrade its performance and increase its cost. So whilst the wings of our 700kg aeroplane might be happy at 6.86G, the engine might fall out!

Obviously, if you are the pilot of this aeroplane, you will have some explaining to do if you bring the aeroplane home without an engine and more than 6G recorded on the accelerometer......so take it easy, your safety net (stall boundary) has just shifted and no longer affords you the protection you thought it did! Monitor the accelerometer and stick to the published G limits. (Your accelerometer should be mounted where it can be easily monitored.)

Once upon a long long time ago, over eastern Thailand, I was ‘on the tail’ of a USAF F4C Phantom II, during one of our regular air combat ‘exercises’, and he was going ‘hard at it’ to shake me. Suddenly the pilot called off the fight as he had heard a loud bang from inside the bowels of the fuselage and had lost thrust from his starboard engine. Later, during the ‘debrief’ in the bar, I learned that his engine mounts had broken. He was manoeuvring at 7.5G at the time!

The different categories of operation of a particular aeroplane are calculated in a similar fashion. If the aeroplane in the forgoing example were to be loaded to 900 kg, its maximum structural strength would be reached at 5.33G (4800 ÷ 900) so its operations would fall within the ‘Utility’ category (4.4G maximum) if it were to operate at this weight. (The ‘steps’ between categories are large and make no allowance for the actual capability of the wings of the aeroplane to safely ‘pull’ more than 4.4G at 900kg.)

Vno

Vno is obviously different for different aeroplanes, but it also differs depending upon when and where the aeroplane was manufactured because different countries have different aircraft design criteria (and change them from time to time). Therefore there are many different gust criteria from which the **Vno** of a particular aeroplane is calculated. The current US Federal Aviation Regulation 23 (FAR.23) specifies a 50ft/sec gust criterion for light aeroplanes, but older US manufactured aeroplanes (including ex-military 'war birds') do not comply with this criterion. Many British and European aeroplanes do not comply. Soviet bloc aeroplanes certainly do not comply and most amateur built and ultra-light aeroplanes do not. Some of these aeroplanes will have a 'top of the green arc' **Vno** marked on their airspeed indicator and some will not. Of those that do have it marked, you may not find the gust criteria upon which this number is calculated, published anywhere in the aeroplane's documentation, making it a pretty useless number for the pilot. So, upon what criteria is the **Vno** of that experimental category home built 'Super Wizzbang' aeroplane you want to buy, calculated?...... Who knows!?

From time to time you will see a new type of aeroplane advertised for sale along with the declaration that it has been designed to 'FAR 23' standards. The manufacturers obviously want to sell their aeroplane in the USA, because if it doesn't meet FAR 23 standards it will not gain USA type certification and could not be sold. Fortunately more and more countries are designing aeroplanes to meet FAR 23 criteria so there is increasing hope that, in the future, pilots will understand what the **Vno** of their aeroplane actually means.

But wait; there is one more aspect of turbulence to consider. Turbulence, by its very nature, will rarely impose 'symmetrical G' on an aeroplane. It invariably imposes some degree of 'rolling G', but none of the gust response speeds, however they are calculated, consider 'rolling G' in the calculation! Further, upon encountering turbulence the pilot will probably attempt to maintain altitude and/or attitude by 'wrestling' with the aeroplane's controls, which means that he/she throws some manoeuvre loads into the 'mix' too!

The combination of gust induced 'rolling G' loads and pilot induced manoeuvre loads defies any sort of quick 'in flight' mental calculation, so if you encounter severe turbulence I suggest that you slow your aircraft to **Vo(rolling)** quickly.

If all of this has left you a little confused, you are not alone. But spend some time studying this lesson, because a basic understanding of the concepts behind these **'V'** numbers, especially **Vo, Vo(rolling)** and **Vno,** will help you understand the limiting airspeeds applicable to the aeroplane you are currently flying and will allow you to interpret the colour coding on its airspeed indicator correctly. Don't give up on it, because this understanding could, at least, save your aeroplane from being 'bent' and may, one day, save your life.

Annex C

Aircraft Structural Limits Tabulation

Category	'G' Limit	+Vo	-Vo	Rolling 'G' Limit	+Vo(roll)	-Vo(roll)
Formula		**Vs√G**	**Vs√-G**	**2/3 Symmetrical G**	**Vs√G roll**	**Vs√-G roll**
Aerobatic	**+6.0 & -3.0**	**2.45Vs**	**1.73Vs**	**+4.0 & -2.0**	**2.0Vs**	**1.4Vs**
Utility	**+4.4 & -2.0**	**2.1Vs**	**1.4Vs**	**+2.9 & -1.33**	**1.7Vs**	**1.15Vs**
Normal	**+3.8 & -1.7**	**1.95Vs**	**1.3Vs**	**+2.5 & -1.13**	**1.6Vs**	**1.06Vs**

To calculate a particular structural limit speed for your aeroplane, simply locate the appropriate category of operation and the type of speed you want and insert your aeroplane's **Vs** into the formula provided and multiply. For example, if your aeroplane is normal category with a **Vs** of 50kts and you wish to know its **+Vo**(rolling) multiply its **Vs** by 1.6. In this case that is 50 x 1.6 = 80kts. If it is an aerobatic category aeroplane with a **Vs** of 55kts its **+Vo** is 135kts, etcetera.

Lesson Fourteen

TURNING AT THE LIMIT

Understanding the relationship between the radius of a turn and the rate of the turn of an aeroplane at different airspeeds, and how to achieve the optimum of both at any airspeed, is a subject not very well understood by the majority of pilots. This lack of understanding has resulted in many unnecessary catastrophes, injuries and deaths, when circumstances have required a turn to be made at minimum radius, such as making a ‘U turn’ within the confines of a valley when flying in mountainous terrain.

In the lesson on manoeuvring I said that, in theory, a minimum radius and maximum rate turn can made by flying as fast as possible and ‘pulling’ as much ‘G’ as possible. At first glance this statement doesn’t seem correct, as our experience with motor cars tells us that to enter a corner too fast is extremely hazardous, and that the tighter the turn the slower we must enter it. This apparent contradiction comes about because motor cars and aeroplanes derive the centripetal force (Cp) required to turn by completely different means.

Before getting into the detail of turning an aeroplane at the minimum possible radius lets go back and review the basics of how anything turns. In annex B to the lesson on Lift I detailed the formula for turning, based upon Newton’s Second Law of motion, I will repeat it here.

From Newton's second law of motion; when a force (F) is applied to a mass (m) the mass is accelerated (a). This law is expressed by the simple formula **F=ma**. Now acceleration is defined as a change of velocity, and velocity is a vector which has both speed and direction. So when either the speed or the direction of a moving mass is changed it is being accelerated, and to do this you must apply a force.

The acceleration (a) experienced by changing the direction of a vector can be calculated by dividing the square of the velocity (v) by the radius (r) of the ‘turn’, therefore **$a=v^2/r$**. So by substituting ‘**v^2/r**’ for ‘**a**’ in the first formula we get:

$$F = mv^2/r$$

Now since we are going to consider the effects of changing velocity and force on something of constant mass we can simplify this formula by removing ‘m’. So the formula becomes:

$$F = v^2/r$$

And if we want to know the radius of a turn at a particular velocity and force we can rearrange the formula to the following:

$$\underline{r = v^2/F}$$

Finally, as we learned from the lesson on Manoeuvring, the sort of force we are talking about is a Centripetal Force (Cp), so for our purposes we can replace **'F'** in the formula with **'Cp'**. Now the final formula for the radius of a turn is:

$$\underline{r = v^2/Cp}$$

With me so far?

Let's look at a diagrammatical representation of what this formula means. First let's imagine an object moving in a straight line in space; no air and no gravity. Refer to Figure One. At 'A' the objects straight line velocity of 1 has been curved by a CP of 1, but if the object increases speed to 2 a Cp of 4 is required to keep it on the same radius curve (RAD1) as can be seen at 'B'. Note that even though the radius of the turn has remained unchanged the faster the object goes the further it moves around the curve in a given time, so its rate of turn increases, indeed in this case it has doubled (ROT2).

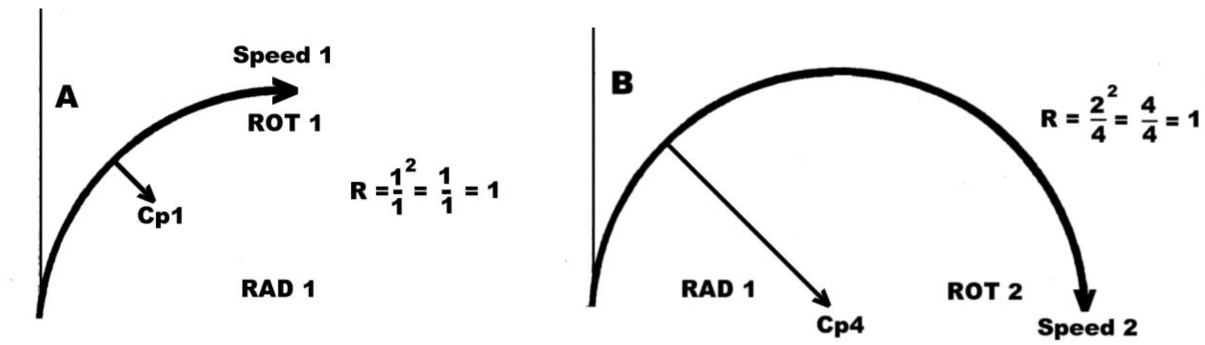


Figure One – Turning with Increased Speed & Cp

If the Cp is doubled without increasing the speed the turn radius would be halved (RAD ½) and the rate of turn doubled (ROT2). Refer to Figure Two.

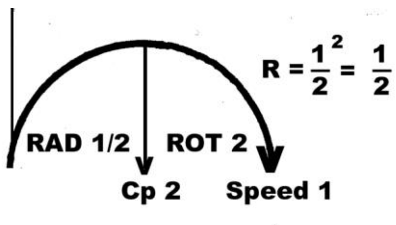


Figure Two – Turning with Constant Speed & Increased Cp

Conversely, if the speed was doubled but the CP was not increased, the radius of the turn would <u>increase</u> by a factor of 4 (RAD4) and the rate of turn would <u>decrease</u> by a factor of 4 also (ROT ¼). Refer to Figure Three.

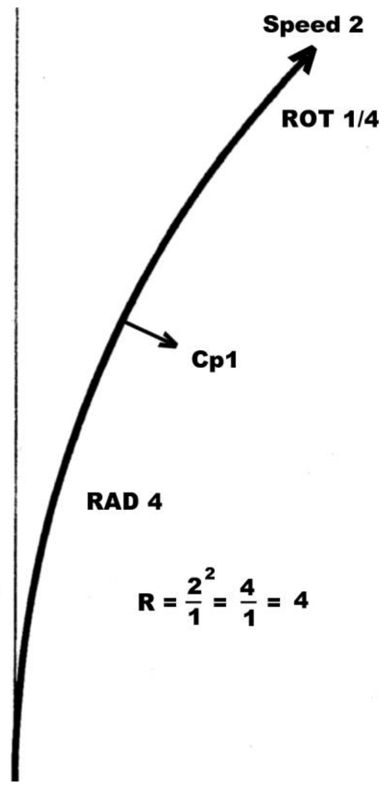


Figure Three – Turning with Increased Speed & Constant Cp

This is the situation confronting a motor car. A motor car derives its Cp from the friction between the tyres and the road and this friction is fairly constant regardless of speed and is limited to a value of about .8 (80%) of its weight (for a standard street car), whereas modern racing cars use fore and aft 'wings' set at a negative incidence to increase the download on the wheels without increasing the weight of the car. These wings enable a 'Formula One' race car to 'corner' with a Cp equivalent to almost twice the weight of the car. But in either case, in order to negotiate a 'tight' corner, a car must slow down, otherwise its turn radius would be greater than that of the corner and it would run off the road, usually with disastrous consequences.

Now let us imagine that our object is an aeroplane travelling within an atmosphere but still without gravity. Would it need wings? Yes, but not to keep it 'up there' but to turn. The wings would provide the Cp required to turn in all of those scenarios depicted above. This Cp could be varied by changing A/A and/or speed, but if we want to turn with the minimum radius at any given speed then, obviously, the A/A should be set to the maximum possible without stalling the wing and held there, that is, at an A/A just short of critical 'on the pre-stall buzz' to obtain maximum lift at that speed. What would the bank angle need to be? Well since the wings don't have to do the work of keeping the aeroplane 'up' all the lift can be used as Cp by using a 90º bank angle. See Figure Four. With 90º of bank the turning scenario shown in figure one would be dealt with virtually automatically because as the speed of the aeroplane doubles the lift from its wings would increase as the square of the speed and provide the increased Cp necessary to maintain the turn radius.

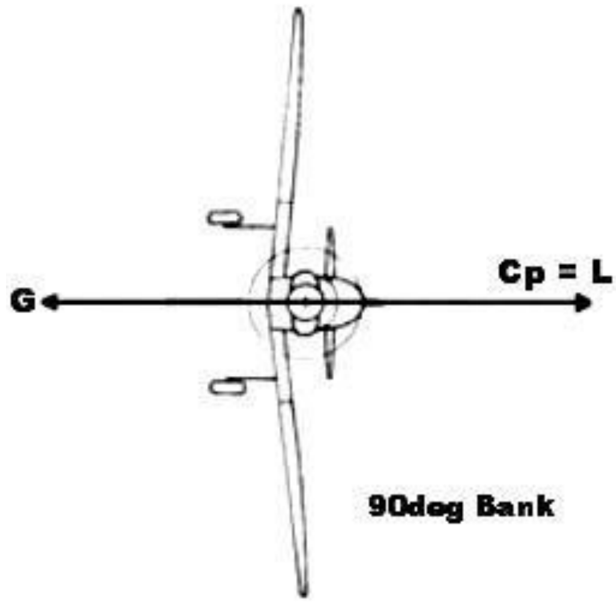


Figure Four – Turning with 90º Bank Angle

So if the maximum lift/Cp that can be generated by a wing at any speed can only increase enough to maintain the turn radius as speed increases, how can this aeroplane turn any tighter? The simple answer is that it cannot! By going faster the only thing that can be improved is the rate of turn, which is very handy if you are a fighter pilot trying to 'out turn' your opponent in order to shoot him, but it is of no use to a light aircraft pilot caught in a valley and needing to make a reduced radius U turn. But the story doesn't end there, read on…..

Let's get back to reality and reintroduce gravity. Now the aeroplanes wings have to perform two functions, the provision of sufficient lift to oppose gravity and the provision of Cp to turn the aeroplane. The provision of the gravity opposing 'share' of the total lift takes priority in order to prevent the aeroplane from falling from the sky, so only the residual lift can be used to provide Cp, and the amount of residual lift depends upon the total lift developed and this in turn depends upon airspeed (assuming, as I have said, that the A/A is already set to max CL). The conversion of this residual lift into Cp will then depend upon the bank angle that can be set. However, because of this prioritized dual requirement the Cp produced can never be as much as it was in the idealized zero gravity situation but it can come close as bank angle is increased and it is this relationship between speed and bank angle which determines the degree to which the turn radius can be decreased. To put it simply; improvement in turn performance can only come from increased airspeed and bank angle.

In Figure Five I have reproduced some diagrams I used in the lesson on manoeuvring showing an aeroplane turning at different speeds and bank angles. Note that the vertical component of the lift required to maintain level flight is always the same, so as speed increases increasing bank angles can be used, and so more of the increasing lift can be used to act as Cp, which results in decreasing turn radius.

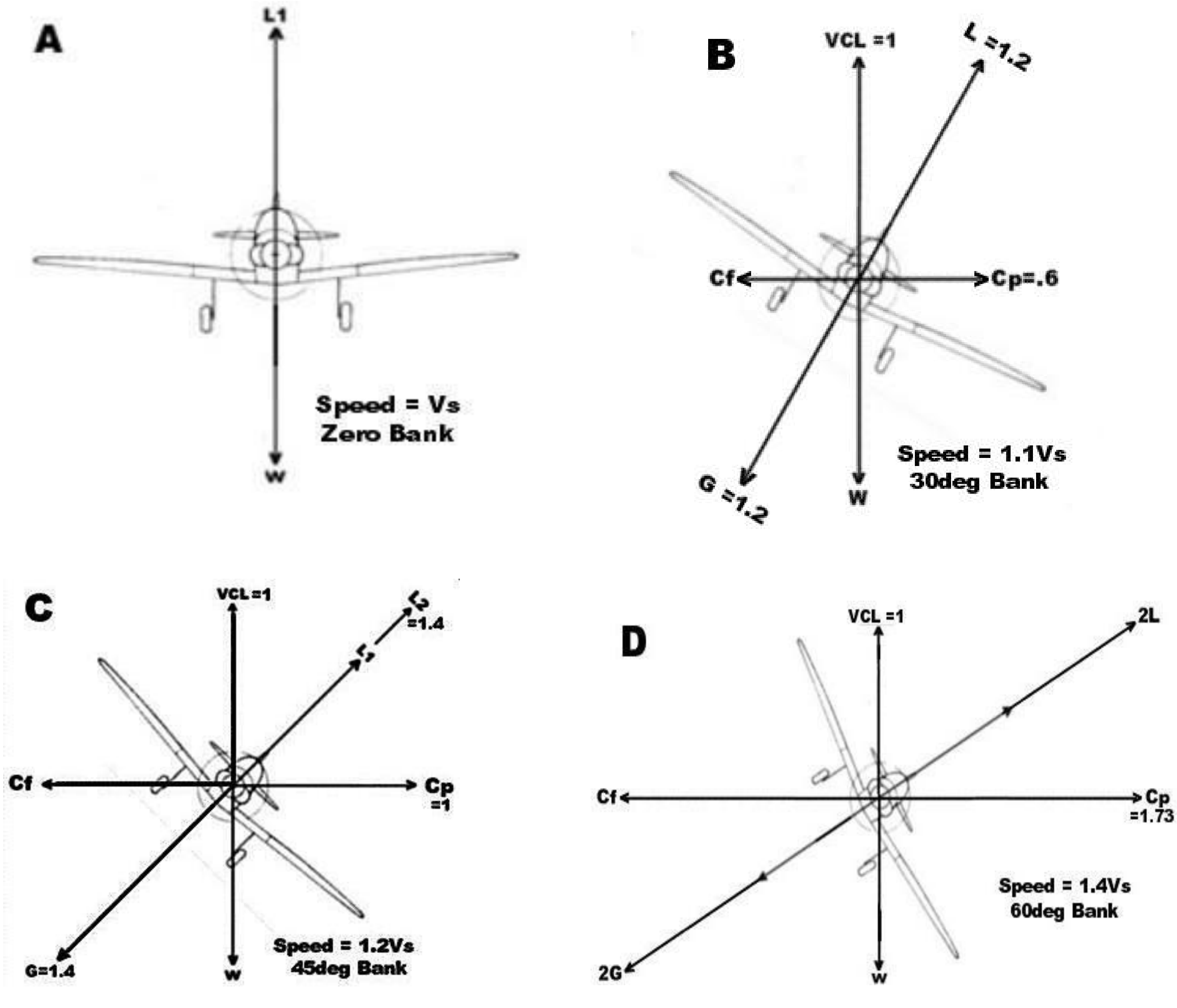


Figure Five – Cp at increasing Bank Angles

Let's be a little more specific. At **A** (in Figure Five) the aeroplane is flying at Vs and maximum C_L, it therefore cannot turn at all because it has no residual lift; all of its lift is required to oppose gravity. At **B** the aeroplane, still at max C_L, is flying at a speed of 1.1Vs (10% faster) and is therefore generating 1.2 times the lift (20% more lift) so it can be banked to 30º whilst still maintaining sufficient vertical component of lift to oppose gravity. Note that the Cp is only 0.6 of the vertical component (which is not as good as a motor car). At **C** the aeroplane is flying at max C_L and 1.2Vs (20% faster) and is generating 1.4 times the lift (40% more lift) so it can be banked to 45º. Note that the Cp is now equal to the vertical component (better than a motor car). At D the aeroplane is flying at max C_L and 1.4Vs (40% faster) and is generating twice the lift so it can be banked to 60º. Note that the Cp is now 1.73 times the vertical component which is only .27 short of the zero gravity ideal (about formula one race car Cp). In the forgoing examples from 30º to 60º of bank there has been a 27% speed increase requiring a 161% Cp increase to maintain the turn radius but the wings have produced 288% increase in Cp, so the turn is tighter, much tighter.

So let me restate what I said before: "In theory, minimum radius and maximum rate turns can made by flying as fast as possible and pulling as much 'G' as possible". Now since the 'G force' is the equal and opposite of the Lift Force, we can modify that statement to read: minimum radius and maximum rate turns can be made by flying as fast as possible and generating as much lift as possible.

The following graph (Figure Six) depicts turn radius versus indicated airspeed when flying at maximum $\mathbf{C_L}$ and the appropriate bank angle. Note that at Vs there is no turn at all, that is, the radius is infinitely large, and that the radius decreases exponentially to a minimum at infinite speed!

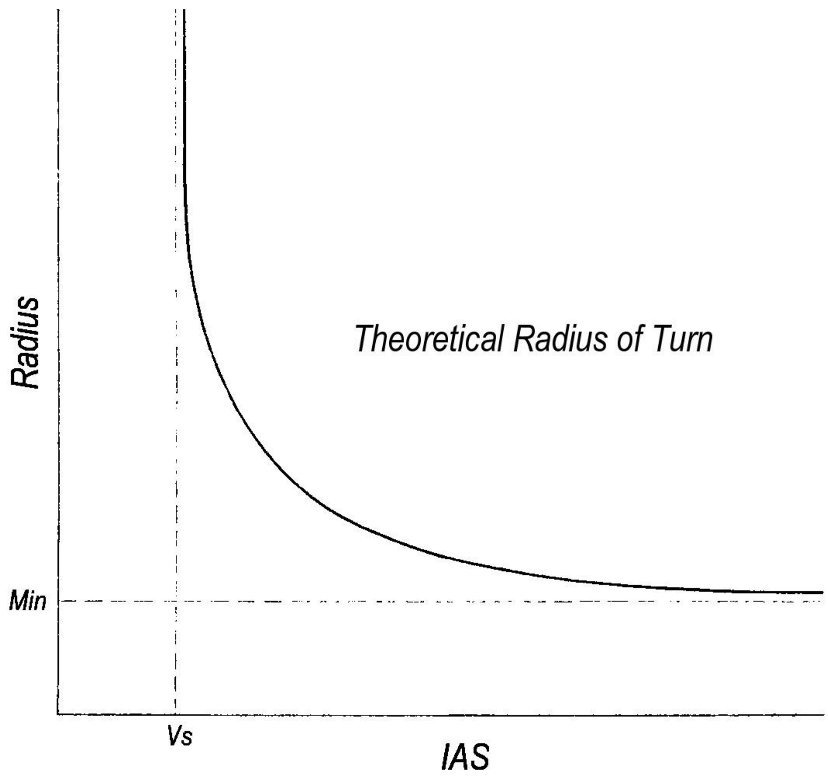


Figure Six – Turn Radius versus IAS

The following table details the appropriate bank angles at representative Vs speeds and the corresponding acceleration (G) at maximum **C**L .

1.0 Vs = 0º = 1.0 G
1.1 Vs = 30º= 1.2 G
1.2 Vs = 45º= 1.4 G
1.4 Vs = 60º= 2.0 G
1.7 Vs = 70º= 3.0 G
2.0 Vs = 75º= 4.0 G
2.5 Vs = 80º= 6.0 G

Note: the higher G loadings and bank angles in the foregoing table have been 'rounded' for simplicity.

At Annex A I have included a nomogram of level turn radius at any speed up to 300kts and any bank angle up to 80º, and I have also included some examples of its use. Try some examples of your own, you will find them 'enlightening'.

Earlier in this lesson I made the bold statement that the maximum lift/Cp that can be generated by a wing at any speed can only increase enough to maintain the turn radius as speed increases in the ideal zero gravity situation, and that the aeroplane cannot turn any tighter! I then went on to explain how, in the presence of gravity, the turn radius can never even be that good, but depending upon the speed and angle of bank which can be sustained the closer to the ideal zero gravity radius it can get. So I hope that all of this has raised the question in your mind…. "What is it that determines this fixed ideal minimum radius of turn in the first place?" And the answer is: **Wing Loading.**

An aeroplanes ideal (zero gravity) turn radius is fixed by its wing loading. If the wing loading of an aeroplane can be reduced by either reducing its weight or increasing its wing area (or both) its Vs will be reduced and its Vsm at any speed will also be reduced proportionally. With a low Vs the aeroplane can start turning at a lower airspeed, then, at any greater speed, the radius will be less than a high wing loaded aeroplane. Some simple mathematics to illustrate: Imagine two aeroplanes turning at 45ºbank (where Cp and the vertical component of lift are equal to 1 to make the sums simple). Aircraft A has a Vs of 42kts therefore a Vsm of 50kts, and aircraft B has a Vs of 59kts therefore a Vsm of 71kts:

A	$r = Vsm\ Low^2/1$	B	$r = Vsm\ High^2/1$
	$r = 50^2/1$		$r = 71^2/1$
	$r = 2500/1$		$r = 5000/1$
	$r = 2500$		$r = 5000$

Aircraft A has a turn radius half of that of aircraft B for only a 17kt difference in Vs. Looking at this aircraft comparison a different way, aircraft A can be turning with 60º of bank at 59kts whereas aircraft B can only maintain straight and level flight at that speed! Therefore A has a good 'head start' on B.

You can see this effect of wing loading in more general terms in the following diagram (Figure Seven).

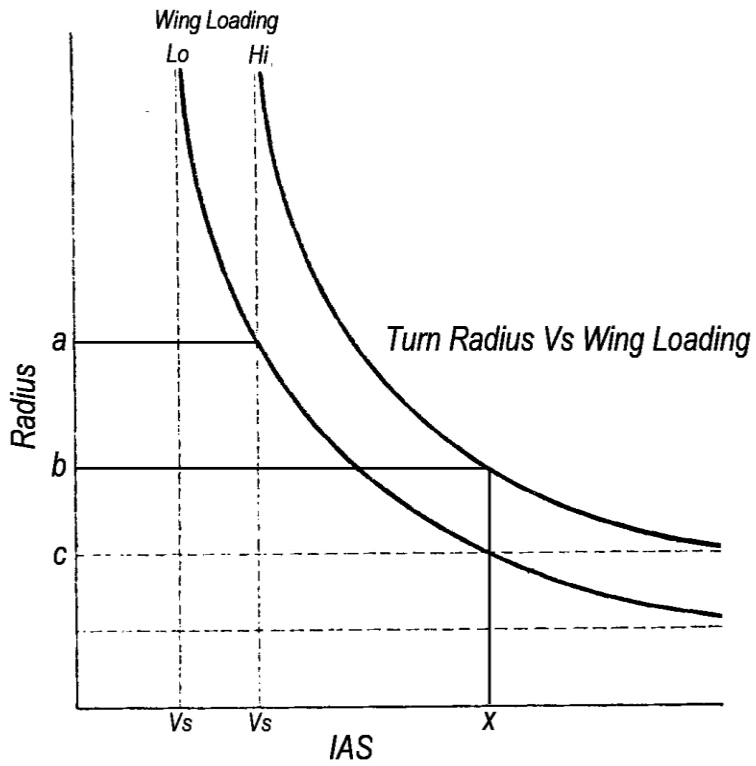


Figure Seven – Turn Radius versus Wing Loading

At a speed of Vs (Hi), the low wing loaded aircraft is already turning at radius 'a' whilst at speed '**x**' the low wing loaded aircraft is turning at radius 'c' but the high wing loaded aircraft is only turning at radius 'b'. Low wing loading is a major factor in a 'fighter' aircraft's ability to 'out turn' its opponent and your ability to turn inside that valley.

Remember at the beginning of this lesson I eliminated **'m'** (mass) from the turn radius formula to make the explanation simple? Well, since the mass of the aeroplane is the same as its weight (on Earth) and provided the wing area of the aeroplane doesn't change, an increased wing loading equates to an increased mass. That is; twice the mass, twice the wing loading, etc. So let's put the wing loading into the formula where **'m'** used to be (I have used the symbol W_L for wing loading):

$$\mathbf{r = W_L v^2/Cp}$$

As we have learned from the lesson on stalling, if we have two identical aeroplanes, except one weighs twice the other, the heavier aeroplane will stall 41% faster than the lighter aeroplane, so if, as in the previous example, the lighter aeroplane has a Vs of 42kts the heavier aeroplanes Vs will be 59kts. So now instead of calculating stall velocities in manoeuvres to calculate turn radius all you have to do is insert the relative wing loading into the preceding formula using the empty weight Vs for **'V'** to get the same result. To put all this simply: double the weight = double the wing loading = double the turn radius.

What happens to an aeroplane's turn capability as it climbs higher into the sky? As altitude is gained the 'gap' between IAS and TAS increases, and since all the lift/Cp generated by the wings depends upon IAS, but the speed component of the velocity we have to change is TAS, the aeroplane doesn't turn as well at height as it does at sea level. Let me give you a simple example: Somewhere around 35,000 ft altitude the TAS is twice the IAS so 'V' in the formula has doubled but Cp remains unchanged (assuming the aeroplane could maintain the same IAS at that altitude, which is doubtful). So the minimum turn radius has increased by a factor of 4 and the maximum rate of turn decreased by a similar proportion (which is what we saw back in Figure Three). Now a light aeroplane cannot climb high enough to experience such a degradation of turn performance, but any difference between IAS and TAS will increase the minimum turn radius and decrease the maximum turn rate somewhat, which is an important point to remember when flying through that valley high up in the mountains. The following graph illustrates (Figure Eight).

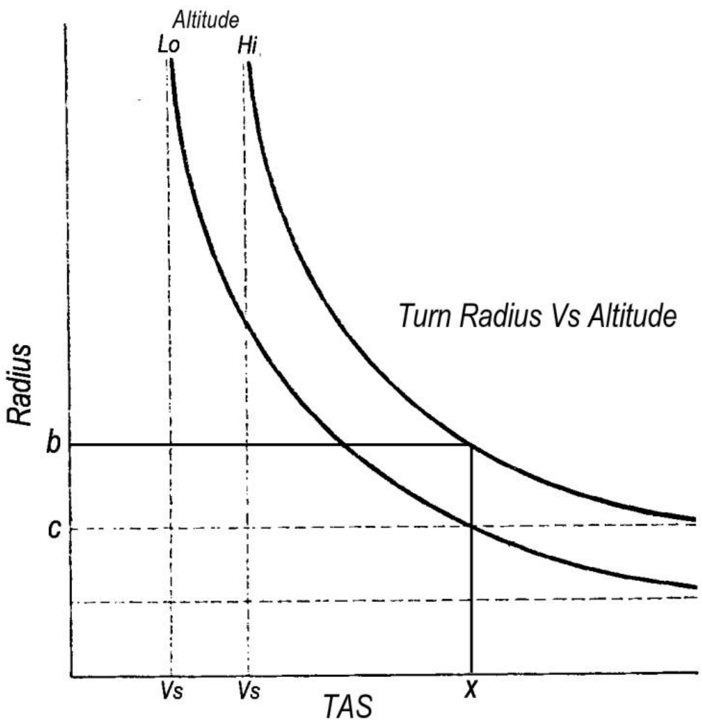


Figure Eight – Turn Radius versus Altitude

You will note that this graph looks very similar to the graph of turn radius versus wing loading, but it has one important difference: the horizontal axis represents **TAS.** At low altitude the TAS and IAS are virtually the same (at zero density altitude), but as altitude increases the graph moves up and to the right, which at any particular TAS (‘**x**’), represents a degradation of turn performance (radius ‘c’ increases to radius ‘b’).

So, to summarize what we have determined so far: to fly a minimum radius and maximum rate level turn we must have the lowest wing loading possible, the lowest density altitude possible, the fastest indicated airspeed possible, the maximum **C_L** possible, and the appropriate bank angle to maintain level flight. Are you still with me?

Now we have seen from the lessons on Drag, Power and Structural Limits, that a light aeroplane is limited in its ability to execute and sustain a tight turn. The power available is usually not enough to meet the power required during the turn, and what power that is available diminishes with altitude. This means that the aeroplane, upon entering a tight turn, slows down rapidly as the turn progresses (See Annex B). Also the ability to operate at maximum **C_L** at high speed is limited by the structural strength limits of the airframe. I refer you back to the manoeuvre envelope diagrams in the lesson on Structural Limits. If the aeroplane is capable of cruising at speeds above **Vo** it must be slowed to this speed before maximum **C_L** can be attained or the aeroplane will be ‘overstressed’. Alternatively, the aviator will have to limit the ‘G’ applied upon entry to the turn to the limiting ‘G’ for its category of operation, and wait for the increased drag to slow it down! Obviously an aerobatic category aeroplane limited to +6 G can initially turn tighter than a normal category aeroplane limited to only +3.8 G. *(However, it would be pretty silly to fly a fully serviceable aeroplane into a valley wall if a little more G than the published limit could prevent it.)*

If you go into the bar in the officers mess (officers’ club in the USA) in the evening at any air force fighter base, and listen to the young fighter pilots talking and bragging about the ‘dog fights’ they have had during the week, you will regularly hear phrases like “corner velocity” or “I was at the corner and turning on a dime” and you could be forgiven for wondering what the devil they were talking about. ‘The corner’ is not the intersection of two streets in the local town, it is where the stall boundary line of the aircraft’s manoeuvre envelope ‘turns the corner’ at the ‘G’ limit line (see Figure Nine). In other words, at **Vo** and Max G on the stall ‘buzz’. That is where a fighter pilot ‘lives’, because that is where he gets ‘min radius/max rate’ turns in order to ‘Wax’ the other guys ‘tail’. (Of course the ‘other guy’ is trying to do exactly the same thing...that’s the fun of it.)

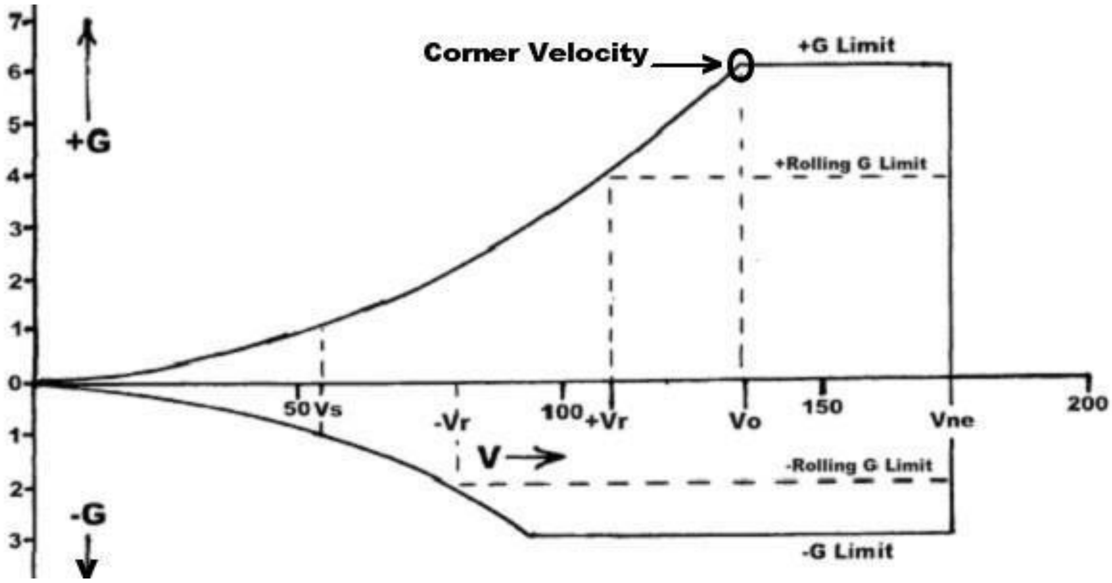


Figure Nine – Corner Velocity

Earlier I said that if we can reduce Vs, the turn radius will be less at all other speeds, so this should have raised the question in your mind about lift augmentation devices like Slats and Flaps. If these devices had no speed or structural limits they could assist a tight turn, but, unfortunately, most of them do have serious limits. The Slats on a Tiger Moth had to be locked closed before performing any aggressive manoeuvres to prevent them being ripped off, and flaps usually have speed limits well below Vo and impose more stringent 'G' limits on the aeroplane too. The Robin 2160 that I used to operate in my flying school had a +6 G limit with the flaps up but only a +2 G limit with them down. This of course made them pretty useless as a manoeuvre augmentation device. If, for some reason, a minimum radius turn had to be sustained for more than just a 'U turn', and if the increased drag had reduced the IAS to 1.4Vs (2.0 G), then setting the flap to the 'Take off' position improved the turn a little, but I cannot imagine any circumstances where this would be necessary in normal operations. Some early jet fighters were equipped with 'combat flaps'; useful at low altitude, but useless at high altitude where high Mach numbers occur at low IAS. (Manoeuvring at high Mach numbers introduces other factors beyond the scope of this book.)

These discussions, mathematics and graphs are predicated upon the need to maintain level flight whilst turning. If, and it is a big **If**, some altitude can be sacrificed safely then an initial bank angle of 90º can be used to start the aeroplane turning effectively whilst it still has speed. Of course without a vertical component of lift the nose attitude will fall and the aeroplane will start descending. Once the attitude has fallen as far as you 'dare' the bank can be reduced to stop it falling further, and then progressively reduced more to hold the new attitude as the speed decays (the technique to hold the A/A and control attitude with bank is detailed in Book Two, Lessons 7 & 8). Of course the airspeed will decay a little slower because the aeroplane is getting a 'downhill' gravity assist. The improvement in turn performance using this technique is hard to quantify as it will vary with how long the over bank can be sustained and the resulting final attitude and airspeed. The biggest pitfall (pun intended) with this technique is that valleys formed by the erosion of rivers get narrower as you get lower, so despite the fact that the aeroplanes turn radius will be reduced a little, the space available as you descend may have reduced more!

If the aeroplane is capable of flying at the 'corner' of the manoeuvre envelope then ideally this is where it should be flown, remembering that it should also have a good roll rate to enable the aviator to quickly reverse the direction of the turn as the topography of the valley dictates. Valley flying at the 'corner' can be a wild ride; it needs proper training to be done safely.

Many years ago I spent a lot of time flying in the high valleys of Papua New Guinea and Irian Jaya in the DeHavilland Caribou. When fully loaded this aeroplane had a structural limit of only 2.8 G (less than civilian normal category) so its Vo was just below the flap limiting speed. The standard valley flying configuration was: Speed = Vo, Flaps 15º, RPM set for climb power (in case more power was needed in a hurry). Also the squadron's standard operating procedures included minimum altitudes to fly in each of the main valleys, which allowed enough room to perform a minimum radius level 'U turn' if the weather conditions prevented the flight continuing in that valley. Obviously the aircraft was flown close to one of the valley walls to best utilize the available space to turn in. It was quite startling to the uninitiated to see just how tight such a big aeroplane could be turned within one of these valleys. Obviously all squadron pilots practiced these turning techniques regularly.

I should close this lesson with the disclaimer that flying in mountain valleys as I have just described requires proper training because it can be quite hazardous. Many years ago a friend of mine was the captain of a Caribou carrying a full load of 28 passengers (plus 3 crew) enroute from Lae to Port Moresby in Papua New Guinea. He failed to complete a 'U turn' in a valley south of Lae and struck the valley wall. Only two passengers survived. The wreckage was found at an elevation below the operational minimum valley height. How he let himself get into that situation I do not know.

Never let an aeroplane take you to a place that your mind hasn't been five minutes before.

Annex A. Level Turn Radius Nomogram

Annex B. Thrust and power required in a 'limit' turn.

Annex A.

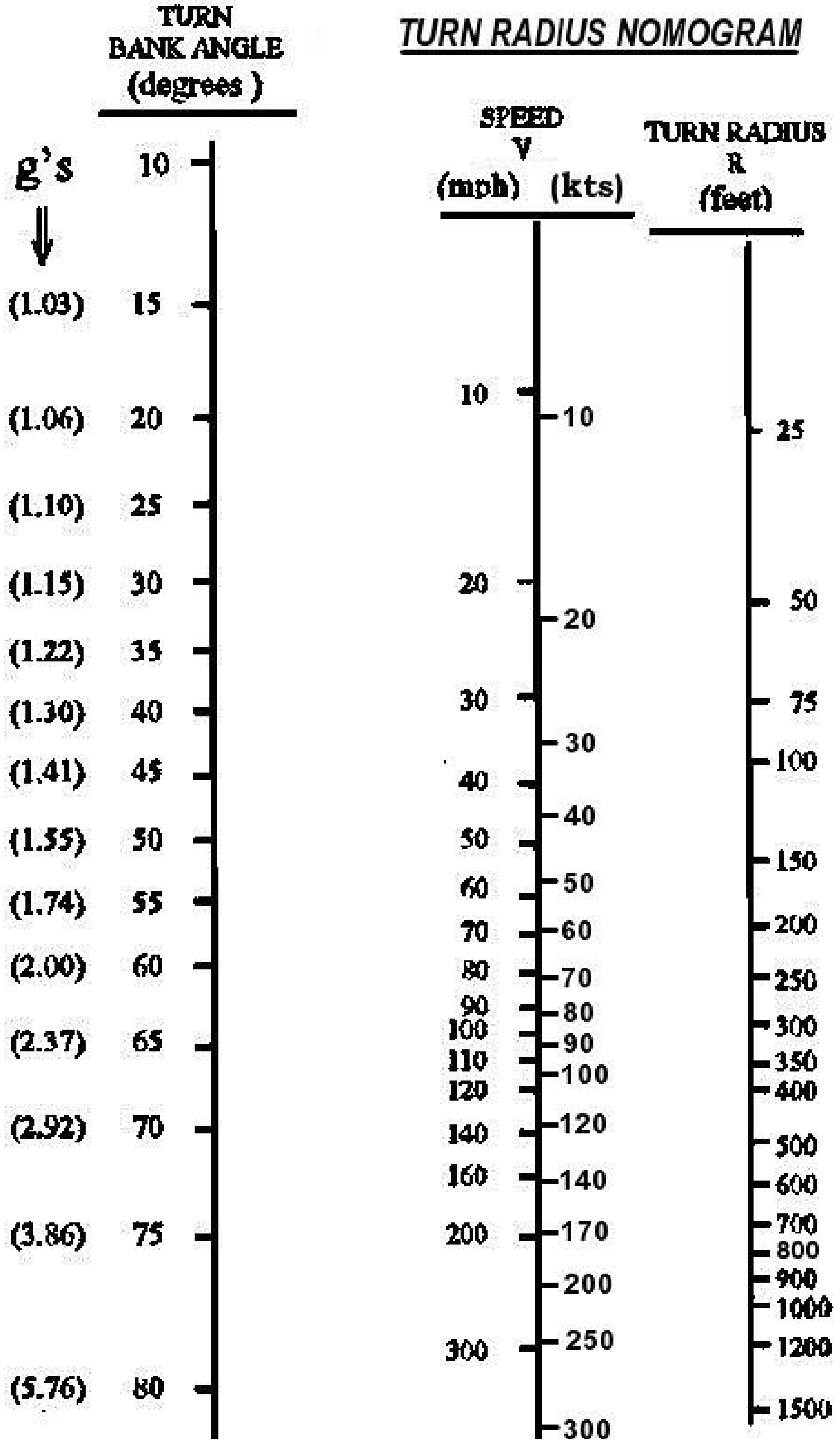


Figure One – Level Turn Radius Nomogram

To use the level turn radius nomogram at Figure One, draw a straight line from any bank angle in the left column through any speed in the centre column continuing to the turn radius in the right column. For example, draw a line from 45º bank through 100kts and note the turn radius is 850ft. Another: 60º at 120kt produces 700 ft radius, etc.

If the nomogram is to be used to determine minimum turn radius, the bank angle should be that which corresponds to the 'G' limit of the aeroplane, and the speed must be Vsm for that 'G' limit, which is Vo. Remember **Vo = Vs√Glimit**. In the following example (Figure Two) I have chosen an aeroplane with a Vs = 50kts, and placed it in four different speed and angle of bank situations.

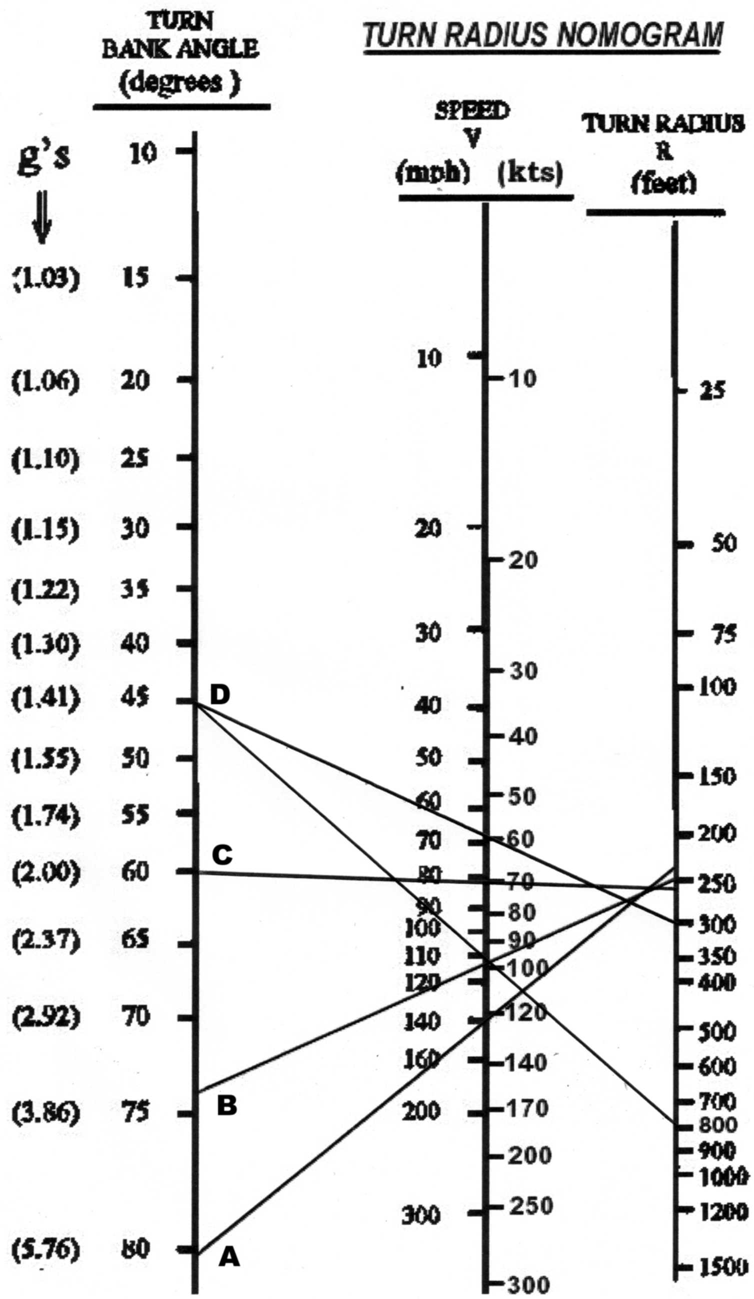


Figure Two – Turn Radius Examples

Referring to Figure Two: line A represents the aeroplane in the aerobatic category turning at the ‘corner’, that is, 6.0G at Vo (122kts).The line starts at 81ºof bank in the left column, runs through the 122kts scale at the centre column and terminates at a turn radius of 230ft in the right column. Line B represents the same aeroplane turning at the ‘corner’ in the normal category, that is, 3.8G at Vo (98kts). The line now starts at 74º of bank, runs through 98kts and terminates at a turn radius of 250ft. Line C represents the same aeroplane only flying at 2G and at Vsm (70kts). The line extends from 60º of bank, through 70kts and terminates at a turn radius of 260ft. Finally at D the aeroplane is back at a Vsm of 60kts at 45º of bank which produces a turn radius of 300ft. You can see from these examples that even though the aeroplane is flying at max C_L in each case, the greater speed, G and angle of bank produces the ‘tighter’ turn radius. Also, the faster aeroplane will fly around its curve much quicker, that is, its rate of turn will be much greater too.

It is interesting to see that all of the different turn radii are within 70ft of each other, the differences being dependent on how much of the lift is converted to Cp. In 90º bank zero gravity turns at these speeds they would all be focused on a single point just a little tighter than A.

Now you could argue that a difference in radius of 70ft over these four examples is not very much, and I would agree with you. If 70ft means the difference between life and death what the hell are you doing flying in such a ‘tight’ situation? However, most non-aerobatic pilots have never been trained to fly anywhere near the limits of their aeroplane and will, therefore, probably not be able to turn the aeroplane at radii anywhere near its actual capability. The Private Pilot Licence training conducted in many countries calls a 45º banked turn a ‘steep turn’ and never even demonstrates turns at higher angles of bank! Most of the private pilots who came to my school for aerobatic training were in this category, but to their credit they recognized their serious limitations and came to me to rectify this deficiency. A pilot trained so poorly when turning with only 45º of bank at 98kts, as illustrated by the second line emanating from point D on the nomogram at Figure Two, will only achieve a turn radius of 800ft! This is more than three times greater than the aeroplane’s capability at that speed, and <u>that</u> could mean the difference between life and death!

I am aware that many pilots and flying instructors advocate that when flying in mountain valleys that the aeroplane should be slowed and flap extended in the belief that it will enable them to turn ‘tighter’, but, as detailed in this lesson, this just isn’t so. The slow speed may give them more time to assess the conditions prior to turning back or running straight ahead into a mountain, but often a slow speed turn will simply take the aeroplane to the scene of the crash! These flying instructors have ‘put the cart before the horse’ in that they are recommending reducing the airspeed to match the maximum angle of bank that the pilot is capable of flying rather than matching the angle of bank (and G) to the airspeed, that is, limiting the aeroplanes potential to that of its pilot. So if this is the way you have been trained and if 45º of bank is the best you can do then you had better reduce speed to 1.2Vs (Vsm for 1.4G) to get anywhere near a reduced radius turn.

So, pick some numbers that fit your aeroplane and how you have been trained to fly it, and then put them into the nomogram to see how far from the aeroplanes potential turn performance your training has left you. If you cannot fly your aeroplane with at least a 60º bank angle whilst holding an angle of attack close to C_L max I suggest you stay well away from mountain valleys or go and find a senior flying instructor who can teach you how to fly properly.

Annex B

Thrust and Power required in a 'Limit Turn'.

Throughout the preceding lessons on Drag, Power and Manoeuvring, I have developed graphs of Total Drag, Thrust Required/Thrust Available, and Power Required/Power Available, at increasing bank angles and G. The following are similar graphs taken to the 74º bank, 3.8G limit of the same (normal category) aeroplane. Study them and you will see why a light aeroplane turning at the limit slows down rapidly. The first graph below (Figure One) shows the 'Drag Curve' in a level 74º banked, 3.8G turn (This relationship of bank and 'G' was taken from the nomogram at Annex A.)

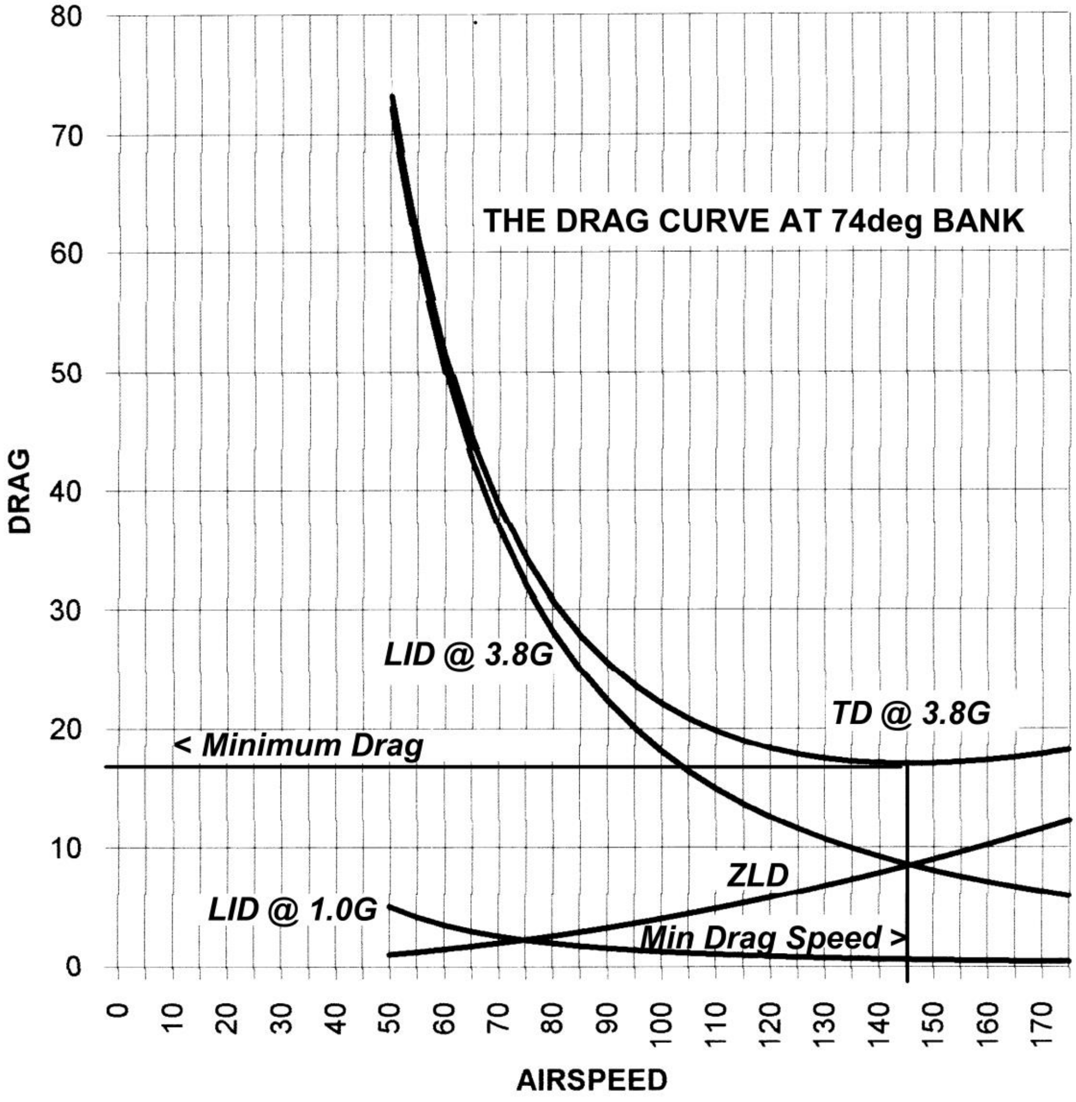


Figure One – Drag Curve at 74º bank and 3.8G

You can see from this graph that the minimum drag speed is now 145kts, which is much faster that the aircraft's cruise speed. Or looked at another way, at cruise speed the aircraft is already on the 'backside' of the 3.8G drag curve!

Also note that the minimum drag is 3.8 times what it was in 1G flight (you will have to refer back to the 1G graph in lesson on Drag to verify this). Let's now superimpose the thrust and power curves and see what we get (Figure Two).

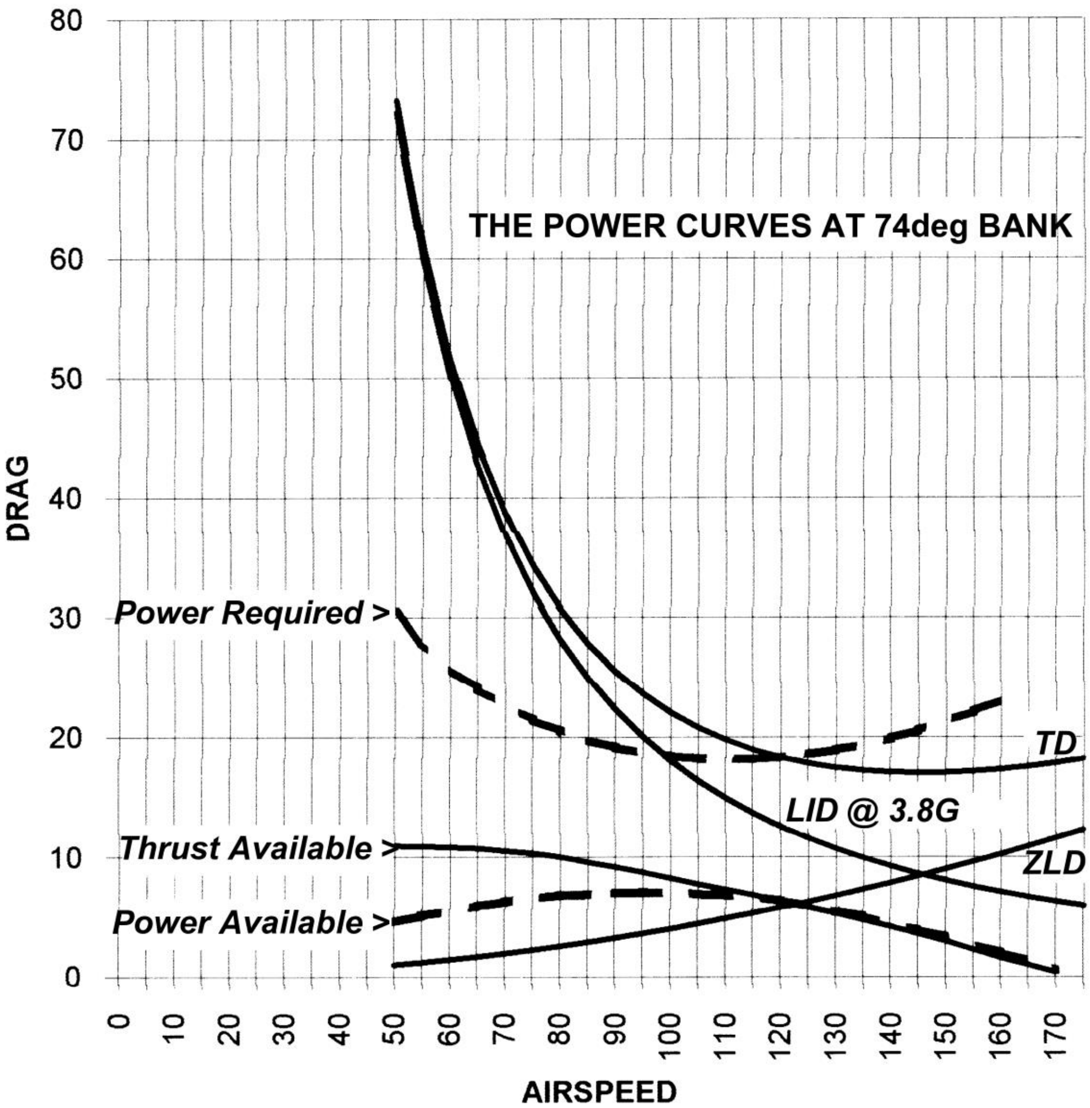


Figure Two – Power Required at 3.8G

The power required and power available curves are closest at about 105kts, but even at this speed the power required is more than twice the power available! Obviously the engine cannot sustain any speed at this 'G', so despite the fact that the airframe is capable of manoeuvring to 3.8G, the aeroplane cannot realize its optimum turn capability. The aeroplane will slow rapidly once a limit turn is commenced and the radius of the turn will increase as the turn progresses.

In order to make a level 'U turn' in a valley most efficiently in this aeroplane, the pilot should initiate a turn at the structural limit of the aeroplane, apply full power, and whilst holding the angle of attack at the critical angle (on the buzz) progressively reduce bank as the aeroplane slows such that the vertical component of lift is always **1**, that is, to maintain level flight.

In the following nomogram (Figure Three) I have shown turn radius lines at three points as the aeroplane slows. Point A is the 3.8G/74º starting point at Vo = 98kts. At point B the aircraft has slowed to 71kts (1.41Vs and 2.0G) so the bank angle has been progressively reduced to 60º, and finally, at point C, the speed is down to 59kts (1.2Vs and 1.4G) and the bank angle has been reduced to 45º. Remember that at all times during this turn, the aviator is holding critical A/A (or just short of it) to maintain **CL** at a maximum.

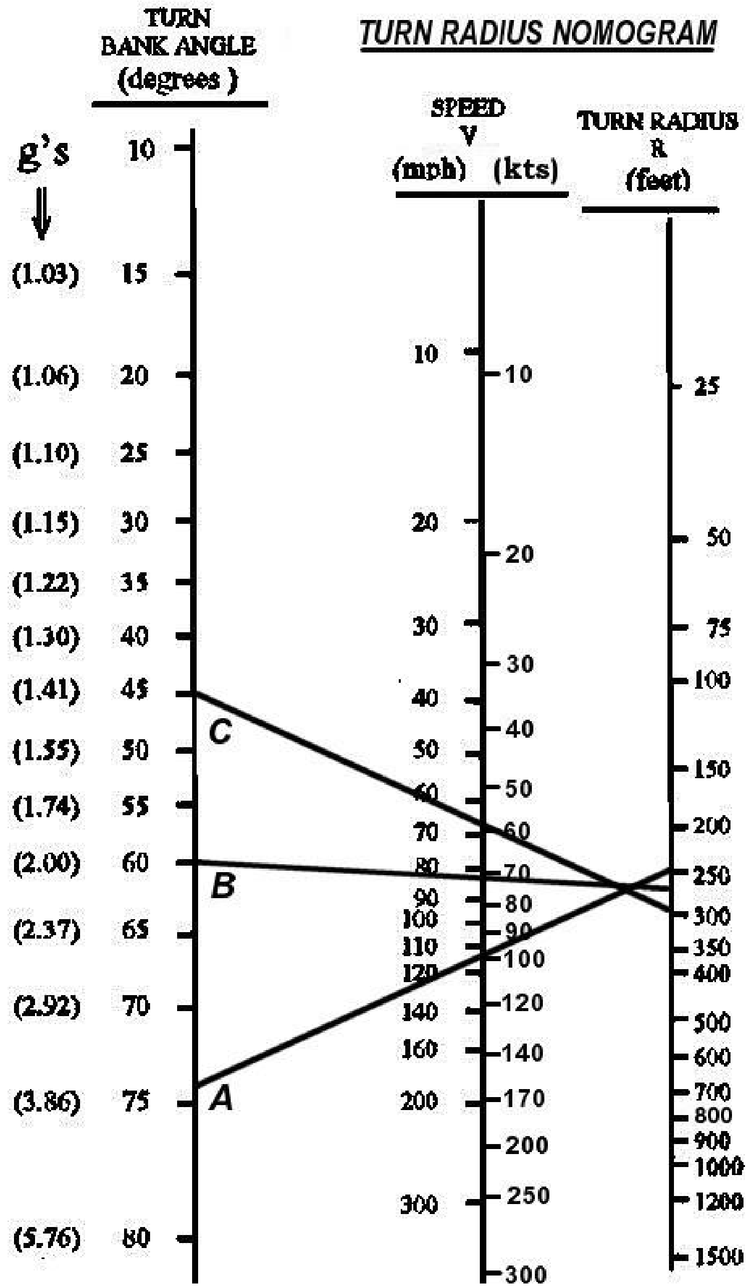


Figure Three – Increasing turn radius as aircraft slows

You can see that the turn radius increases from 250ft to 300ft as the aeroplane slows. However 300ft is still not too bad and sometime during the latter part of this turn the heading will have changed 180º, thereby enabling the pilot to stop turning and fly home and change his underwear!

Footnote:

I have often been asked about the advantages of thrust vectoring during a limit turn by those aeroplanes capable of it. The only aeroplanes that I am aware of that have this capability are the Hawker Harrier and its derivatives, the F-22 and F-35 (and their Russian counterparts), all of which are ‘heavy metal’ military aeroplanes. Of course this capability is beyond a general aviation aeroplane and the scope of this book, but it is interesting to ponder its implications for a moment, if for no other reason than to see if you have understood this and previous lessons.

Imagine a Hawker Harrier tuning at 6G. It will need all of its available thrust to overcome the very high drag at the near critical A/A in order to maintain the airspeed and enable the wings to continue to generate the lift/Cp to sustain this acceleration. If, during this turn, the pilot alters the direction of the thrust to the ‘take-off’ position the aeroplane will experience an increase of centripetal force sufficient to increase the G to 7 (6 from the wings plus 1 from the thrust, assuming a 1:1 thrust to weight ratio) with the associated decrease in turn radius, but for how long? Once the thrust has been ‘vectored’ there is no longer any propulsive force so the aeroplane will slow rapidly. How much airspeed needs to be lost before the wings 6G capability is reduced to 5G and this momentary 7G ‘boost’ reduced to the original 6G?

Well 5G is 83% of 6G, so the lift must reduce to a value of .83 of the original, and this will occur with a speed reduction to √.83 which is .91 of the original. Therefore it only needs a 9% reduction in initial airspeed to reduce the turn radius from its momentary 7G back to the original 6G, and this will happen in just a few seconds, (indeed it will be like hitting a brick wall) and it will now continue to reduce rapidly towards no turn at all! If this were used in an air combat situation it would be a “last ditch manoeuvre” which may avoid being shot but would leave the Harrier quite vulnerable to further attack.

Wings are a much more efficient generator of lift than engines, so it is far better to let them produce the lift and let the engines overcome the drag.

Hmm… something to do with Lift/Drag Ratio perhaps…think about it.

Lesson Fifteen

HUMAN LIMITS

In the lesson on Aircraft Structural Limits we looked at the effects of acceleration on the structural integrity of the aircraft. I would now like to address the effects on the Aviator, particularly the cardio/vascular/circulatory system, during these same accelerations.

Every living cell in the human body needs oxygen every second of the day and night, especially the brain and the eyes. (Two vital organs which are particularly sensitive to oxygen flow). This oxygen is carried to the cells throughout the body by the bloodstream via the arteries, veins and capillaries as a result of positive pressure provided by the heart. The heart itself is simply a double chamber pressure pump driven by variable muscle power.

For the majority of the population (99.9%), this blood circulation goes on day and night in 1G acceleration due only to the Earth's gravity. The rest of the population (.1%), that venture into the air, expect this circulation system to continue unaffected by accelerations many times greater than 1G, and within reason it can, but there are limits. It is these limits that I wish to talk about.

When the body is subjected to accelerations greater than 1G the heart has to pump harder to maintain blood pressure to the upper body, particularly to the brain and the eyes. In a normal sitting or standing position the brain and the eyes are about 30 centimeters above the heart, so under 1G the heart has to maintain a 30cm 'head of pressure' to keep them oxygenated. In a 2G environment the heart has to pump twice as hard to maintain the equivalent of a 60cm head of pressure, and at 3G, three times as hard to maintain the equivalent of a 90cm head of pressure, etc. If at 3G the heart is only pumping hard enough to support a 60cm head of pressure there is going to be a significant drop in blood pressure and an associated reduction of oxygen flow to these two vital organs.

Pressure sensors in the brain send signals to the heart telling it to "pick up the stroke" if any drop in blood pressure is sensed. The heart does this, but it can take up to 15 seconds to fully respond to the demand, depending upon the rate of drop in pressure (rate of application of G), and it can only ultimately sustain an increased pressure equivalent to about a 120cm head of pressure (4G).

All of the figures I am stating here are approximations for 'Joe Average'. Each persons 'G tolerance' is a little different, and they are in themselves different at different times of the day depending upon fatigue, exertion, meals and general fitness, and a host of other physiological things. But individual variations from Joe Average are usually no more than 10-15%.

Now each cell carries within it a small oxygen reserve, as if it was wearing a mini ‘Scuba Tank’. The tank size is about the same for all cells but the duration of the reserve supply depends upon how fast the cell uses oxygen. The brain cells use oxygen at a prodigious rate and usually consume their reserve within 5 seconds! Are we starting to note a design defect here?

If the heart can take up to 15 seconds to respond to increased demand but the brain’s oxygen reserve can be consumed in only 5 seconds, what does the brain do for the other 10 seconds? ......Why, it goes to sleep!!

Now the brain is the human body’s ‘central processor unit’ (CPU), to use modern computer jargon; information about the external world streams into the brain through our senses and is then processed and integrated into thoughts words and actions. If the brain goes ‘off line’ for any period of time whilst flying an aeroplane the result can be disastrous. An aviator, in addition to understanding the structural limits of his/her aeroplane should also understand the physiological limits of their body’s ability to keep its CPU ‘on line’.....that is, not putting it to sleep with excessive acceleration.

The modern acronym for this ‘going to sleep’ is ‘GLOC’, which stands for **G** induced **L**oss **O**f **C**onsciousness. Back in the ‘good old days’ this was called ‘Black Out’, because you obviously lose vision when you ‘go to sleep’. But it is possible to ‘Black out’ without GLOC! How can this be? Well, the different cells of the eyes use the oxygen in their ‘Scuba Tanks’ at different rates, so it is possible to progressively loose vision prior to GLOC as the G builds. First colour acuity goes, then peripheral vision and finally focal vision fails over about a 1G range. So what we see initially goes grey, followed by ‘tunnel vision’ and finally black. This progressive loss of vision is often regarded as the ‘early warning’ of impending GLOC, but occasionally the rate of increase of G can be at such a rate, and the G sustained at such a level, that only black out occurs and the increasing heart rate ‘saves the day’ for the brain. It is a fine line to draw. I have only experienced this phenomena a couple of times.

As the ‘onset rate’ of G increases, this ‘fine line’ gets even finer, to the point that the ‘grey out’, ‘black out’ and the GLOC occur virtually simultaneously, so the aviator gets no warning at all! This is called ‘instantaneous GLOC’.

A common mis-belief is that once the G is relaxed, consciousness returns immediately. It doesn’t! Vision is the first thing to return once the G is relaxed, but it takes ‘Joe Average’ 20-30 seconds to regain useful consciousness once he has GLOC’d. By “useful” I mean being able to respond to the situation around him. His eyes will be open and he may be able to utter phrases like “what happened?” or “where am I?” etc, after 10-15 seconds, but this is hardly useful.

So if Joe Average Pilot GLOC's at 4G at 3000 feet altitude going downhill at 120Kts (203 ft/sec) he is going to reach the ground right about the time he first opens his eyes! He may even have time to think "what is that big green thing coming toward me?" But it will be his last thought.

Going back to the 'good old days' once more, in England in 1940 at the height of the 'Battle of Britain', many fighter aircraft were seen diving away from an 'engagement' for no apparent reason, often diving into the English Channel. Those pilots who did recover had no recollection why they had 'lost contact' with the fight and most were reluctant to talk about it.

The aero medical specialists of the time drew a chart to assist these pilots understanding of what they thought was happening at high G. It looked like this (Figure One).

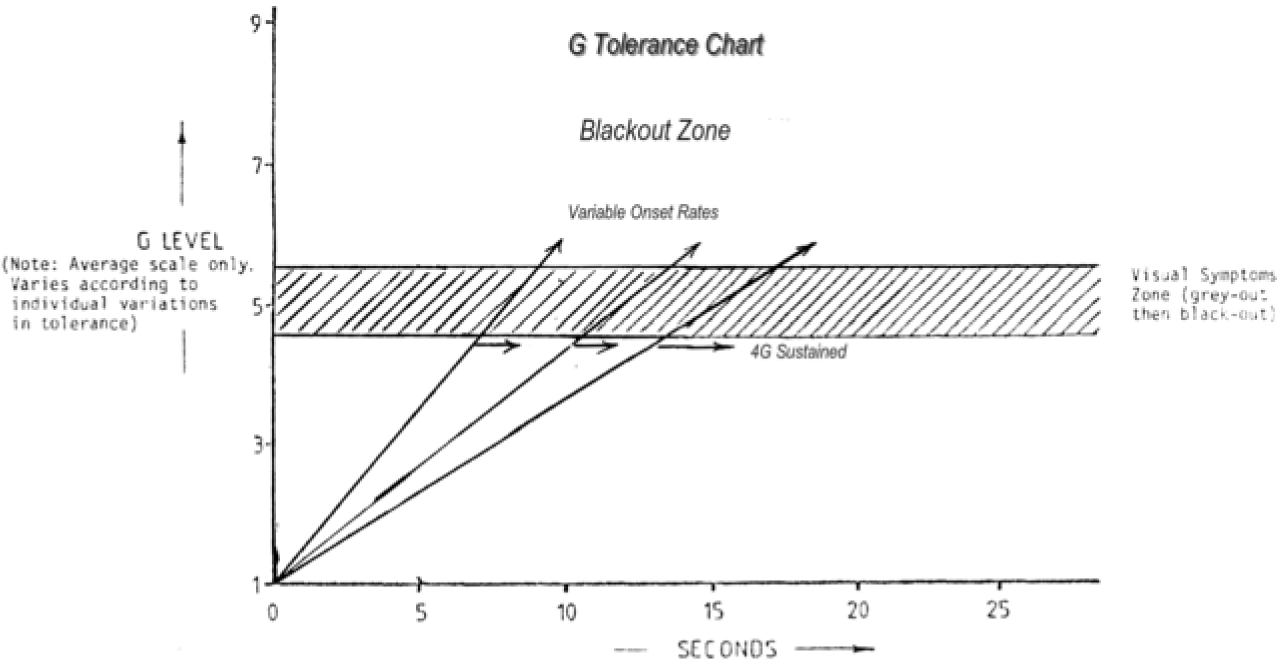


Figure One – Early 'G' Tolerance Chart

This diagram shows three different rates of 'onset' of G, and a band where the eyes start to progressively lose vision, which was called the 'Grey Out' band, within which the eyes first lost colour vision, then peripheral vision, before the final 'Black Out'. The diagram made no distinction between the various rates of application of G, and no allowance for the 'Scuba Tanks'.

This was the chart that I and my class mates were presented with during air force pilot training in the early 1960's. It was extracted from an old RAF manual written in the 1950's.

The next development of this chart was to allow for the 'Scuba Tanks' and this is shown in the following diagram (Figure Two).

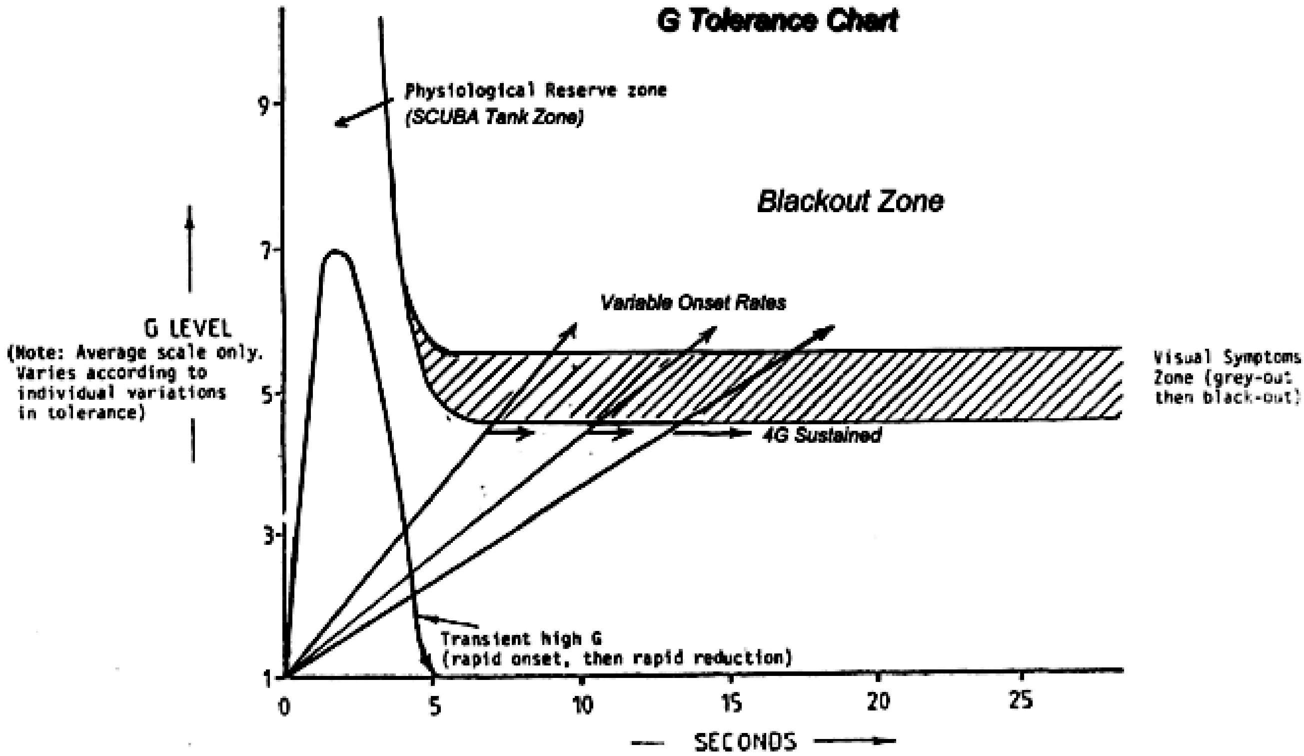


Figure Two – 'Scuba Tank' improvement of 'G' Tolerance Chart

This chart showed that the aviator could withstand quite high G for a few seconds before any adverse effects were experienced. For example: A very rapid onset rate is experienced if you were to hit a large bump in the road whilst driving a car at speed – wham! It could be 6 or 8 G instantly. This is depicted by the line representing the rapid application and relaxation of G within that 5 second time frame (the 'transient high G' line), but there was still no distinction between the various 'onset rates' outside of the 'Scuba Tank Zone'.

Up until only a few years ago, a fighter pilot, upon firing his ejection seat, could experience up to +25G with an 'onset rate' of 300G/second!! It was like being shot out of a cannon.....literally. Each of these experiences occurs within the duration of the 'Scuba Tanks' and therefore has no effect on the pilots useful consciousness. The car may have broken suspension and the pilot a broken back, but loss of consciousness is not a problem. (Nowadays ejection seats are rocket propelled for a smoother 'ride'.)

Wild turbulence, like that experienced within a thunderstorm, or 'snatching' the stick back at speeds above Vo (and then releasing it) can have the same effect. In the 1960's there were few aeroplanes that could allow the pilot to 'snatch' the stick back to 6G and then sustain a 6G manoeuvre for more than a few seconds (remember the induced drag leaps to 36 times normal at 6L), but by the 1980's there were aeroplanes developed, like the F-15 and F-16, and similar types which can pull and sustain 6 or 7G!

Pilots of these types of aeroplanes were losing consciousness without warning after 4-5 seconds in such manoeuvres. It was then found that this could happen at much lower G if the onset was too quick for the heart to 'keep up' and the G sustained. Whilst the heart is capable of maintaining blood pressure at 4G it cannot effectively respond to it being applied at a rate of more than about ½G per second (remember it takes a while to 'pick up the stroke'), so this effect had to be incorporated into the chart too. Figure Three shows a modern GLOC chart.

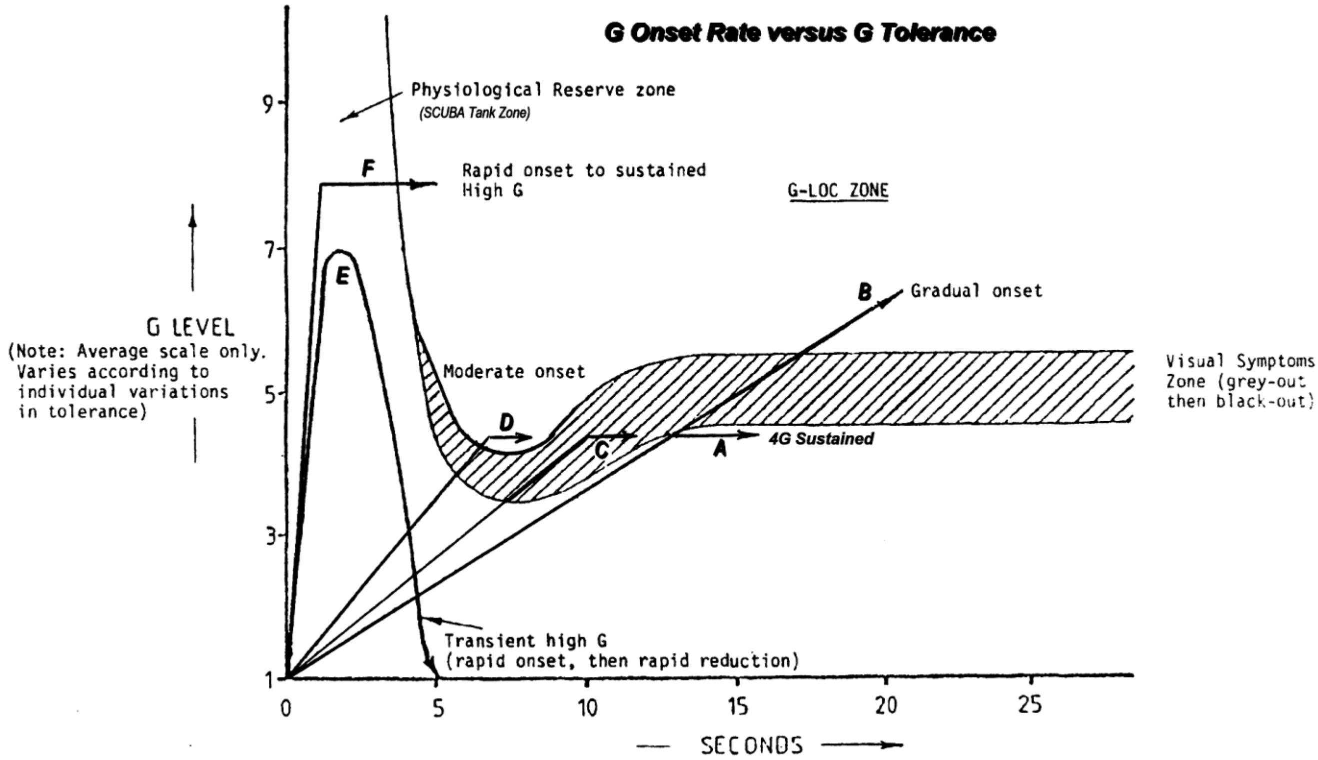


Figure Three – Modern 'GLOC' Chart

The 'dip' in the chart between 5 and 15 seconds is the result of the 'design defect' in our bodies. This is the time it takes the heart to 'pick up the stroke'.

I have shown different onset rates versus G tolerance on this chart. Study it for a few moments and compare it with the previous chart. The gradual onset of rate A stays fully in the 'safe' zone to a sustained 4G acceleration, but if it is continued to B it will pass through the 'grey out' warning zone to the GLOC zone. Onset rate C enters the 'grey out' zone to a sustained 4G, and vision returns as the heart 'catches up'. Onset rate D enters the GLOC zone at the same 4G with less 'grey out' warning. Onset rate E stays within the 'Scuba Tank' zone whilst onset rate F causes 'instantaneous GLOC'!

Modern aerobatic aeroplanes can 'pull' 8-10G for a couple of seconds (onset rate E), or pull <u>and sustain</u> 4-5G, for a lot longer (onset rate D). This latter situation puts their pilot's right in the middle of the dip in the chart - right in the danger zone!

Knowing about this problem allows us to assist the heart in providing the extra blood pressure necessary, and thereby improve our G tolerance. How do we do this?

Imagine the human body is a long rubber tube full of blood. When this tube is held at one end (the head) and whirled around, the centrifugal force causes the blood to flow away from the head and pool in the boots, causing the 'rubbery' arteries to distend to accommodate it. Squeezing the bottom half of this rubber tube stops the arteries distending and gives the blood nowhere to go. Another analogy: take a toothpaste tube and squeeze it at the bottom...toothpaste flows out of the hole at the top (provided we have removed the cap of course). Either way you look at it, what we have to do with the human body is to squeeze the bottom half to stop the blood pooling in our boots, and forcing some of it back up to our head, thereby helping the heart provide the required blood pressure.

Of course all of this talk of "up and down" assumes that the pilot is sitting about the same way as you are now, that is with the upper part of the body near vertical and the legs much lower. Modern jet fighters and specialist aerobatic aeroplanes have the pilot's upper body reclining at an angle of about 30º and his legs elevated to near horizontal. This decreases the head to heart distance to about 20cm whilst the legs are no longer where the blood wants to pool. Space shuttle astronauts lie on their back during the launch phase as the space shuttle accelerates away from the earth at 9G sustained for about 10 minutes!

For those of us who don't fly a space shuttle or an F-22 or the latest 'plastic fantastic' aerobatic aircraft, we have to sit a little more upright and deal with the problem another way. We have to tension the muscles of our abdomen and legs to constrict the arteries in that area as we apply the G. It is a sort of 'isometric exercise' for the lower body. The "as we apply the G" part is important; if we only do it as we feel the grey out coming on it will be too late for this straining manoeuvre to have any effect. This will take a little practice and can become physically fatiguing within a short time, which is counter productive as fatigue decreases our G tolerance. But done properly this straining manoeuvre can increase our G tolerance by about 1.5G.

Jet fighter pilots are provided with a 'G suit', which is an elasticized pair of pants which look like a cowboy's 'chaps', but which contain inflatable bladders over the calves, thighs and pelvis. These bladders are connected via tubes to a 'G' activated compressed air valve which inflates the bladders with +1¼ psi overpressure per +1G and does the squeezing for the pilot. These pants are a tight fit so they have zippers down the inside of each leg for ease of fitting (and getting out of them after the flight). When a zipper fails at 6G the result is quite amusing as the now unconstrained rubber 'leg' flails around the cockpit bumping switches and controls and making a general nuisance of itself. (I speak from experience.)

I do not know of any civilian aeroplane in which a G suit can be used, so training the leg and abdomen muscles to perform this ‘straining manoeuvre’ is the only solution if you wish to get into the business of pulling ‘serious G’. Aerobic fitness alone, whilst good for general health, does not help G tolerance because an aerobically fit persons heart rate is slower than Joe Average which means it takes even longer to ‘pick up the stroke’. This doesn’t mean that couch potatoes have better G tolerance either. A good ‘fitness for flight’ regime should include aerobic and muscular training and include short ‘stop/start’ sprint training to give the heart ‘rapid response training’.

Having said all of that, there is one other way that an aerobatic pilot can help him or herself stay conscious during a sustained aerobatic routine, and that is in the way the sequence of manoeuvres is designed.

Remember that I said that there are individual variations in a person’s G tolerance depending upon a number of physiological factors? Well one factor which affects G tolerance in all pilots at any instant in an aerobatic sequence is what the preceding manoeuvre was. If the preceding manoeuvre involved zero or negative G for longer than about 3 seconds the heart will have responded to an over pressure signal from the brain and begun slowing down! If at that point the pilot slams on +4G, he/she is ‘flirting’ with instantaneous GLOC, because the slowing of the heart rate can drop the entire ‘G tolerance chart’ down about 2G!

It seems that the heart is capable of responding faster to ‘over pressure’ signals from the brain than ‘under pressure’ signals. Trials of heart rate versus G on advanced aerobatic pilots have shown that the heart slows down faster than it can speed up when going from high +G to high –G. In one trial a transition from 175 beats per minute to 40 beats per minute occurred within 5 beats! That is, the heart rate dropped from 175 to 40 in 2 seconds!

This combination of manoeuvres, from negative G to high positive G, has been nicknamed ‘sleeper’ manoeuvres because they are going to put the pilot to sleep! Sleeper manoeuvres have caused the death of a number of aerobatic pilots over the years, which is the main reason I am giving this lesson. If those pilots had attended such a lesson I am sure they would be alive today.

The trick in aerobatic sequence design to avoid ‘sleepers’ is to insert a low positive G manoeuvre, like a roll, between the negative G and the high positive G manoeuvre, to give the heart time to ‘catch up’.

What about negative G? Most aeroplanes are incapable of ‘pushing’ much negative G as they have cambered wing sections which don’t work as well at negative A/A, and their carburetors don’t operate properly under negative G either. Also, even aerobatic category aeroplanes are limited to -3G, which is not extreme. Early thinking about negative G (included in that same old RAF publication) suggested that a pilot would experience a phenomenon called ‘Red Out’, which was said to be caused by the lower eyelid becoming engorged with blood and being pulled up over the eyeball, causing the pilot to see red. I have never experience this phenomenon, nor have I met any other pilot who has, and I have met some pretty serious aerobatic pilots over the years, who have regularly pushed -6G in their purpose built aerobatic aeroplanes. I have pushed -5G a few times and regularly go to -3G, and all I can tell you about it is that it feels damn uncomfortable!

Obviously there is no problem keeping the brain ‘on line’ during negative G as there is plenty of oxygenated blood around. But what about the over pressure of blood in the brain? Can that cause problems? It doesn’t appear to, because the brain has its own ‘negative G suit’. Let me explain.

Before the ‘inflatable chaps’ G suit I described earlier, was invented, a Canadian medico experimented with putting pilots in water filled rubber pants (like ‘Irish’ waders, with the water on the inside!). The idea was that as the G increased, so did the weight of the water, which then exerted a proportional increased pressure on the pilot’s legs and abdomen and improved his G tolerance. It worked, but there were a few practical problems associated with flying an aeroplane whilst wearing water filled rubber pants! So what has this got to do with the brain and negative G? Well, the brain is immersed in a fluid inside the skull, so as the negative G increases so does the weight of this fluid, which exerts a pressure on the brain to counter the increasing blood pressure within. Problem solved!

It appears that the brain can function better under moderate negative G than it can under positive G! So it is a pity that negative G is so uncomfortable on the rest of the body.

If you plan to be a ‘touring pilot’ most of what I have said in this lecture will not apply to you, but if you plan to participate in the sport of aerobatics you need to understand it and stay fit.

Oh, and watch out for those ‘sleeper’ manoeuvre combinations.

Lesson Sixteen

SPINNING

PLUNGES TO DEATH.

Aviator Johnstone Is Killed Instantly.

Biplane Drops Like Shot from Five Hundred Feet in the Air.

Nearly Every Bone in Body Broken — Famous Spiral Glide Fatal.

Denver Ghouls Fight for Gory Souvenirs Torn from Victim's Corpse.

[ASSOCIATED PRESS NIGHT REPORT.]

DENVER, Nov. 17.—With one wing of his machine crumpled like a piece of paper, Ralph Johnstone, the brilliant young aviator, holder of the ...

he swooped down in a narrow circle, the aeroplane seeming to turn almost in it own length.

As he started the second circle the middle spur which braces the left side of the lower plane gave way and the wing tips of both upper and lower planes folded up as though they had been hinged.

For a second Johnstone attempted to right the machine by warping the other wing tip.

Then the horrified spectators saw the plane swerve like a wounded bird and plunge straight toward the earth. Johnstone was thrown from his seat as the nose of the plane swung downward. He caught on one side of the wire stays between the planes, and grasped one of the wooden braces of the upper plane with both hands Then working with hands and feet he

fought by main strength to warp the planes so that their surfaces might catch the air and check his descent.

FIGHTING GRIMLY.

For a second it seemed to the white-faced spectators almost under him that he might succeed, for the foot-ball helmet he wore blew off and fell much more rapidly than the plane.

The hope was only momentary, however, for when only about 300 feet from the ground the machine turned completely over, and the spectators fled wildly as the broken plane with the tense-faced boy still fighting grimly in its mesh of wires and stays plunged among them with a thud and crash that could be heard over the big field.

DEATH INSTANTANEOUS.

The machine fell on the opposite side ...

With graphic headlines like this 1910 Denver Colorado newspaper report of a fatal accident which resulted from a "Famous Fatal Spiral Glide", it is no wonder that the spin became the most maligned and misunderstood manoeuvre in aviation. In those early days of aeroplane development little was known of the aerodynamics or dynamics of spinning. As a consequence many aeroplanes were designed and built with unsatisfactory spin characteristics. These poor spin characteristics coupled with a lack of pilot understanding and training resulted in a significant number of spin related accidents and fatalities and the myth of the 'dreaded tailspin' was born.

Over the subsequent years this myth has become part of our culture, and I don't mean just that of pilots. I can recall, as a small boy, my father saying to me "don't bother your mother now; she is in a flat spin!" I have heard similar statements since from all sorts of people outside the aviation fraternity; it has become synonymous with being 'out of control.' So a person starting out as a student pilot, probably already has this preconceived notion that in a spin you are 'out of control', and in a life threatening situation; therefore spinning is to be avoided at all costs. Yes, unintentional spinning should be avoided, but avoiding spin training is not the answer. The cost of not receiving proper spin training could be your life!

Today the aerodynamics and dynamics of spinning are thoroughly understood, and those aeroplanes that have been 'cleared' for spinning have completely predictable spin characteristics. This means that modern aeroplanes which have been designed built and tested to spin, can be spun and recovered with complete reliability and safety. Unfortunately modern pilot education about spinning is little better than it was back in the 'good old days', so the myth is perpetuated.

There was a period of about 20 years after World War Two, when all civilian flying schools were equipped with purpose built flight training aircraft which could be spun, and all flying instructors were adept at teaching student pilots the vital skill of spin recovery, and spin training was a mandatory part of all flight training syllabuses. All military flying schools are still equipped with these types of aeroplanes and conduct spin training, but during the late 1960's the civilian training aeroplanes were progressively replaced with mass produced touring aeroplanes which were not suitable for spin training, so the skills were slowly lost. Today there are very few 'spin-able' training aeroplanes on the market or on flying school flight lines, and the average flying instructor shakes more than an aeroplane in a stall at the mere suggestion of spinning.

This raises the question, "if modern aeroplanes are not 'cleared' to spin, why bother teaching pilots anything about spinning if this is the only type they are likely to fly?" The answer is simple; just because an aeroplane is not cleared for intentional spinning does not mean it cannot be spun, indeed, it could mean that if mishandled, this 'un-cleared' aeroplane could get into quite a 'nasty' spin. Any aeroplane if mishandled sufficiently will spin, some more violently than others, but in all cases if the pilot has not been trained in the appropriate method of recovery the spin will quickly turn into a disaster. It is my belief that all pilots should be trained in spin recovery techniques as part of their initial training the way they used to be. I am not alone in this belief, but unfortunately because the aeroplanes now used as flight trainers by the flight schools of most countries are incapable of spinning safely, the regulatory authorities of those countries have been pressured to remove the requirement for spin training from their 'official' pilot licence training syllabuses. The argument often used to justify this policy change was that when spin training was required there were more accidents during spin training than non-training spin related accidents. However, I believe that this is an argument for a better standard of spin training, not its abolition. A large percentage of aircraft accidents occur during the landing phase of flight, but no one is going to suggest the abolition of landing training!

My flying school was the only one in Australia which insisted upon proper spin training as an integral and mandatory part of licence training, and before any other licenced pilot was considered fully ‘checked out’ to use my aeroplanes.

Spin training must be done by a competent flight instructor who is comfortable in the sky, and therefore, will not add to the student’s apprehensions about this phase of their training, because, let’s be frank, a spin is an awesome experience....initially. The sensations which result from whirling around and around whilst plummeting vertically toward the ground are rather over powering, and can cause the student pilot a degree of ‘sensory overload’ and ‘brain lock’. Until the student has been exposed to a number of spins, and directed through a methodical recovery technique in a calm way, he or she will not relax and appreciate just how simple the entry and recovery from a spin is. It is a manoeuvre which gives the aviator the ‘most bang for his buck’; it’s a wild ride which is very easily controlled...once you know how. I have had a number of students who were literally ‘quaking in their boots’ prior to their first spin, but by the end of the flight were totally ‘in love’ with the sensation and their new found ability to control the manoeuvre, and couldn’t wait to show their friends!

I am now going to attempt to bring some clarity to the subject of spinning in this lesson. I am first going to talk about the theory of spinning, and then I am going to talk about how poorly trained pilots can get into one and how they can mishandle the recovery. Finally I am going to talk about the controversy which still surrounds spin recovery techniques.

Okay let’s start with the theory. In the lesson on stalling I described the process of ‘autorotation’ which is the precursor to any spin, (indeed many pilots believe that a one or two turn autorotation is a fully developed spin. It’s not!). Let me recapitulate what I said in that lesson.

As the Angle of Attack of a wing approaches the critical angle and if, for whatever the reason, a ‘wing drop’ has occurred and the A/A of the down going wing then exceeds the critical angle, its A/A will continue to increase, because all of those things that we learned about lateral stability and roll rate damping are reversed. That is, the increased A/A of the down going wing no longer increases lift to correct the situation but loses more lift, and takes the wing deeper into the stall, causing it to lose even more lift and gain a whole lot more drag. Meanwhile the up going wing ‘backs off’ from the stall and retains its lift. So a significant lift and drag asymmetry is created wherein the roll continues and the drag imbalance produces a rapid yawing motion. This whole process is called ‘Autorotation’. This ‘Autorotation’ effect on the difference in lift and A/A is shown in the following diagram (Figure One).

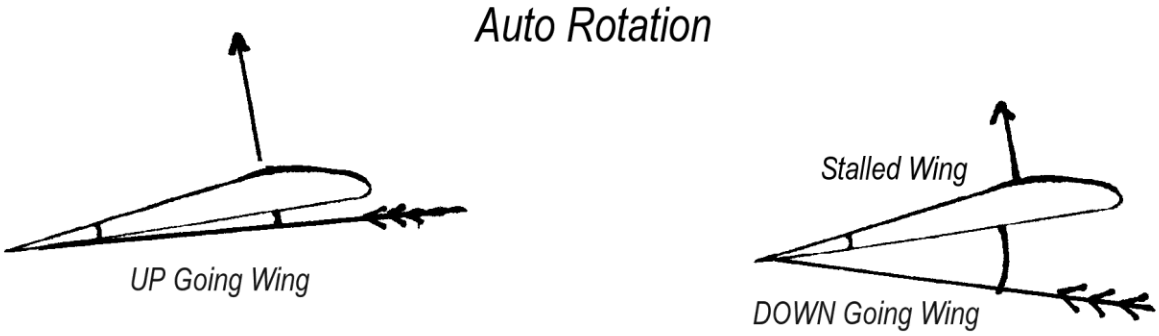


Figure One – Lift & A/A Difference during Auto Rotation

In an intentional spin entry this ‘autorotative’ imbalance can be further ‘enhanced’ by deliberately moving the aileron control ‘out-spin’ (opposite to the yaw) after about one rotation. This action will deepen the stall on the down going wing. On aeroplanes prone to tip stalling, the aileron can be moved out-spin immediately, but on aeroplanes which are designed to maintain normal aileron control right up to the critical angle of attack (washed out wingtips), it is best to wait until you are sure that the wingtips have stalled before you move it, otherwise the ailerons may work in the ‘normal’ sense and slow or even stop the autorotation. Usually aileron input is not necessary to enter a stable spin. (You can see from this that applying opposite aileron to prevent a wing drop during an inadvertent stall is not the correct action. More on this later.)

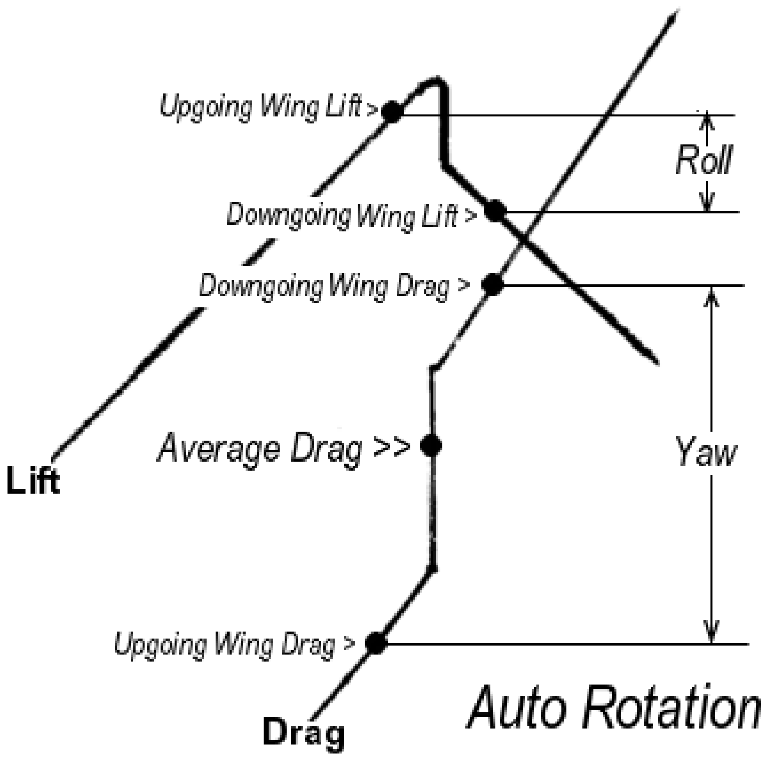


Figure Two – Graphic representation of Lift & Drag during Auto Rotation

The preceding diagram (Figure Two) is a graph showing what is going on with the lift and drag of each wing during this initial autorotation. In this graph only the top end of the 'Lift Vs A/A' graph, and the 'Drag Vs A/A' graph are shown for clarity. (I have used a simplified version of the lift and drag 'curves' for the NACA 23015 wing detailed in Annex A to the lesson on Lift.)

On this graph I have marked the positions on each of the curves for each of the wings at the start of autorotation. Note the difference in lift between the 'up going wing' and the 'down going wing', causing further roll, and the even greater difference in drag, causing significant yaw. I have also marked the average drag at this stage of the autorotation.

If we have approached a level stall prior to the autorotation then the aeroplane is, at that point, still flying a level flight path which will, during about two to three rotations, curve down into a vertical flight path with the associated increase in airspeed. It is at this point that an interesting aerodynamic phenomenon 'kicks in', which is best explained if I step back for a moment to the lesson on Stalling, wherein I explained the relationship between the stick position and the A/A of the wing.

In that lesson I explained that for a given tail volume and elevator area, the stick position will always cause a corresponding A/A, and if we have pulled the stick back far enough it will cause the A/A to exceed the critical angle and the wing will stall. I also explained that once the wing has stalled the downwash over the tail is altered, and the counter moment of the tail is reduced, tending to un-stall the wing, but, if the stick is brought back further (fully back), this un-stall tendency can be overcome. However, the interesting phenomenon is that during an autorotation the effective elevator area is reduced and, as a result, the counter moment is reduced. How can this be?

After about 2-3 rotations the yaw rate of the autorotation has increased to the extent that the airflow is approaching the tail section of the aeroplane at a very high side angle, and the fin and the side of the fuselage are shielding or 'blanketing' the airflow over a significant proportion of the horizontal tail and elevator. This blanketing reduces the effectiveness of the elevator, and despite the fact that the stick is back past the stall point, the reduced counter moment of the elevator is unable to hold the A/A at the critical angle and the aerodynamic pitching moment of the wing pitches it to a lower A/A, and it un-stalls! It is as if someone has suddenly chopped off a large 'chunk' of the elevator, thereby reducing its area and effectiveness. So the end result of this blanketing is "anti-spin". The following diagram illustrates this 'blanketing' effect (Figure Three).

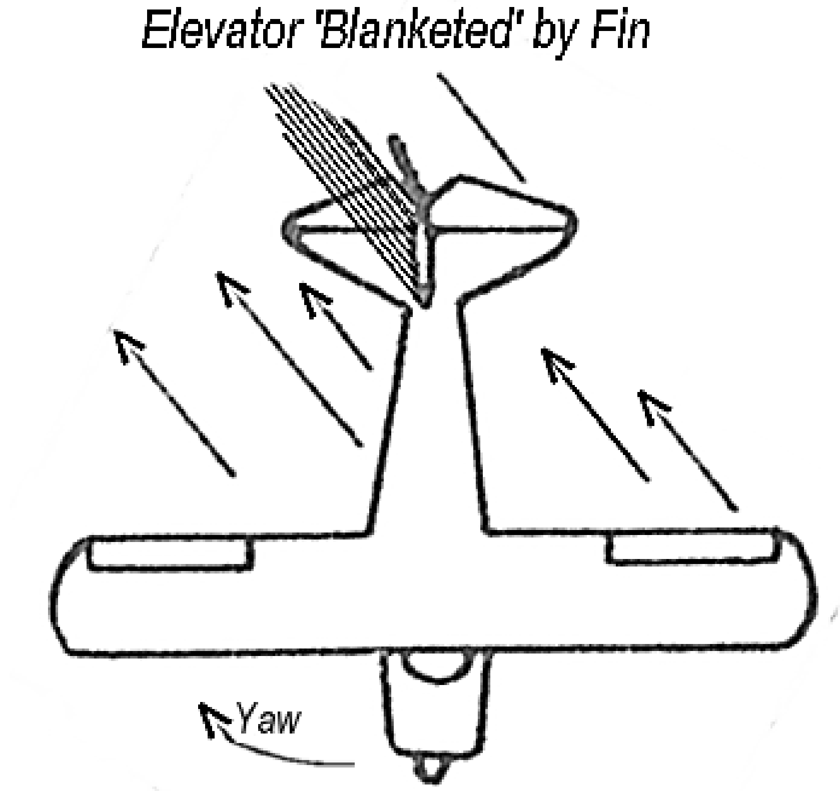


Figure Three – Elevator 'Blanketing'

If aerodynamic forces were all that was affecting this situation at this stage, the aeroplane would transition from an autorotation into an accelerated spiral dive, necessitating the aviator to take prompt recovery action before reaching the structural limits of the aeroplane. Indeed this is what happens in many, so called, 'spin trainers', and is often the reason why they are limited to only 2 or 3 rotations. But in proper, 'spin-able' aeroplanes, something else now happens.

Remember our aeroplane's flight path is now curving down toward a vertical descending flight path, with an initial A/A of about 16º and a fuselage angle of about 13º (A/A minus wing incidence), and yawing very rapidly. Inertia coupling starts to take effect. Remember that? We discussed inertia coupling back in the lesson on Stability and Control. This time it is not about a horizontal roll axis but about a vertical yawing axis. This inertia coupling 'overpowers' the aerodynamic 'anti-spin' pitching moment and tends to 'flatten' the aircraft attitude and increase the A/A still further! The degree to which it does this depend upon the aeroplane's 'B/A ratio', which I will explain in a moment.

The following diagram (Figure Four) shows the transition of the aeroplane's flight path from horizontal to vertical and the competing aerodynamic pitching moment versus the dynamic inertia coupling forces. (The aerodynamic and the dynamic components are shown artificially split into two separate parts for clarity.)

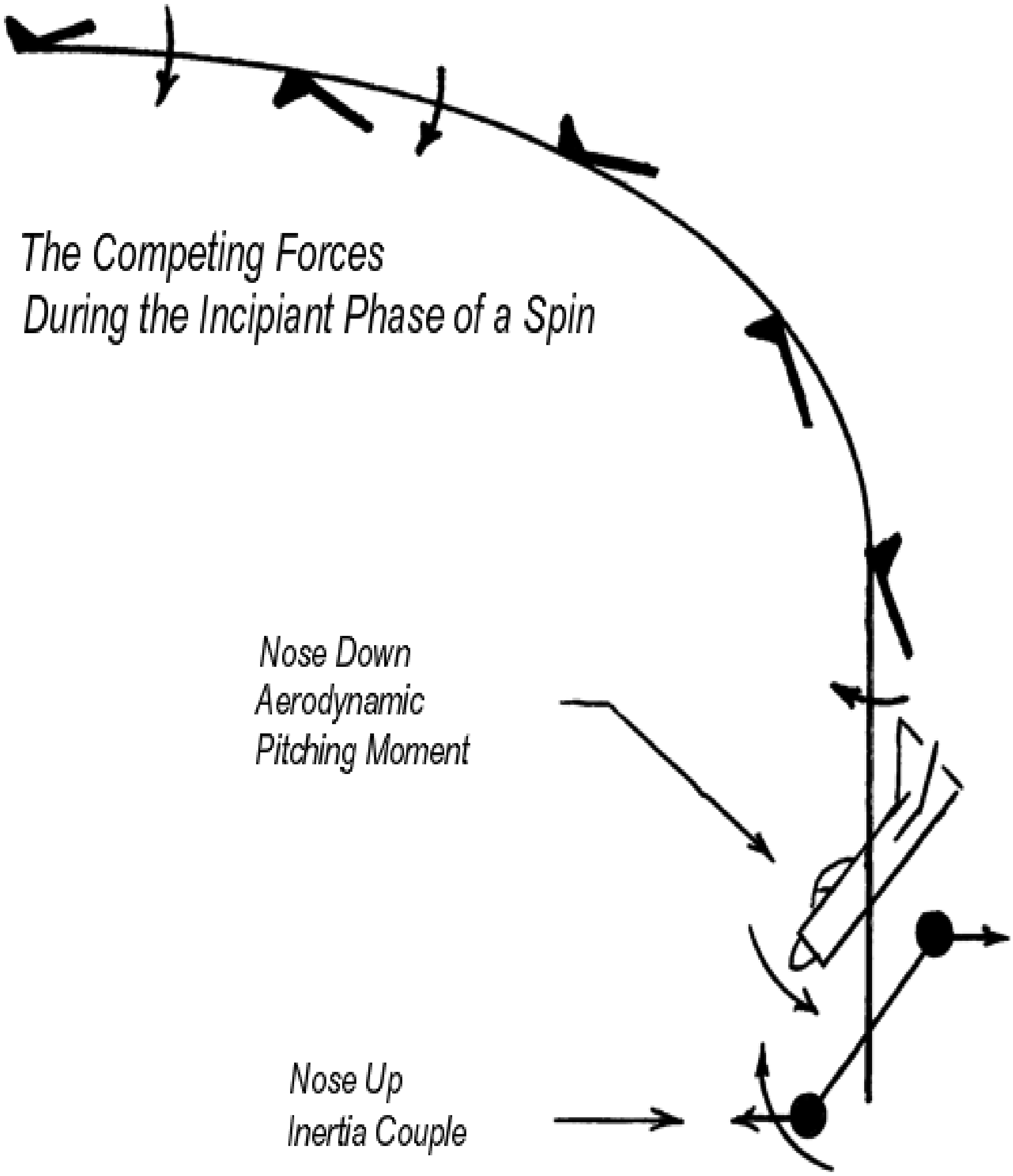


Figure Four – Competing Aerodynamic and Dynamic Forces

The following diagram (Figure Five) is a repeat of the previous graph of lift and drag (Figure Two), showing the new position of each wing as the inertia couple begins to pitch the aeroplane into a 'stable spin'. Both wings are now fully stalled, but the down going wing is still 'more stalled' than the other, so the autorotative lift and drag imbalance is still present. Note how much the average drag has increased as the spin flattens. A turn later the fuselage angle could reach as much as 45° to the vertical and the drag will have gone 'off the chart!'

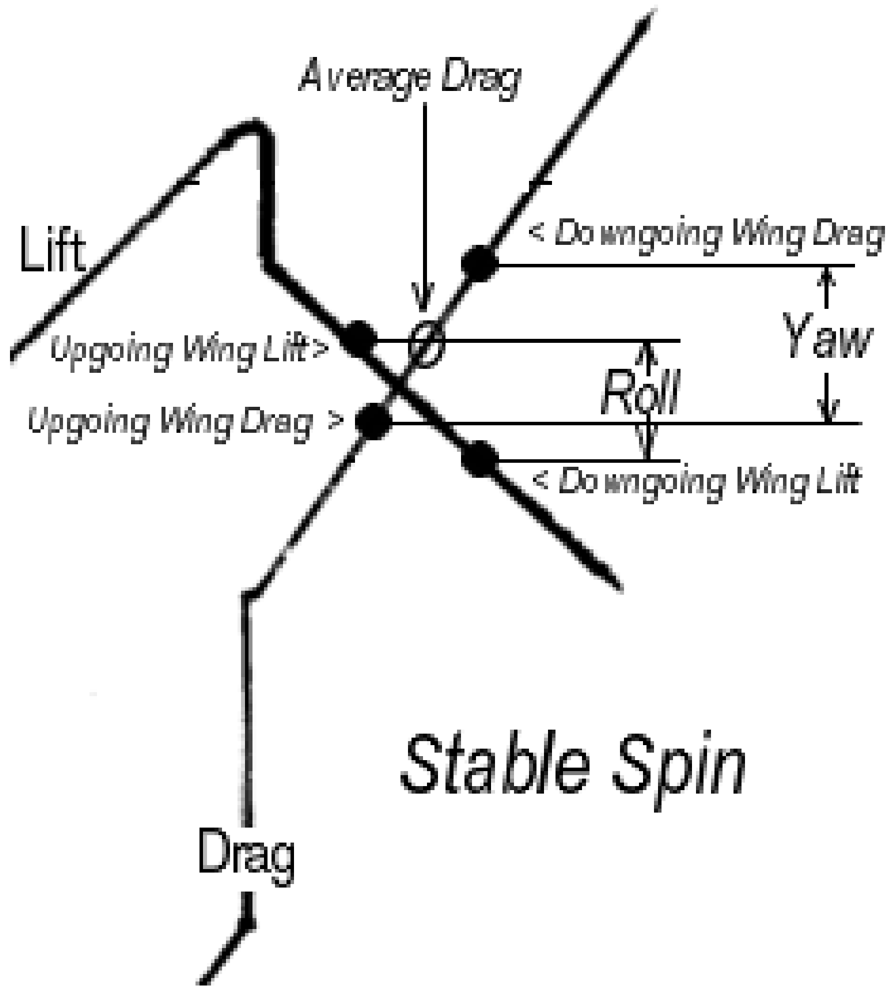


Figure Five – Graphic representation of Lift & Drag in Stable Spin

Okay, I mentioned previously a thing called the B/A ratio. The B/A ratio is an expression of the relative distribution of the mass of the aeroplane about the lateral (A) axis and the longitudinal (B) axis. That is, the ratio of the mass in the wings to the mass in the fuselage. Single engine training aeroplanes have the greater proportion of their mass distributed along the fuselage and therefore have large B/A ratios. Whereas a twin engine aeroplane with engines mounted on the wings and fuel tanks in the wings outboard of the engines, would have a low B/A ratio. See Figure Six below.

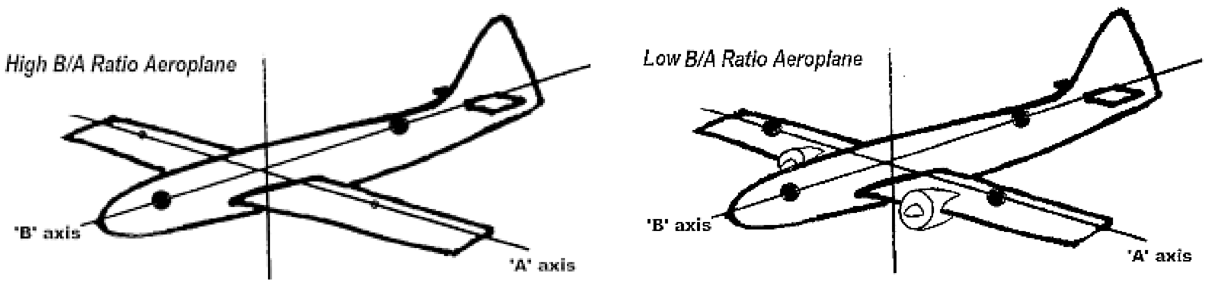


Figure Six – B/A Ratio of Single and Twin Engine Aeroplanes

Aeroplanes with high B/A ratios have, as a group, more uniform and predictable spin characteristics than aeroplanes with low B/A ratios. Low B/A ratio aeroplanes may have spin characteristics more unique to that particular design, requiring special handling techniques. I am not aware of any twin or multi engine aeroplanes in civilian use, that are 'cleared' for spinning, so my discussion will focus on those single engine, high B/A ratio, aeroplanes that are.

So let's consolidate the situation so far. Having initiated an autorotation from slow speed (about 1.1Vs), in straight and level flight, the aeroplane's flight path will curve from horizontal to vertical as it makes the first 2 to 3 rotations, and its airspeed will increase. Airflow blanketing from the fin and fuselage, because of the high yaw angle, will cause reduced elevator effectiveness, allowing the wing pitching moment to pitch the wing to an A/A less than critical and un-stall the wings. The aircraft will enter an accelerated spiral dive - UNLESS, the inertia couple forces, which have also been building up during this phase of the manoeuvre, overpower the aerodynamic pitching moment, flatten the aeroplane's attitude, and increase the A/A of both wings to greater than critical; thereby increasing the drag, and putting the aeroplane into a stable spin. Are you with me so far?

This phase of the spin is called the 'incipient phase'. It is the phase where the aeroplane 'decides' whether it is going to enter a stable spin or an accelerated spiral dive (the latter outcome is often called an 'unstable spin'). What factors can effect this 'decision'?

Assuming a training situation, the best method of initiating a spin is to approach a 'clean' wings level stall, and just prior to the critical A/A being reached (at about 1.1Vs), apply full rudder in the desired direction of rotation whilst simultaneously pulling the stick fully back. If either of these control inputs are not made positively enough, the yaw rate may be insufficient to generate the inertia forces needed to put the aeroplane into a stable spin. So the first factor affecting the 'decision' is pilot technique.

Now not entering a stable spin may sound like a safe outcome, but remember the aeroplane is still rolling and yawing rapidly at a high angle of attack, and it is now accelerating rapidly too. It is entering an accelerated spiral dive, necessitating a quick response from the pilot before the rolling 'G' limit of the aeroplane is exceeded! So a safe outcome from a 'gentle' spin entry is not necessarily guaranteed.

Another factor affecting the 'decision' is the position of the centre of gravity of the aeroplane. If the centre of gravity is too far aft, the aeroplane's normal longitudinal static stability will be reduced, giving the inertia forces an easier job of dominating the situation. Indeed, any load aft of the C of G will both move the C of G back, decreasing static stability, and increase the inertia couple.

If the C of G is aft of the aft limit the situation may be irrecoverable, so it is imperative that the aeroplane always be loaded such that its C of G remains within the correct limits for spinning.

A third factor influencing the decision is one of aircraft design. The rudder may not be big enough or effective enough to yaw the aeroplane rapidly enough for it to enter a stable spin. I had such an aeroplane; it was a Siai Marchetti SF260. It was a beautiful aeroplane capable of smooth graceful aerobatics and spinning, but its rudder was too small to drive it into a stable spin. Fortunately the stick was able to take the A/A way beyond critical, so it didn't accelerate into a spiral so fast that you couldn't enjoy the ride for a few turns. The SF260 also had wingtip fuel tanks which had to be empty before deliberately spinning the aeroplane, because full tanks would alter the B/A ratio, which would have a detrimental effect on its spin recovery.

Previously I mentioned 'so called' spin trainers that do this too. Often it is the size of the rudder that is the culprit. I believe all aeroplanes should have 'adequate' rudders. You may not need them often but when you do it is nice that they are there.

So how does the aviator tell when the aeroplane has made its 'decision' so that he or she can, if necessary, react in time? **AIRSPEED** is the answer. If the aeroplane is entering an accelerated spiral the airspeed will continue to increase toward **Vo(rolling),** but if the aeroplane enters a stable spin, the airspeed will stop increasing, indeed it may even decrease a little from where it got to after a couple of rotations. Go back and look at the drag build up in graph at Figure Five again. As the spin stabilizes, the drag increases to the extent that, despite the fact that the aeroplane is going vertically down, it is also slowing down! It is as if a large parachute has been deployed above you. So a critical part of pilot technique when initiating a spin is to **watch the airspeed indicator 'like a hawk'.** If the airspeed stabilizes at a moderately low figure (usually less than 1.5Vs), the spin has stabilized, and there is no rush to recover. If, however, the airspeed keeps increasing, the aeroplane is entering an unstable spin (accelerated spiral), demanding immediate recovery action.

There is a further indication of a stable spin which becomes obvious during spin training, and that is that the controls will tend to remain in the 'pro-spin' position. Let me explain. In a stable spin, since the inertia forces have flattened the aeroplane's attitude to about 45º to the vertical, and since the airflow is now coming predominately from below, the elevator will be 'blown' fully UP. Also because of the very high rate of rotation (up to 360º per second), the airflow is impinging upon the rudder from the side, 'blowing' it into the spin. Now since these control positions are where the aviator first put them she will not feel them move, but they will no longer try to 'spring' back to neutral either, so she will feel them go 'light' in her hand and under her foot. If the controls were released the elevator and the rudder would stay there. What about the ailerons? Since the inside wing has the greater angle of attack, that aileron would be ‘blown’ up more than the outside wing, so the stick would, if released, move in-spin.

Okay, we are now in a stable spin having deliberately entered it from straight and level slow speed flight, but how is it possible to enter such a spin inadvertently? I have, for many lessons now, been emphasizing the correct use of rudder during normal flying, turning, gliding, climbing, etc because it is the incorrect use of rudder that can get you into an inadvertent spin. Any time the wing is stalled whilst the aeroplane is yawing, autorotation will result, and if not quickly corrected, will result in a spin.

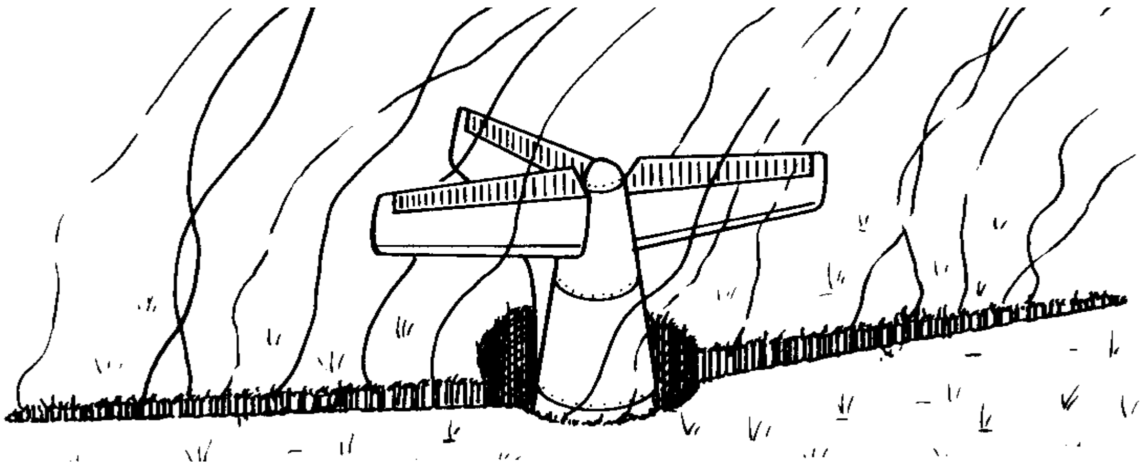
The most common way an inadvertent spin is entered is via a skidding gliding turn. In the lesson on gliding I described how, in a properly executed gliding turn there is a necessity to ‘hold on’ bank, that is, hold a small aileron input into the turn. (If you have forgotten why this is so, go back and read it again now.) I also explained that there was no problem with using a reasonable amount of bank to execute a gliding turn, as the rate of turn resulting from increased bank always increases more than the rate of descent. Unfortunately many pilots do not know either of these facts.

Imagine the following scenario, wherein an ignorant pilot is practicing a forced landing procedure and is about to make a gliding turn onto his final landing approach. He only uses about 20º of bank because he does not want the rate of descent to increase, but he notices that his turn radius will cause him to overshoot the ‘runway centre line’, so he applies rudder into the turn to ‘speed it up’. Now the yaw caused by the rudder appears to do the trick, but it also causes the aeroplane to want to ‘roll on’ more bank, the very thing he is trying to avoid, so to prevent the bank angle increasing he ‘holds off’ bank with opposite aileron.

The aeroplane is now skidding around the turn, its drag has increased and its airspeed is decreasing, so its nose also wants to pitch down. Our hero will have none of this, he is determined to hold the correct nose attitude and maintain the bank angle, blissfully unaware that in order to achieve this the stick is moving back and further ‘out’ of the turn, causing the aileron on the inside wing to increase the A/A. Now the inside wing already has the greater A/A (going down the spiral staircase, remember?), and the back stick and down going aileron increases it further, until suddenly, the inside wingtip stalls without warning! No buffet and no horn, because the turbulent wash from the wingtip is outboard of the tail, and the switch which works the horn is on the other wing with the less A/A. The resulting autorotation is quite rapid, and out of fear and lack of correct training, he instinctively applies more back stick and out-spin aileron. Wrong! But anyway the spin has no time to stabilize - remember where we said he was? He was turning onto the landing approach, probably at about 500feet! Goodbye.

During my very early flight training in the Chipmunk, which quite noticeably exhibited these 'hold on' and 'hold off' bank requirements, I was taught a very simple but appropriate poem which I would like to share with you at this point.

Watch him spin, watch him burn.
He held off bank in a gliding turn!



If you find yourself holding off bank in a gliding turn you are doing a skidding turn, and are close to spinning out of what appears to be the gentlest manoeuvre you have done all day, a gentle 20º bank gliding turn! Check your balance ball and move your rudder pedals to put it back in the middle. If you want a smaller radius turn, or a greater rate, use more bank.

Many pilots believe that you can only spin out of aggressive aerobatic style manoeuvres, and will quite happily do skidding turns all over the sky unaware of the risk they are taking. I am aware of one young flying instructor who would teach his Cessna 152 students to make skidding turns to final approach "as the wing blocks your view of the runway if you use too much bank." Good Grief!!

In the lecture on Side Slipping I said that many flying instructors do not teach side slipping because they believe they may spin. I also made the statement that "you can no more spin off a properly 'set up' side slipping approach than you can off a properly set up 'straight' approach." This is because in a side slip the aircraft is not yawing. It may have yawed a little to get into the side slip, but once it is established, the yaw rate is zero. Obviously the side slip has to be properly controlled, as any uncoordinated flying on the part of the pilot can produce yaw, but this also applies during a non-sideslip approach.

If the aeroplane is inadvertently stalled whilst side slipping, it will behave the same as if it were stalled 'wings level'. That is, if the aeroplane is prone to dropping a wing at the stall, it will drop a wing, but if it isn't, it won't. So, no wing drop, no autorotation, and no autorotation, no spin.

It is also a common misconception that the 'stall speed' of an aeroplane increases in a side slip because the aeroplane is banked. The relationship of stall speed to bank angle only applies in a balanced turn, because, in a balanced turn, there is a relationship between bank angle and load factor, and it is the increased load factor which actually causes the increased stall speed. If the aeroplane is not turning both of these relationships are broken. It may surprise you to learn that the stall speed of the aeroplane actually decreases in a side slip! This is because a degree of lift is provided by the fuselage, so the A/A can be reduced slightly. This 'sharing' of the responsibility for lift production is biased more toward the fuselage as the side slip is increased (albeit not very efficiently). The following pictures illustrate this situation (Figure Seven).

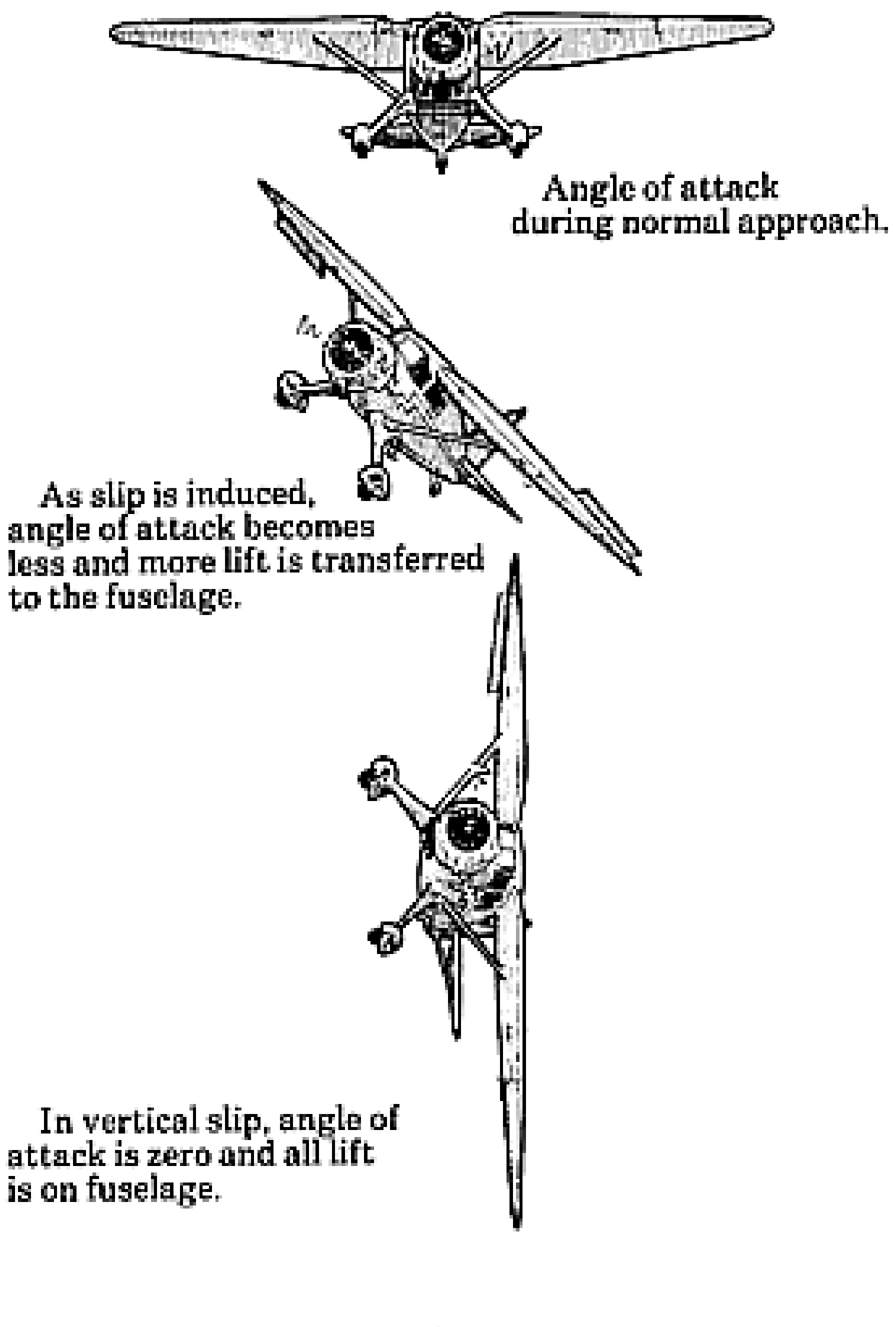


Figure Seven – Angle of Attack in a Side Slip

Most touring aeroplanes are unable to generate the extreme side slip angles depicted in Figure Seven, so this reduction in airspeed is hardly noticeable. Also there will be a small amount of elevator blanketing from the fin and rudder, necessitating a slight increase in ‘back stick’ to maintain angle of attack, and even more to generate the critical A/A.

Now let’s get back to our deliberate stable spin. During this stable spin the aviator can relax and enjoy the ride for a short time; how long will obviously depend upon how high the aeroplane was when the spin was initiated, and this in turn will determine the altitude at which the recovery process should be started. I used to commence training spins at least 5500 feet above ground level and initiate recovery action at, at least 4000 feet. During this altitude loss the aeroplane would perform approximately 10 to 12 rotations. I say approximately because neither I nor the student was looking out the front windscreen during this phase of the spin, so I didn’t count them. Indeed counting would have been difficult because the world outside is whirling around at about one revolution per second, and trying to focus on it would become quite disorientating. So where were we looking? After the first rotation we transferred our gaze inside the cockpit and focused initially on the airspeed indicator (for the reasons previously stated) and then, once the spin had stabilized, we focused on the altimeter and turn indicator. The altimeter would of course indicate when it was ‘time’ to initiate recovery and the turn indicator would verify the direction of the spin. We were not blind to what was going on outside the window, our peripheral vision took care of that, it is just that the most useful information about the spin was now coming from inside the cockpit.

When I say the turn indicator I don’t mean the balance ball, I mean the turn needle, or that little aeroplane on the more modern instruments. Figure Eight shows the indication of both of these instruments in a LEFT spin.

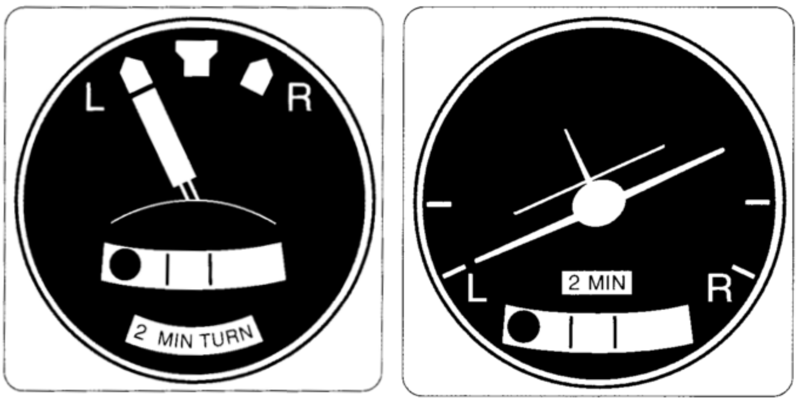


Figure Eight – Turn Indicators showing LEFT Spin

The turn needle is driven by a yaw rate gyro which is very sensitive to the size and direction of yaw, and after all wasn’t it yaw that got us into this situation in the first place? The balance ball, in theory, should be in the corner of its tube opposite the direction of spin but, depending upon the angle of bank during the spin, it may not be (something to do with the B/A ratio)....SO IGNORE IT!

Of course this begs the question, if this was a deliberate spin don't we know the direction anyway? Absolutely correct, but the purpose of spin training is to prepare the aviator for the situation where the spin may be inadvertent and unexpected. In this case the aviator may be momentarily disorientated, but the turn needle won't be. So it is a good idea to include the turn needle in the recovery procedure.

Okay, so now the recovery altitude has arrived, what do we do to recover from this spin? I am going to work though the recovery technique that I teach now, and discuss where it came from and what its advantages are later, because as I said at the beginning of the lecture there has been some controversy surrounding it. The recovery procedure is:

1. **Throttle off**
2. **Confirm spin direction**
3. **Hands off**
4. **Full opposite rudder.**

When the rotation stops centralize the rudder, take the stick and pull out of the dive. It's that simple!

Why throttle off? If you are flying an aeroplane which has an engine that is capable of delivering power during the spin, the gyroscopic precession that the propeller can throw into the mix of competing forces can significantly affect the spin and the recovery....and you don't have time to figure it out so get rid of it. If you have an engine with a carburetor, the lateral 'G' of rotation will probably cause it to 'flood', and cause the engine to fail (indeed the propellers of my aeroplanes would completely stop!). The throttle should be closed for the subsequent re-start (to prevent engine over speed), so closing it at the start of the procedure standardizes the steps to be taken.

Confirm spin direction? Use the turn indicator to confirm which way the aeroplane is spinning as you may be disorientated. Remember; refer to the turn indicator NOT the balance ball.

Hands off? Yes, release the stick completely! I would have my students grab the instrument panel coaming with both hands as it is a more positive action than just letting go. I am going to discuss this particular step and its associated aerodynamics and controversy later in the lesson.

Full opposite rudder? This seems fairly self-evident, if it was yaw that got us into the spin then stopping the yaw will get us out, but use FULL rudder, do not ‘pussy foot’ around here. The correct (positive) use of the rudder is the most important step in the recovery process.

When the rotation stops, centralize the rudder. This is obvious, right? Yes, but it may not be so obvious when you are the aviator, and you have just been whirled around 10 times in 10 seconds! Most people get a little dizzy when this happens (although keeping your gaze inside the cockpit helps), so even though the spin has stopped there will be a residual sensation that it is continuing, so the rudder may not be completely centralized when the aeroplane is pulled out of the dive! This can cause a spiral in the other direction and really spoil your day.

So when my students put their hands up on the coaming I would have them simultaneously lift their gaze and look out the windscreen to see the world stop rotating a few of seconds later. When it did stop rotating (as seen not felt), I had them stamp both feet on the floor, thereby ensuring that no residual rudder was applied. At this instant both the student’s hands and feet were off the controls!

With the hands off the stick during the recovery, the ailerons and elevators were free to float in the relative airflow, and as the spin stops, the airflow resumes its normal path from straight ahead, so the stick moves to the centre of the cockpit awaiting the aviator to grasp it and pull out of the dive, being careful not to exceed the critical A/A, and air starting the propeller on the way (if required). The rudder would, of course, have ‘streamlined’ itself with the relative airflow and ‘self-centered’ during the pull out, so the pilot can now resume normal control once the aeroplane has returned to level flight.

What about recovery if the spin goes unstable and enters an accelerated spiral? Whilst the recovery procedure from the steep phase of a spiral dive was detailed in a previous lecture, the foregoing simple spin recovery procedure works well too. The power is reduced to idle, the stick is relaxed (released) and the aeroplane is rolled ‘wings level’ using the secondary effect of rudder by virtue of its lateral stability. Obviously the result will be quicker than a spin recovery because the wings are no longer stalled and there will be no inertia forces to overcome. Using this technique in an accelerated spiral dive recovery means the aviator doesn’t have to suddenly change technique when confronted with a rapidly increasing airspeed, he just has to decide to do it NOW. When is ‘Now’? It is a speed approaching **Vo(rolling)** making an allowance for reaction ‘time’. I use **Vo(rolling) minus 20kts.**

When I was doing my initial flying training on the Chipmunk I was aware that it had gained a questionable reputation amongst some pilots for its spin recoveries. Many pilots claimed that sometimes during spin recoveries, using the ‘correct’ technique, the spin rate actually sped up! There were two reasons for this; the first was a matter of dynamics and the second was a matter of pilot technique. I will discuss the pilot technique later, so for now let’s look at this dynamic effect.

Remember that a stable spin is not just a function of aerodynamics but is also a function of the dynamics of rotating masses. Once the spin has stabilized the fuselage (along which most of the mass is concentrated in our high B/A ratio aeroplane) is at an angle of about 45º to the spin axis, but as the recovery rudder starts to 'bite' and the yaw rate and inertia couple are reduced, the fuselage starts to pitch down toward the vertical. As this pitch down happens, the radius of rotation of the fuselage mass is reduced, and a thing called 'conservation of angular momentum' kicks in. If you have never heard of conservation of angular momentum before don't worry about it, but I am sure that at some time you have seen (live or on television) ice skaters who spin on the ice with their arms out, and then increase their spin rate significantly by pulling their arms into their sides. The ice skaters are using the principle of conservation of angular momentum to speed up their spin rate and the Chipmunk did the same thing. The following diagrams depict this dynamic process (Figure Nine).

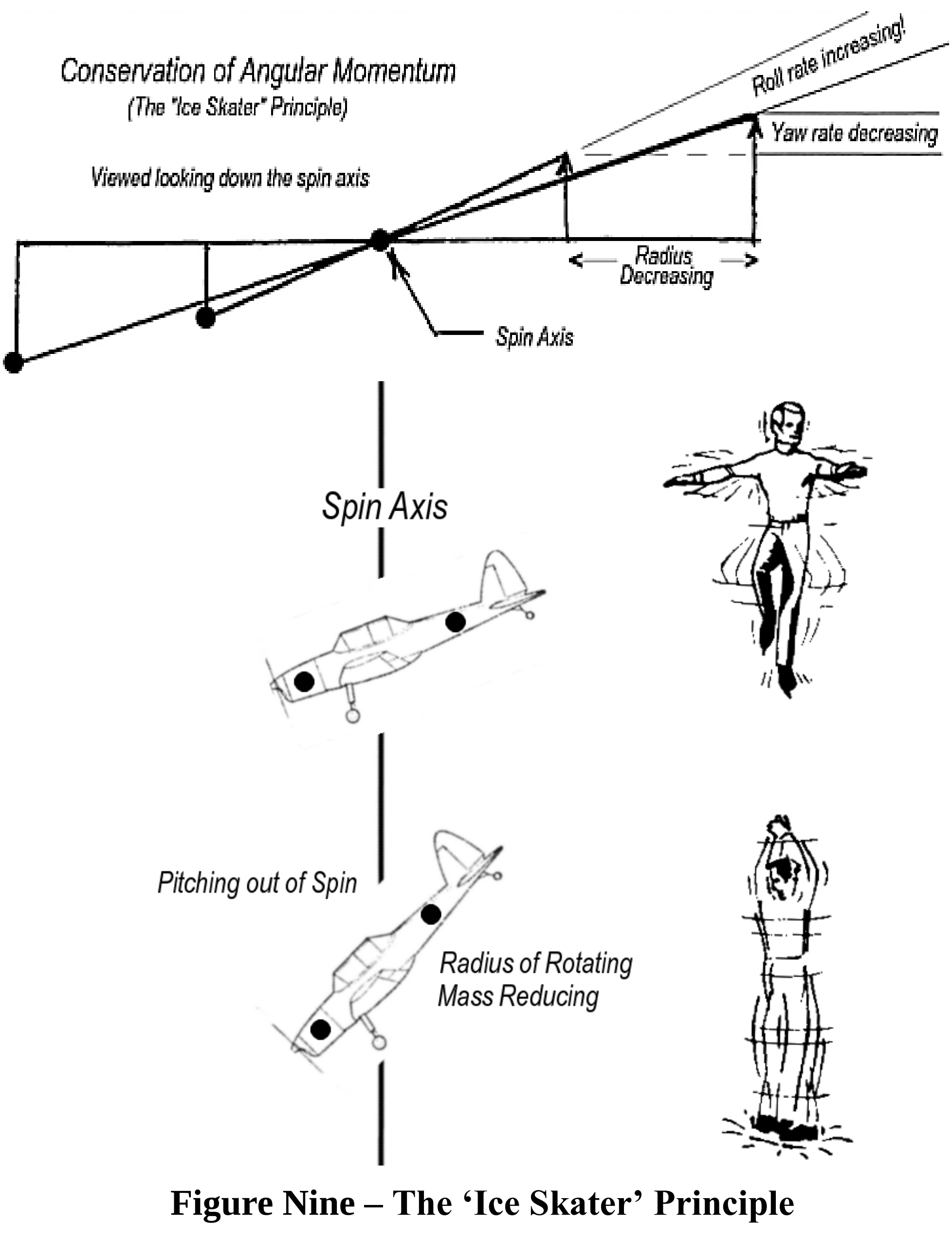
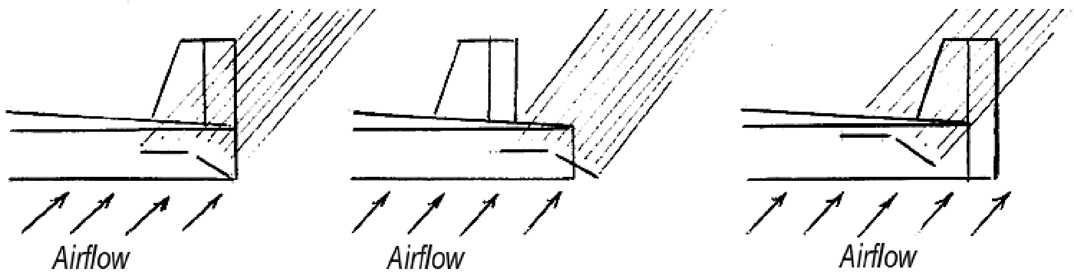


Figure Nine – The 'Ice Skater' Principle

You can see from the foregoing diagram that as the yaw rate is reduced by the application of opposing rudder, the inertia couple decreases and the nose pitches down. This causes the radius of rotation to decrease, and, if it decreases faster than the yaw rate, the angular rotation rate actually increases! This effect lasts only as long as it takes for the rudder to stop the spin completely. The aviator, when looking out the windscreen during the recovery, sees this effect as an increase in roll rate as the nose pitches down.

The "ice skater principle" is present during the spin recovery phase of all aeroplanes, but in some it is more obvious than others; it depends upon how powerful the rudder is, how quickly the nose pitches down, and exactly what the aeroplane's B/A ratio is. But the good news is, if you see the roll rate start to increase as the nose goes down during your next spin recovery, don't panic, you are well on your way out.

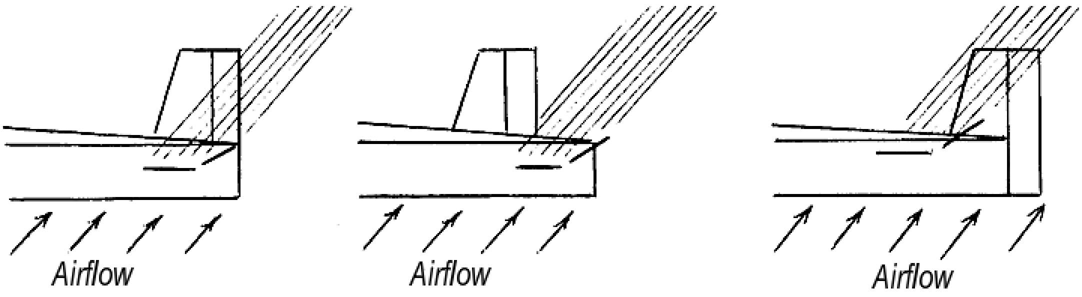
Before moving to the final part of this lesson I would like to discuss 'tail configurations', that is, the relationship of the position of the fin and rudder to the position of the stabilizer and elevator, and the effect this relationship has on the spin characteristics of an aeroplane. Most touring (non -spin-able) aeroplanes have a simple cruciform tail assembly, that is, the fin/rudder makes a cross with the stabilizer/elevator which means that regardless of the position of the elevator, the rudder will be in its airflow shadow during a spin. Whereas aeroplanes designed for safe spin training have the rudder positioned clear of the blanketing effect caused by this airflow shadow as much as possible. This is achieved by either setting the fin/rudder forward of the stabilizer or setting the stabilizer and elevator forward of the rudder. The latter design also extends the rudder below the elevator, as seen in the following diagrams, thereby increasing the area of the rudder significantly. Note that because the airflow is from a large angle below the aeroplane, the stabilizer/ elevator of the 'touring' aeroplane (on the left) blankets the rudder regardless of the position of the elevator and seriously reduces the effectiveness of the rudder. This configuration would not enable effective spin recoveries whilst the other two work quite well. The following diagram (Figure Ten) shows the airflow 'shadow' over the rudder (or not) on each of these three tail configurations with 'forward stick' applied.



Airflow 'Shadow' over rudder caused by forward 'stick'.

Figure Ten

The next diagram (Figure Eleven) shows the airflow shadow over the rudder on the same three tail configurations with the 'stick free'.



Airflow 'Shadow' over rudder, 'Stick Free'.

Figure Eleven

It is interesting to note that most military training aeroplanes have the forward fin configuration whilst most civilian spin trainers have the forward elevator configuration, and all serious aerobatic aeroplanes have the rudder extending well below the elevator as shown. The emphasis in both designs is to ensure that the maximum amount of undisturbed airflow gets to the rudder when we need it the most....during spin recovery. Releasing the stick during the spin recovery so that the elevators can trail 'stick free' in the airflow also helps.

Okay, I have said a lot about the spin with many asides into aerodynamics and dynamics and tail design but I also said that, despite the 'wild ride', the actions required to get into and out of a spin are very simple, so let me spell out the whole process in a 'nut shell'. (Also see Figure Twelve.)

Entry

1. Approach a clean, power off, level stall.
2. Just before the stall (1.1Vs) apply full rudder and full back stick.
3. Hold the controls firmly in this position till the spin stabilizes. (Speed stable and controls remaining pro-spin)
4. Relax and enjoy the ride.

During

1. Note the spin direction from the turn needle
2. Monitor the altimeter.

Recovery

1. Throttle off.
2. Confirm spin direction.
3. Hands off.
4. <u>Full</u> opposite rudder
5. When the rotation stops get off the rudder.
6. Grasp stick and pull out of the dive.
7. Airstart the engine if necessary.

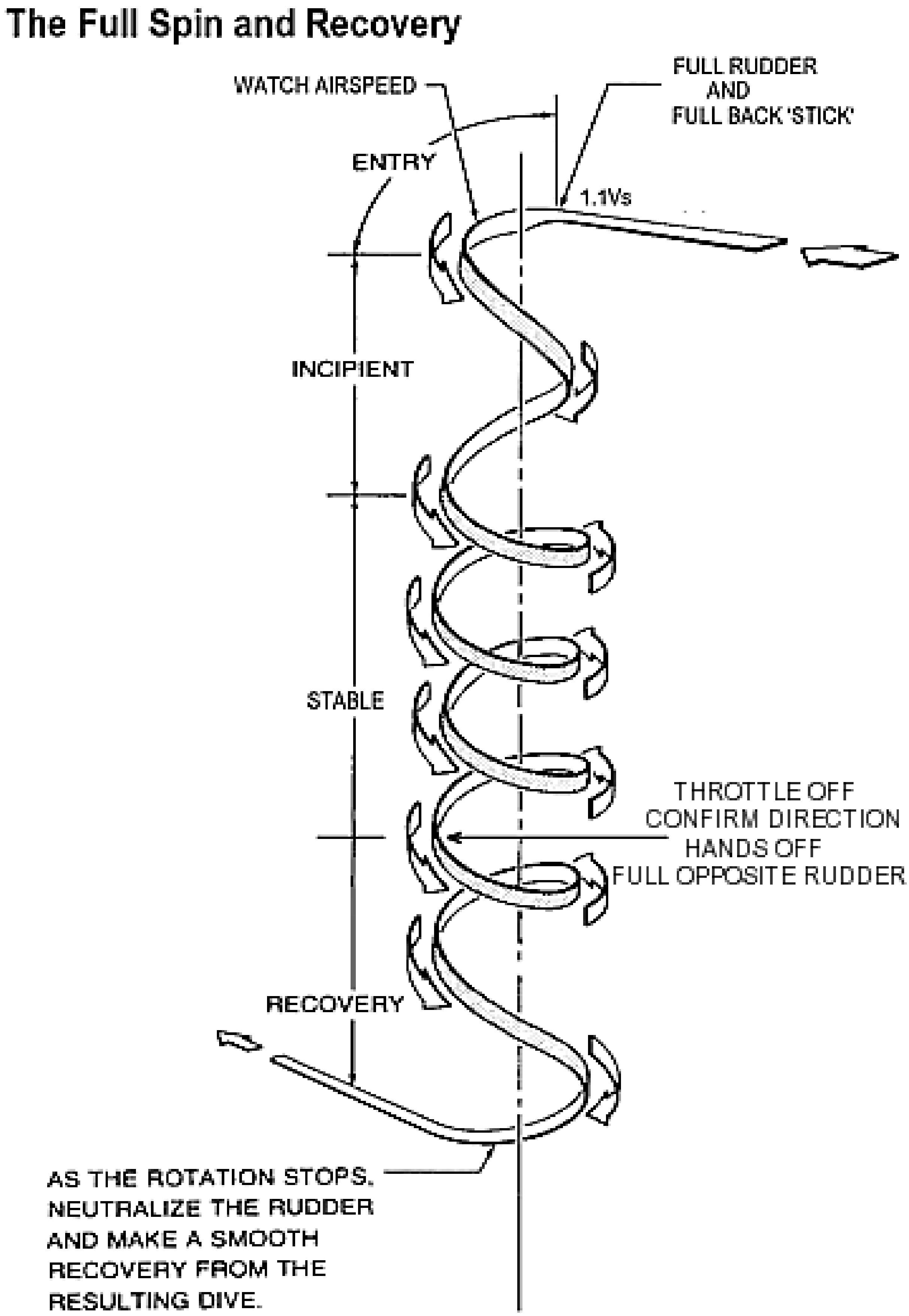


Figure Twelve – The Full Spin and Recovery

This procedure is so simple that, literally, anyone can do it.

Many years ago I was approached by the producers of a TV show called ‘Who Dares Wins’. It was a program in which an unsuspecting person was approached in the street and offered a massive prize if he or she could accomplish some terrifying task. My ‘victim’ was a woman who had never been in an aeroplane before, and her task was to recover from a spin! I was allowed to brief her on what to do and show her once in the air. Then she had to do it; on national television in that same flight (the cockpit was bristling with ‘lipstick’ cameras). When the time came I put the aeroplane into a stable spin and then put my hands up where they could be seen clear of the controls (little did the producers know that this is what I would have done anyway), then this very brave lady (who was really quaking in her boots) proceeded to recover from the spin using the forgoing technique. She did it superbly and won for herself and her husband an all expenses paid trip to Europe!

If she can do it, you can do it....it <u>is</u> that simple!

So what was the controversy I spoke of earlier? First I need to go back a few years to explain the ‘traditional’ spin recovery technique and its limitations.

I mentioned at the beginning of this lesson the fact that ‘way back’ there were some aeroplanes created which had some ‘dodgy’ spin characteristics. There were also about as many different recovery techniques as there were different types of aeroplanes, so there was a degree of confusion surrounding the question of what was the best spin recovery technique. By the mid 1930’s the American FAA had decided on a ‘universal’ spin recovery technique which should work on all aeroplanes. If a particular aeroplane did not respond to this technique it lost its spin approval until it was redesigned to comply with this new requirement. This approach to the problem worked well and rapidly ‘weeded’ out the dodgy aeroplanes. The spin recovery technique decided upon was:

1. Close the throttle.
2. Identify the direction of the spin.
3. Centralize the ailerons.
4. Apply <u>full</u> opposite rudder.
5. Pause (for about two seconds).
6. Smoothly move the stick fully forward.
7. When the rotation stops, centralize the rudder and stick.
8. Pull out of the dive (air start the prop if required).

This is the technique that I was initially taught in the Chipmunk, and later in the RAAF ‘Winjeel’ trainer. It is also the technique I used and taught in my flying school during the first couple of years. Nowadays it is called the PARE technique: Power/Ailerons/Rudder/Elevators.

When I first started the ‘Sydney Aerobatic School’ in 1984 I chose a European designed aeroplane as my primary trainer (which has the ‘forward elevator’ tail configuration.) The manufacturer had recommended a spin recovery technique which did not conform to the ‘traditional’ method. Their recommendation was to keep the stick fully back until the rotation ceased in order to prevent the elevators blanketing the rudder. The Australian CAA would have none of that, believing that they knew better than the aircraft manufacturers, and changed the flight manual to detail the ‘traditional’ FAA method, which delayed the recovery by up to half a rotation! (Fortunately it had a large enough rudder to overcome both the yaw and the CAA.)

Now don’t get me wrong, the ‘traditional’ FAA spin recovery technique is a technique which has worked well for many many years and still works well (and I am told is still taught in military training schools), but its application has a couple of drawbacks.

The first of these was simply one of inadequate training. It was found that if the sequence of control inputs was confused such that the stick was pushed too aggressively forward without the pause or worse, was pushed forward before the opposite rudder was applied, airflow blanketing of the rudder by the elevator would significantly delay the recovery, but this same action forced the nose down without the associated reduction in yaw so the ‘ice skater principle’ would really wind up the roll rate (It also extended the time during which the ‘ice skater principle’ could act), and this is how the Chipmunk got its reputation.

Aviation authorities in the UK decided that the way to prevent this potential problem was to fit ‘spin strakes’ to all of the current spin trainers to prevent them from entering a stable spin! These strakes were leading edge extensions fitted to the ‘root’ end of the leading edge of the tailplane, increasing its aerodynamic pitching moment and preventing the inertia couple from ‘having its way’. The result was an aeroplane only capable of doing an unstable spin. This meant that the ‘standard’ spin recovery technique would work even if the pilot did it in reverse order. This spin strake fitment spoiled the wonderful spinning characteristics of the Chipmunk and the Tiger Moth, and diminished their effectiveness as spin trainers.

The second was a new ‘breed’ of aerobatic aeroplane coming onto the scene during the late 1950’s. It had a symmetrical wing section and an engine capable of running upside down. These aeroplanes were capable of doing ‘outside loops’ and spinning inverted! Whilst they were not plentiful, the American National Advisory Committee for Aeronautics (NACA) suggested a small revision to the traditional spin recovery technique which better suited this type of aeroplane. It simply changed the emphasis from “moving the stick forward” to “allowing the stick to move forward”. The word “allowing” suggests that the pilot let the stick find its own position during the recovery process (releasing it?). Unfortunately this subtle change was not adopted by the FAA with some unfortunate results.

By the 1970's these new aerobatic aeroplanes were becoming available for a reasonable price 'off the shelf', which meant that pilots with inadequate or no spin training could acquire and fly one. The best example of this new type of aeroplane was the factory built Pitts Special (home build kits had been available for a while but were not approved in many countries). I first checked out on a Pitts S2A in 1975 but before my type endorsement was accepted by the Australian CAA, I had to demonstrate recoveries from both upright and inverted spins using the 'traditional' recovery technique, including transitions from upright to inverted and inverted to upright spins. It was a wild time but I became reasonably comfortable with them and even instructed a few other people in the techniques. I also discovered that if the sequence of control inputs was reversed the spin became flatter! That is, if during an upright stable spin I simply pushed the stick forward, the rotation would speed up and the spin would flatten out more! (Blanketing of the fin and rudder by the down elevator.) This is one of those drawbacks in the application of the traditional technique I mentioned previously.

Now spinning inverted sounds horrendous, but from an aerodynamic and dynamic point of view it is no different to an upright spin, except the position of the pilots head and the wheels is reversed. Obviously an inverted spin is entered by stalling the wing inverted by applying forward stick and appropriate rudder and, using the traditional technique, was stopped by pulling the stick back in conjunction with opposite rudder. If the inverted spin was entered inadvertently the pilot needed to be able to recognize that it was inverted so that the appropriate stick input could be made to recover. Herein was a problem because, from a pilot's point of view, whirling around and around whilst hanging upside down can be quite disorientating, and can lead to mishandling, and late or no recovery.

I should explain the 'transitions' from upright to inverted spins, and vice versa. The traditional spin recovery technique involves moving the stick fully forward for an upright recovery and fully back for an inverted recovery, but if you did that in the Pitts the elevators were so powerful that the recovery from one type of spin would pitch the aeroplane straight through into the other type! The yaw would reverse but the roll would be in the same direction, which was very confusing. (Think about it.)

The requirement was to be able to recognize when this transition had taken place and reverse the elevator input accordingly. Obviously what you did with the elevator was critical to the eventual outcome of the spin. As you can imagine this had the potential for a lot of mishandling, and all over the world pilots were scaring themselves and even killing themselves by mishandling spin recoveries using the traditional technique in these and similar types of new aerobatic aeroplanes. This is what the NACA's suggested revision was intended to avoid and is the other drawback of the traditional technique.

In 1985, when I was teaching people how to spin and recover using the traditional technique, I decided it was time to buy a more advanced aerobatic aeroplane to enable those of my students who were capable, of proceeding to a higher standard of aerobatics. I purchased a Pitts S2A. It then dawned on me that I would have to teach all of these very confusing spin recognition and recovery techniques, which I hadn't done myself for a number of years, and I wasn't looking forward to.

About that time a good friend gave me a copy of a very interesting article published in the International Aerobatic Clubs magazine on a 'new' approach to spin recoveries in these new 'fully reversible' aeroplanes. I read it and I was immediately 'hooked'. The article was written by an American aerobatic instructor named Gene Beggs who had been teaching this new technique for a while and he credited its creation to a European aerobatic champion named Eric Muller. It espoused the simple technique that I have detailed in this lesson. It explained that, using this simpler technique, no longer did a pilot need to recognize if she was in an upright or an inverted spin, as once she released the stick the elevators would float free in the air stream and not interfere with the airflow over the primary recovery control...the rudder. All the pilot had to do was recognize the direction of rotation and shove on the opposite rudder, then as the rotation slowed, the wings pitching moment and aeroplanes 'natural' longitudinal stability would pitch the nose down and return the A/A to its trimmed position. (It was, in effect, a simplified version of the NACA suggestion of 30 years previous!)

I tried out this new technique on my primary training aeroplane first, and found it came out of a spin a quarter to half a turn sooner (which didn't surprise me). I then took my new Pitts up and found that upright recoveries were so much simpler and inverted recoveries were just as simple but also as quick as lightning; out within one turn! It turns out the Pitts spins and recovers better upside down than in does right side up because the fin and rudder are down there in that nice clean uninterrupted airflow working at 100% efficiency.

I quickly developed a spin training program on the Pitts which culminated in me throwing the aeroplane around the sky whilst the student, sitting in the back, had his eyes closed! I would then put it into a stable inverted spin and ask the student to open his eyes and tell me where he was and what was going on. Quite often the answer was "I don't know I am sooo disorientated", whereupon I would hand over control and say "good, now recover!" Using the Beggs/Muller technique we were always out of the spin within two rotations. All the student did, with the throttle closed and his hand off the stick, was push on either rudder and if it wasn't out within one turn he pushed on the other one! How simple is that?

I abandoned teaching the traditional technique in my primary trainer and ever since have taught the Beggs/Muller technique, because not only is it more effective in that aeroplane but so much simpler to teach and to learn. One of the reasons that many pilots use to avoid spin training is that they are afraid of the consequences if they mishandle the recovery. With the Beggs/Muller technique it is almost impossible to mishandle spin recoveries. It enables an aviator to become more comfortable in the sky and that, as I have said previously, is my primary goal in this business.

For those of you who expect one day to move up to aeroplanes capable of spinning inverted, I have included in Annex A, a more detailed discussion on recognizing spin direction when performing this manoeuvre.

A question which often arises during discussions about spin recovery is, "what do you do with the flaps if they are extended?" The effect that extended flaps will have on the aerodynamics of a spin depends upon their effect on the downwash over the tail and to what extent they will 'blanket' the rudder during recovery. (Refer back to the lesson on Stability and Control if you have forgotten.) Also there may be the problem of exceeding the flap limiting airspeed during the recovery. For these reasons it is best to retract the flaps prior to initiating the spin recovery actions; however, I must ask "why were the flaps extended in the first place?" I cannot imagine a situation where an aeroplane inadvertently enters a stable spin with its flaps down, high enough for the pilot to have time to retract the flaps before initiating recovery action. Flaps are a lift augmentation device used primarily during the landing phase of flight, which means the ground is not very far away!

If the aeroplane starts to autorotate in the landing configuration close to the ground then survival is the governing principle. The pilot should regain control as quickly as possible and to hell with the flap limiting speed.

So what was this controversy I spoke of? Well, any new technique has its detractors, and in this case there were some who tried it on some older type aeroplanes and found that it didn't work! The stick still had to be moved forward. When I heard about this 'problem' I tried the new technique on a Chipmunk, and found that it took about 5 turns to recover, which of course was unacceptable. Apparently the same problem occurred with the T6 Harvard and similar older types, so the new technique was declared by many to be 'unsatisfactory' because it didn't work on all types of spin approved aeroplanes. (I subsequently learned that it may not work on many non-approved types if they inadvertently get into a spin, but then neither does the traditional technique; which is why they are 'non-approved'.)

So where does that leave the Beggs/Muller Technique? Well despite this controversy the Beggs/Muller spin recovery technique is widely used by all modern aerobatic pilots around the world as an emergency spin recovery technique. Those flying schools which actually teach spinning, and are using modern aeroplanes, find it works well too. They find, as I did, that it gives the student pilot confidence whilst gaining experience with spinning. If those same pilots then wish to fly and spin older types on which the technique doesn't work, they should be trained in the appropriate technique on that aeroplane. At least they will undertake that training being already comfortable in a spin, and can therefore concentrate and learn the technique properly, without being overawed by the sensations.

When trying out the Beggs/Muller technique on the Chipmunk I found that this new technique would actually lead me into the traditional technique in the correct sequence, and with the correct timing. How so? Well, the only fundamental difference between the two techniques is the manual control of the stick position, as opposed to simply letting it go. So when I used this new technique in the Chipmunk, and the aeroplane kept spinning, I was able to note that the stick was still full back (and in-spin), so I then moved it forward (with my thumb), and the aeroplane immediately stopped spinning. I had in effect built in the correct sequence of control inputs and the minimum two second pause required by the traditional technique. So even on these older aeroplanes the Beggs/Muller technique establishes the correct sequence and timing to use when followed by the traditional technique.

So they are not competing techniques, they are complementary techniques.

Perhaps it is time for the regulatory authorities of the principle aircraft manufacturing nations to once again step in and declare that the Beggs/Muller technique is now the new standard spin recovery technique and that all current production and proposed production spin trainers should comply with this new standard. Those aviators wishing to fly older types which do not comply, should be required to have additional training in the appropriate spin recovery technique specific to that aeroplane as part of the 'type check'.

I am pleased to say that among some of the regulatory authorities of 'user nations' there has been a general acceptance that the traditional spin recovery technique may not be the most suitable for modern spin-able aeroplanes, and they are now accepting the manufacturers recommended spin recovery techniques as detailed in the aircraft's flight manual, and have 'softened' the wording of their regulations, and their 'we know best' attitude, to allow for these alternate techniques.

I must emphasize at this point that no one should go out and attempt to train themselves in spin recovery techniques based upon what I have said in this lesson (or anything else they may have read about spinning). You <u>must</u> do it under the guidance and supervision of a competent and qualified flying instructor and use the technique most suitable to the aeroplane type.

I have, in this lesson, talked of two spin recovery techniques and two fundamentally different types of spin training aeroplanes, those that are capable of fully developed stable spins and those which will go unstable after about 3 rotations. From a purely instructional point of view, the best spin training will come from the best combination of these two variables. An aeroplane capable of stable spins allows the instructor time to direct the student steadily through the recovery process and the student time to take it all in, especially if the simpler of the two recovery techniques is being taught. On the other hand, if the traditional technique is being taught in an aeroplane limited to only 3 rotations, there will be a wild flurry of activity in the cockpit for a few seconds leaving the student with information overload and a touch of bewilderment after each spin. This is not a good learning situation. So the correct choice of aeroplane and instructor is important.

At the Sydney Aerobatic School I used the Robin 2160 as my primary trainer. It is, I believe, the best all round flight trainer available today. It has excellent stable spin characteristics and can do reasonably advanced aerobatics whilst remaining an excellent basic flying trainer in all other respects too.

I am regularly asked how many spins are needed to ‘qualify’. My training program included three separate spinning flights, on the first, six spins of 10-12 rotations were done, and on the second and third flights, four each. The rest of the time on the second and third flights was spent exploring the various ways the aeroplane could be mishandled and put into an inadvertent spin. At the conclusion of these flights the average student was then competent enough to undertake a solo spinning flight, but, if the student expressed any lack of confidence we would repeat as many spins as was necessary for him or her to gain that confidence. Avoid any flight school that will tell you “you are okay” after just one flight, particularly if was in a 3 turn limited aeroplane using the traditional technique.

Why do it? Why bother to learn how to spin and recover? Surely just knowing how to avoid a spin is sufficient. This is a question I hear all the time.

Humans, when suddenly confronted with a life threatening situation, react first and think later. If this reaction is to be effective, it must be instinctive and based upon correct training. If there has been no training then the reaction is likely to be incorrect. An untrained pilot suddenly confronted with an asymmetric stall will probably react to the pitch and roll by pulling the stick back more in an attempt to stop the nose down pitch and apply opposite aileron in an attempt to stop the roll.

This is exactly the opposite of the correct reaction and will result in the aeroplane spinning out of control.

Any aeroplane, if mishandled to the point that an asymmetric stall is induced, will start to autorotate, and if this is not corrected quickly and instinctively, especially in aeroplanes not approved for deliberate spins, an ugly and possibly irrecoverable spin can result. Unfortunately most flying instructors who have no training in spinning, avoid giving much training in asymmetric stalls, even in aeroplanes capable of spinning, because they are unsure if their student will be too aggressive initially or too slow responding, and take the instructor out of his ‘comfort zone’. In other words, in the mind of the instructor, asymmetric stalls are ‘limit’ manoeuvres teetering on the brink of loss of control! The instructor’s inhibitions will ultimately pass on to the student who, after graduation, will lack the confidence to continue practicing them, so whatever skill has been learned will quickly be lost.

If, on the other hand, the instructor is properly spin trained, then teaching the recovery technique from asymmetric stalls and incipient spins from any attitude is nowhere near the limit of his comfort zone, so they cease to be a ‘limit’ manoeuvre and his students can receive proper and thorough training in spin avoidance. It won’t matter if the manoeuvre goes a little too far during early training, the instructor will be able to ‘handle it’, and the student will get to see the consequences of his actions.

If the student is to be equipped with the skills to continue practicing these vital techniques after graduation then he too must be trained in full spin recovery techniques. Recognition and recovery from incipient spin situations is a motor skill which, if it is to become and remain instinctive, requires regular reinforcement, just like landing skills, so the post graduate student needs the spinning skills and the confidence to be able to practice these manoeuvres in safety.

That is why full spin training should be a part of every aviator’s basic training.

Flying schools and regulatory authorities have, over the past 50 years, gone to a lot of trouble to keep from teaching people how to fly properly. Horns blowing, lights flashing, bells ringing and even electronic voices shouting warnings, all trying to substitute for learning the full range of controllability of an aeroplane. In other words, the things that you should be taught when learning to fly.

I am aware that the cost of good flying training is regarded as a limiting factor by some people, and I know that many other people think, “Why do that much training for an event that may never occur?” But if you have decided to learn to fly I offer you this quote that I saw recently on a ‘bumper sticker’.

If you think education is expensive
Try ignorance!

Being able to control the angle of attack of the wing, and being able to control the ‘dreaded tail spin’ with confidence, opens the sky to you. It <u>is</u> worth it.

Annex A - Inverted Spin Direction

Annex A

Inverted Spin Direction

In the main text of the lesson I emphasized that the best way to determine the direction of rotation of a spin is to refer to the turn instrument. However in an inverted spin one of the two types of turn instrument commonly fitted to aeroplanes has a design difference which could lead to an incorrect indication.

First we should be clear about what is going on in an inverted spin. As previously described, an inverted spin is entered when the aeroplane is yawing at the point of an inverted (negative) stall. This will mean that, from the aviators and the turn instruments 'point of view', the aeroplane is rolling in the opposite direction to the way it is yawing! Check out Figure One.

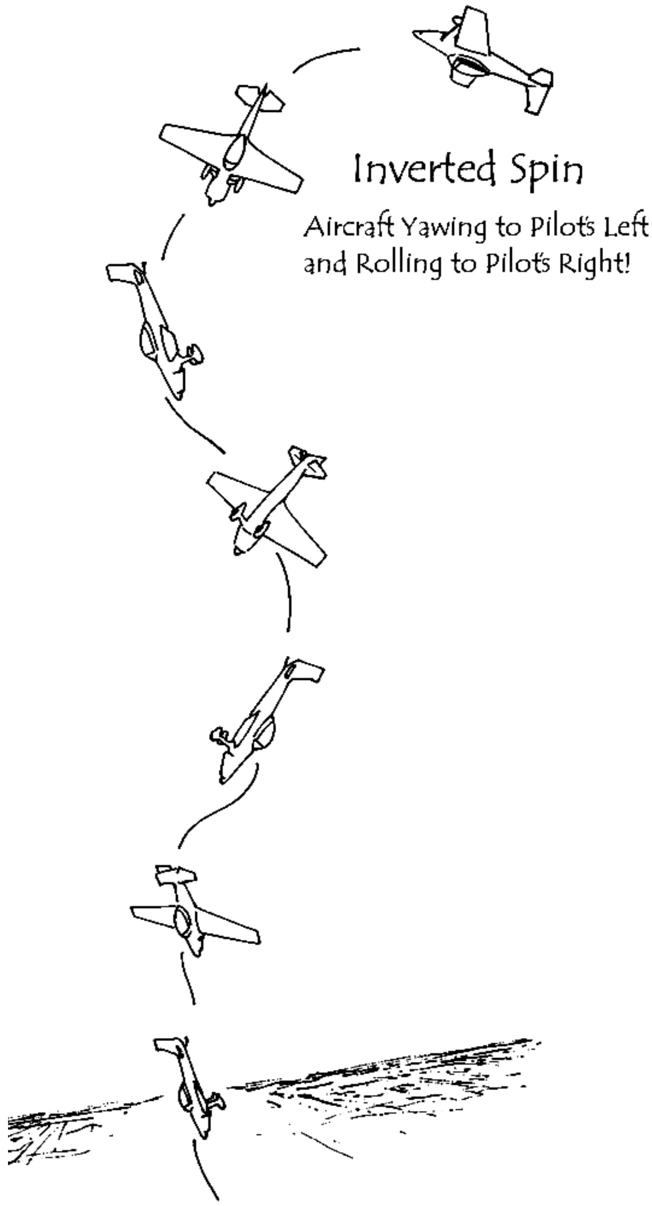


Figure One – Inverted Spin

Imagine you are flying the aeroplane in the forgoing diagram, you are approaching a wings level inverted stall, hanging in your straps, and at 1.1Vs you apply full left rudder (your left) and shove the stick fully forward and hold them there. The aeroplane will enter an inverted spin, and you will see the nose yaw to your left and the wings roll to your right. From the point of view of an observer sitting right way up, the roll will be seen the same but the yaw will be seen differently because ‘right’ and ‘left’ are relative to the way you are sitting, and in this case they would be reversed.

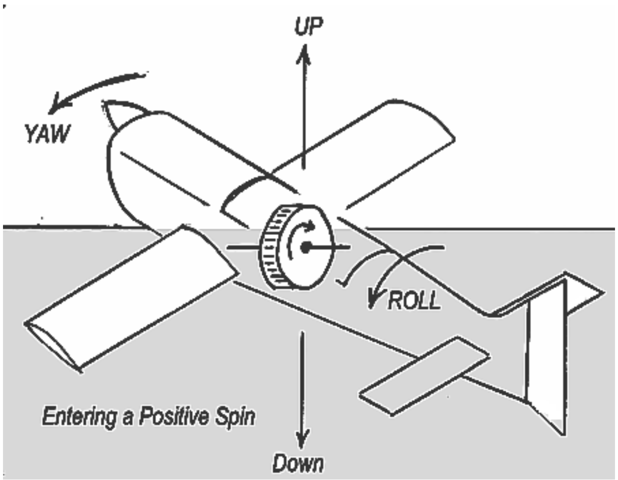
This difference in point of view is not a problem for the aviator because when it comes to the recovery, opposite rudder is still opposite rudder, regardless of how the yaw direction is perceived. (To circumvent this potential confusion when instructing inverted spinning I use the terms “Right Foot Spin” and “Left Foot Spin”.) However, from the point of view of the modern turn instrument called the ‘Turn Coordinator’ this difference in roll and yaw could cause a problem.

The old style ‘Turn Indicator’ is, as I have said previously, a ‘Yaw Rate Gyro’, and that is all it is. The axis of spin of the gyro inside this instrument is aligned with the lateral axis of the aeroplane so that it will only react to yaw and is not affected by the difference in the orientation of the longitudinal and the roll axis at high angles of attack. However the ‘Turn Coordinator’ has the axis of rotation of its gyro aligned ‘fore and aft’, and tilted about 30º to the longitudinal axis. This ‘tilt’ is such that the rear end of the gyro axis (that is the one closest to the pilot) is higher than the front end. This modification was developed to make the instrument sensitive to the initial roll input when entering a turn, and thereby eliminating the lag experienced with the ‘Turn Indicator’. This made ‘limited panel’ instrument flying easier and, in this context, is a great idea. However, this improvement in design is predicated on the idea that the roll and yaw are in the same direction when entering a turn. Not so when entering an inverted spin!

Whilst the ‘Turn Coordinator’ gyro axis is tilted 30º to the aircraft’s longitudinal axis, the longitudinal axis is itself “tilted” about 15º to the aircraft’s flight path (A/A) when approaching a stall. When the stall is positive the gyro axis aligns more with the flight path (only 15º of ‘tilt’), and its roll sensitivity is reduced, but its yaw sensitivity is increased, so no problem. But when the stall is negative, the gyro axis is about -45º to the flight path, which means its yaw and roll sensitivity are similar. The following diagram (Figure Two) shows this Gyro Axis to Flight Path Relationship.

Figure Two – Turn Coordinator Gyro Axis

Upon entering an inverted spin, the yaw and roll are in opposite directions to each other, so a ‘Turn Coordinator’ receives conflicting yaw/roll rate and direction inputs. The following diagrams (Figure Three a & b) show the pilot’s (and the turn coordinator’s) perspective when entering a positive and a negative spin, (note the direction of the roll and yaw in each case).



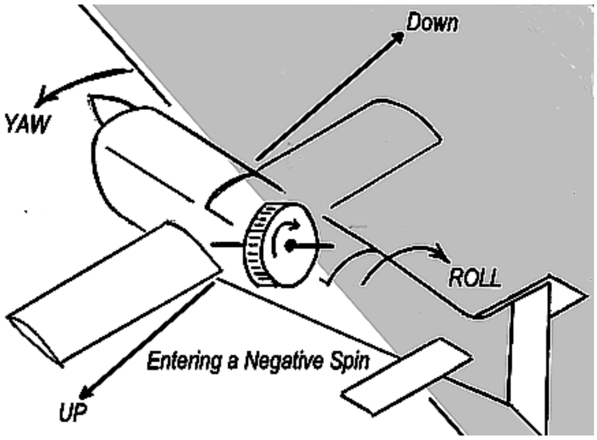


Fig 3a - Left Foot Positive Spin Entry. **Fig 3b - Left Foot Negative Spin Entry**

Which of these roll and yaw inputs dominates, and which spin direction is indicated by the ‘Turn Coordinator’ during a negative spin depends upon the B/A ratio of the aeroplane and how ‘flat’ the final inverted spin is, but during the incipient phase it is quite likely that the roll input ‘wins’ and the instrument gives the wrong information! The following diagram (Figure Four a & b) is a repeat of one seen previously so there is no confusion about which instrument I am talking about.

Fig 4a

Fig4b

Turn Indicator’ No problem.
Inverted Spinning LEFT

‘Turn Coordinator’ Big problem.
Inverted Spinning ????

The good news is that very few aeroplane types which are capable of inverted spinning have any sort of turn instrument fitted to them. If you come across an aeroplane that has one fitted, be very sure you know which type of instrument it is. If you are unsure, don’t rely on it.

So if the aeroplane doesn't have a turn instrument of any sort (or one you can trust), how can a confused pilot determine the direction of an inverted spin? Simple, pick a point on the airframe straight ahead of you like the engine cowling or a strut and focus your eyes on it. Yes focus, don't just look vaguely in that direction. You will then become aware, through your peripheral vision, which way the aeroplane is yawing, and that is the spin direction. (The peripheral vision is what the brain uses to get balance and orientation information, which is why you can walk down the street whilst focused on 'texting' with your mobile phone and not fall over, and why flying on instruments is nothing like flying visually, despite what your flying instructor might tell you to the contrary.)

There is one place the pilot in an inverted spin should NOT look for information about the spin direction and that is straight UP. If the pilot looks straight up by craning his head back and casting his eyes up, he will be looking behind the spin axis and will perceive the spin direction to be the opposite of what it really is! Check out the following diagram (Figure Five).

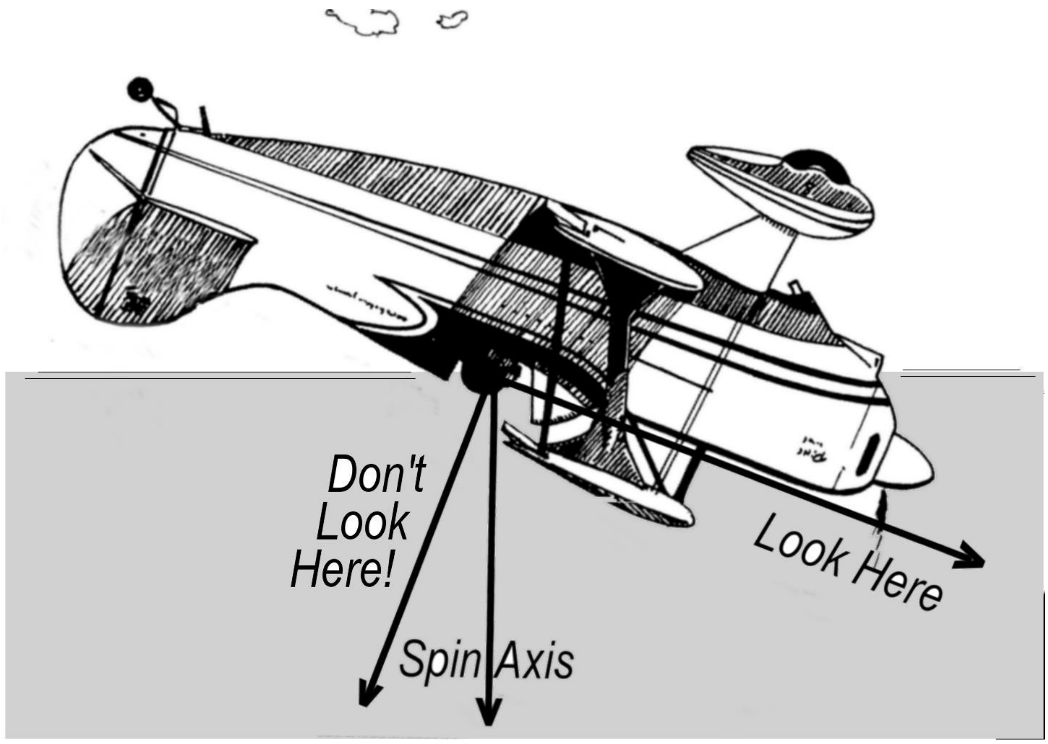


Figure Five – Where to look in an Inverted Spin

This might all sound very confusing and slightly hazardous, but remember this Annex is intended for those of you who are 'at home' in a normal positive spin and are now moving on to a modern high performance aeroplane approved to perform negative spins. Once you have become familiar with this new aeroplane's negative spin recovery characteristics, and if all else fails, all you have to do is stomp on one rudder, and if nothing happens as expected, stomp on the other!

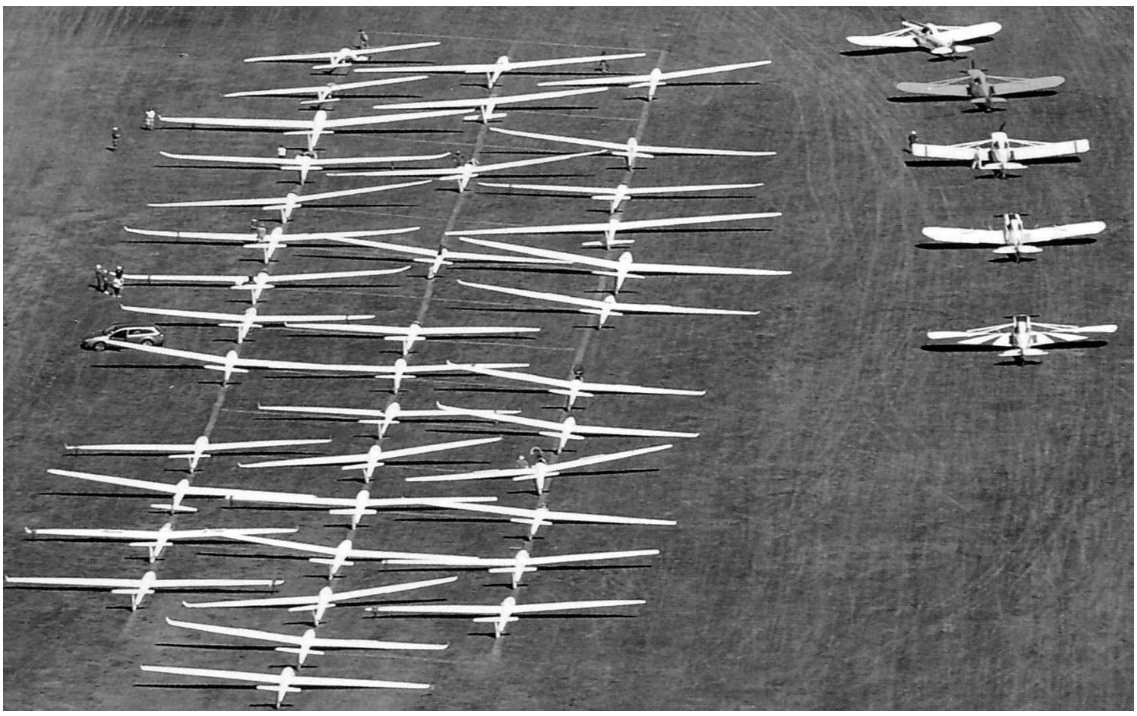
Supplement

SAILPLANES

'Sailplane' is the modern name for a Glider. The first things you notice when looking at a modern sailplane, apart from its lack of an engine, is its slender shape and the very high aspect ratio wings. Closer inspection will also reveal a beautiful smooth and uniform finish with no ripples and only hairline gaps between the moving and fixed flying surfaces of the wings and tail. This slender shape and surface finish is, of course, to reduce 'Zero Lift Drag'.

The development of modern carbon fibre reinforced plastics has also enabled the construction of very long wings strong enough to withstand the flight loads experienced. In Annex A to the lesson on Drag, we learned that induced drag varies inversely with the aspect ratio of a wing (at a particular lift value), so this new material now enables very high aspect ratio wings to be manufactured. These new materials are a major contributor to the performance of a modern sailplane because induced drag is the greatest inhibitor of sailplane performance.

If you have ever seen the starting 'grid' at a major gliding contest, where dozens of sailplanes are lined up ready for launch you will also notice something else. They all look the same! There may be many different brand names and models amongst them, but they all look very much alike. Unlike powered aeroplanes which come in a wide variety of shapes and sizes to suit the various roles required of them, sailplanes have only one role and that is to glide as efficiently as possible, so over the years a sailplane's general shape has undergone an almost Darwinian evolution into what we see on the grid today.



Because of this similarity of design and performance, gliding competitions are about piloting skill. Not just flying skill but skill in finding energy within the air mass surrounding them, in order to keep the aeroplane up there and enable it to fly around a set course faster than all the others...without an engine!

This supplement is not about how that is done; there are many good books written about how to learn the art of soaring (as it is called). This supplement is about the unique aerodynamic characteristics of sailplanes compared to powered aeroplanes, for both sailplane students and powered pilots, to assist them to better understand the aerodynamics of gliding, and where all of those ‘rules of thumb’ I spoke of in the lesson on gliding come from.

Before discussing the performance aspects of sailplane aerodynamics I would like to discuss three other things which relate to structural limits, handling and spinning. First, because I think it the most important, I want to discuss a sailplane’s preponderance to spin!

“Watch him spin watch him burn, he held off bank in a gliding turn!” A ‘nursery rhyme’ for student pilots I used in the lesson on spinning. I also said that if you are holding off bank you are doing a skidding turn and are flirting with auto-rotation as the airspeed reduces. The fix of course is to balance the aeroplane properly and remove this risk. However, when flying a sailplane you may have to hold off bank when turning even though the aeroplane is balanced! How can this be?

Do you remember the spiral staircase analogy I used to explain the difference in angle of attack between the ‘inside’ and the ‘outside’ wing during a gliding turn? Well that difference is still present when gliding a modern sailplane, but because the glide angle is so ‘flat’ the difference is not so great AND those very long wings cause a much greater speed difference between the inside and the outside wing, resulting in a much greater difference in the lift generated by each of them. This asymmetric lift due to the airspeed difference, either overrides or balances the asymmetric lift due to the A/A difference, and this causes the aeroplane to want to either ‘roll on’ bank or stabilize at that bank angle. So in a perfectly balanced gliding turn in a modern sailplane the pilot may have to ‘hold off bank’. Couple this with the fact that sailplanes are normally operating at a low airspeed and high angle of attack (for reasons I will cover later) and, despite their elegance and efficiency, they are the type of aeroplane most likely to enter an inadvertent spin during normal operation! This is why spin training is a vital part of a glider student’s curriculum <u>before</u> they fly solo.

Sailplanes have an additional flight control that a light powered aeroplane doesn’t have. A sailplane has wing mounted ‘brakes’ or ‘spoilers’ controlled by a lever in the cockpit; these brakes are, primarily, a ‘variable drag control’, and are very useful when approaching to land (Figure One).

The brakes are either large flat panels which pop out of the wing at the point of maximum thickness or deploy along the trailing edge of the wing. The following pictures show these two types of brake.

Figure One – Glider 'Air Brakes'

As I said, the primary purpose of these brakes is to increase drag and this happens in two ways. The first and most obvious way is the increase in ZLD which occurs when the brakes are deployed, but they also 'spoil' the lift generated by that section of the wing. This means that, if the flight path is to be maintained, additional lift has to come from the remainder of the wing by way of an angle of attack increase, and we know what happens to LID when the A/A is increased don't we? So we can say that the brakes initially increase ZLD which is then followed by an increase in LID. They have a sort of "double whammy" effect.

Sailplane brakes should be used judiciously when manoeuvring for two reasons. The first stems from the loss of lift when they are deployed. This will degrade turn performance and pitch performance, particularly when 'flaring' the aeroplane just before touchdown. The rate of change of flight path required to 'flare' can be adversely affected if the extension of the brakes is increased during the 'flare'. Doing this could result in a very 'positive arrival'. The increased glide angle which results from the use of brakes can also alter the 'spiral staircase' effect when turning, and change the 'roll on', 'roll off' bank tendency too.

The second reason is the affect the brakes have on the structural limits of the aeroplane. A modern sailplane is subject to all of those structural limits that I have discussed earlier in this book, but it is a very 'slippery' aeroplane and will accelerate rapidly when pointed 'downhill' too steeply. Sailplane brakes can be used right up to and beyond the Vne of the aeroplane, so there are no speed limits involved, (indeed it would be strange to have brakes which couldn't be used when you really need them), but remember the brakes don't only increase drag, they also destroy the lift generating capability of that whole section of wing and this has some interesting structural implications.

Imagine the following scenarios: you are exiting a 'botched' loop at a speed above **Vo**, or recovering from an inadvertent spiral dive above **Vo**. Either way, you are pulling high G at high speed. You might think that the use of the brakes could help control the excess speed in these situations; well, yes and no! "Yes", the extra drag will help slow the aeroplane, but "No", the acceleration limits have just changed and you could overstress the aeroplane! How so?

Once the lift generating capabilities of the inboard area of each wing have been destroyed all of the lift must come from the remaining outboard area, and if the pitch rate to pull out of the manoeuvre is to be maintained the angle of attack of the wing must be increased. The end result is that the size of the lift vector from each wing is unchanged but the aerodynamic centre has moved outboard, thereby increasing the bending moment at the same G. Since the G limit of the sailplane is predicated upon the bending moment of the wing with the aerodynamic centers of each wing in their 'un-braked' position, the G limit must be reduced when the brakes are used. (This applies to negative G limits too.)

The following is the manoeuvre envelope of a typical modern sailplane (Figure Two). Note the restricted acceleration limits (positive and negative) with the brakes open.

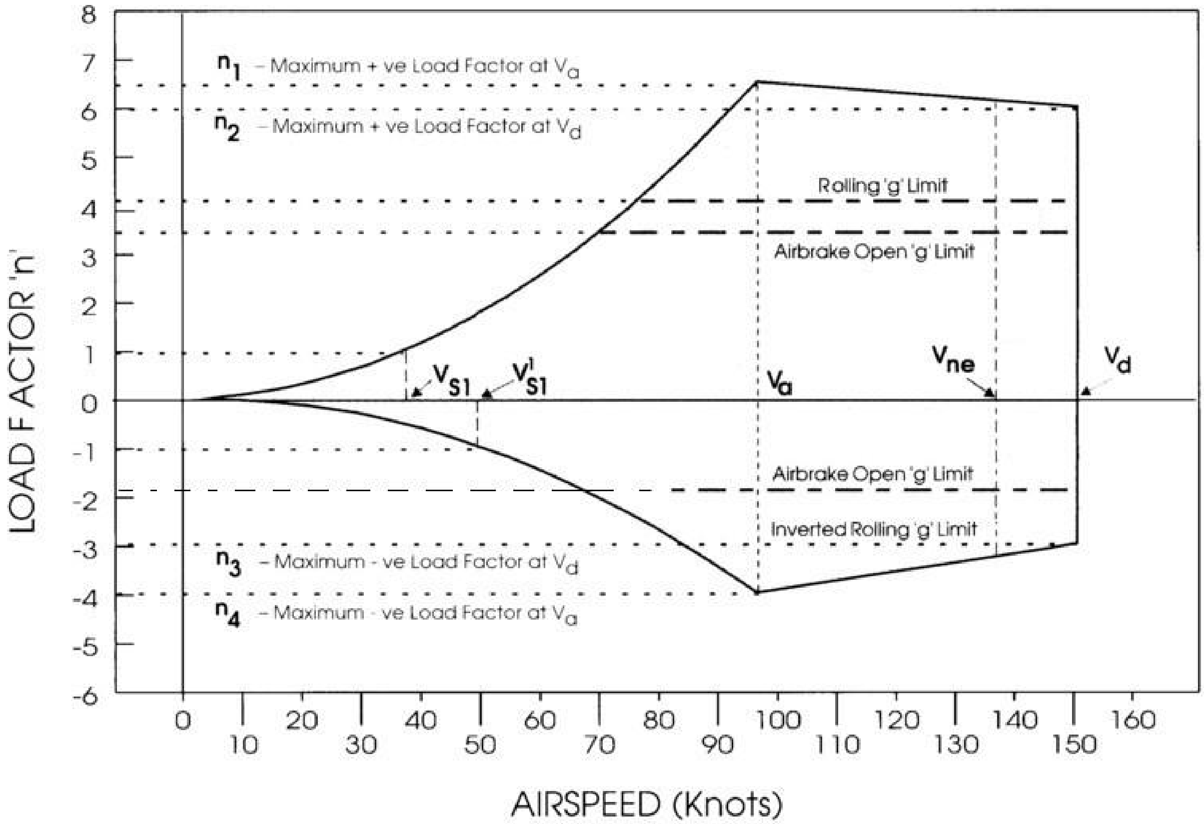


Figure Two – Glider Manoeuvre Envelope

The following picture (Figure Three) shows a sailplane flying level (at 1G), but with a high angle of attack, with the brakes extended. The wings outboard of the brakes are 'bent' more than normal as a result, (and no, I haven't exaggerated this picture, this particular sailplane has quite flexible wings).

Figure Three – Wing 'Bending' exacerbated by use of Air Brakes

You can see from the manoeuvre envelope diagram that the published G limit of a sailplane can be reduced by as much as a half when the brakes are used (the actual reduction is detailed in the particular aircraft's flight manual), so if you are pulling out of a manoeuvre at 4G in a 6G limited sailplane, and you deploy the brakes whilst maintaining the G, you could overstress the aeroplane by 1.0G! (Think about it.) If you throw some 'Rolling G' into the mix too, say recovering from that spiral dive incorrectly, then you are definitely going to exceed the aircraft's structural limits!

Now let's talk about sailplane performance. Obviously, since a sailplane doesn't have an engine, the criteria for measuring its performance are quite straight forward. How long can it stay up and how far can it glide? I am of course talking about this performance within the air mass surrounding it. I am not concerned here with how to find and harness the internal movement of this air mass in order to improve the sailplane's performance relative to the ground. Extracting the energy contained within a moving air mass is, as I have said, the art of soaring, and is beyond the scope of this supplement.

So, I start with the simple premise that a sailplane is always gliding 'downhill' through the air. How efficiently it does this depend upon how little drag it creates throughout its speed range. I am of course talking about its total drag at every speed and which is represented by its 'Total Drag curve'. Now you may think that the sailplane's total drag curve will reveal to the pilot all he or she needs to know about its performance; however, the vertical scale on a Total Drag graph indicates drag values, which give no useful operational information to the pilot. You should remember from the lesson on power that I said that "power is the rate of conversion of energy" into thrust, be it chemical energy (fuel) or potential energy (height). To move a sailplane forward so that it can fly requires power, and this power comes from the conversion of its height into motion. The rate of descent of any aeroplane in a glide has a direct relationship to the power required to sustain its speed, so the 'Power Required' graph is the graph which gives the most useful information regarding this process, provided we make a couple of simple modifications. The first modification is the conversion of the scale on the left of the graph from 'Power Required' to 'Vertical Speed' (Rate of Descent). This conversion is quite straight forward since 'speed' is a fundamental part of the concept of 'power' in the first place. The following (Figure Four) is a graph you will be familiar with (from the lesson on Power), on which I have converted the 'Power Required' scale into a 'Rate of Descent' scale. (Note that the curve itself has not changed shape or position on the graph.)

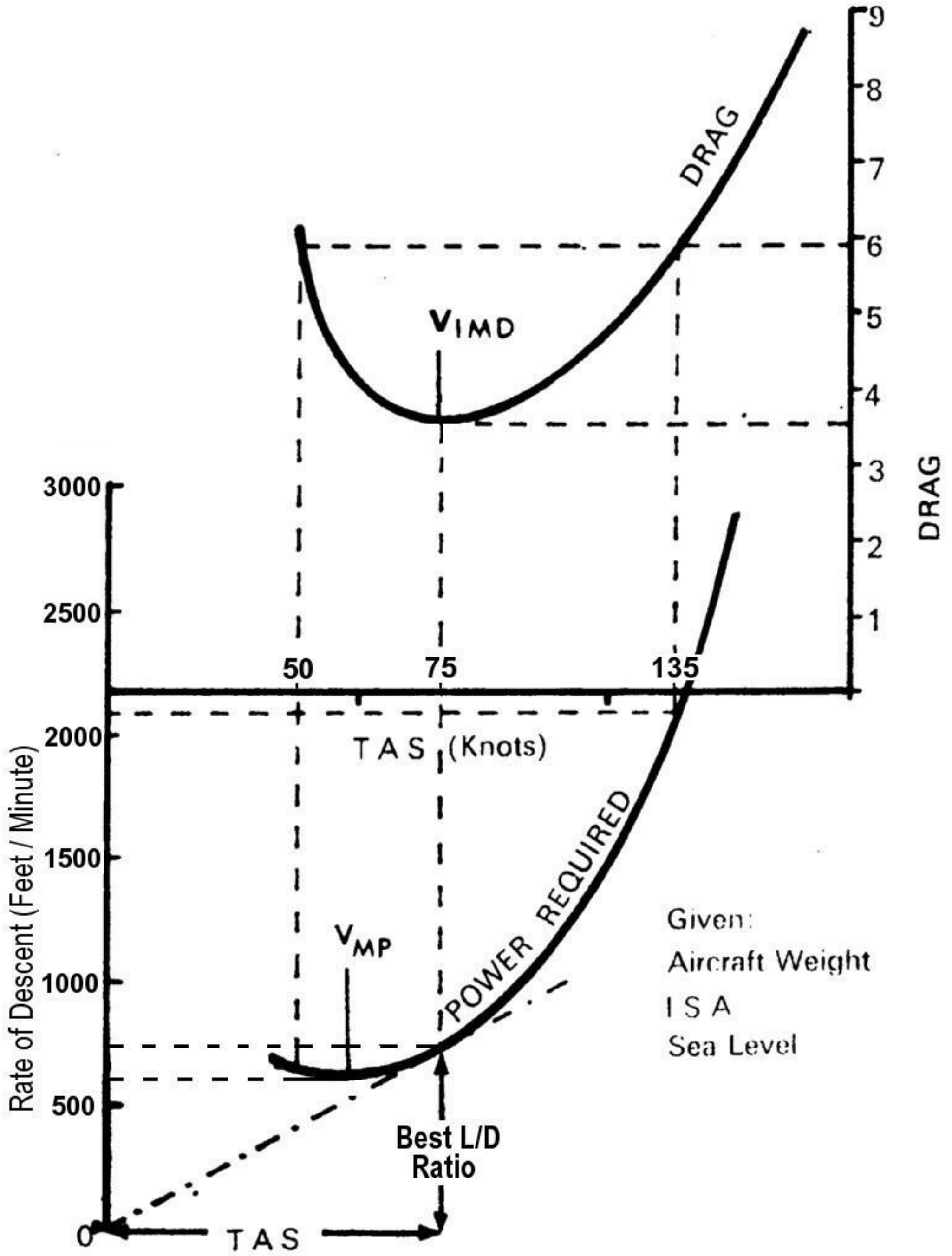


Figure Four – Rate of Descent/Power Required Graph

You can see from this graph that the minimum power speed (Vmp) equates to the minimum rate of descent (minimum 'sink') and the best L/D ratio occurs where a line from the 'zero zero' origin touches the curve at a tangent. Which you can also see is the minimum drag speed (Vmd).

What about the second modification? Well this is simply a matter of orientation. You will note from the preceding graph that the increasing rate of descent scale is going **up** the page, but indicates the rate that the sailplane is going **down.** This doesn't feel quite right to most sailplane pilots; so they flip the whole chart upside down. Now the graph curves **down** more as the sailplane's rate of **descent** increases, so it looks like this (Figure Five).

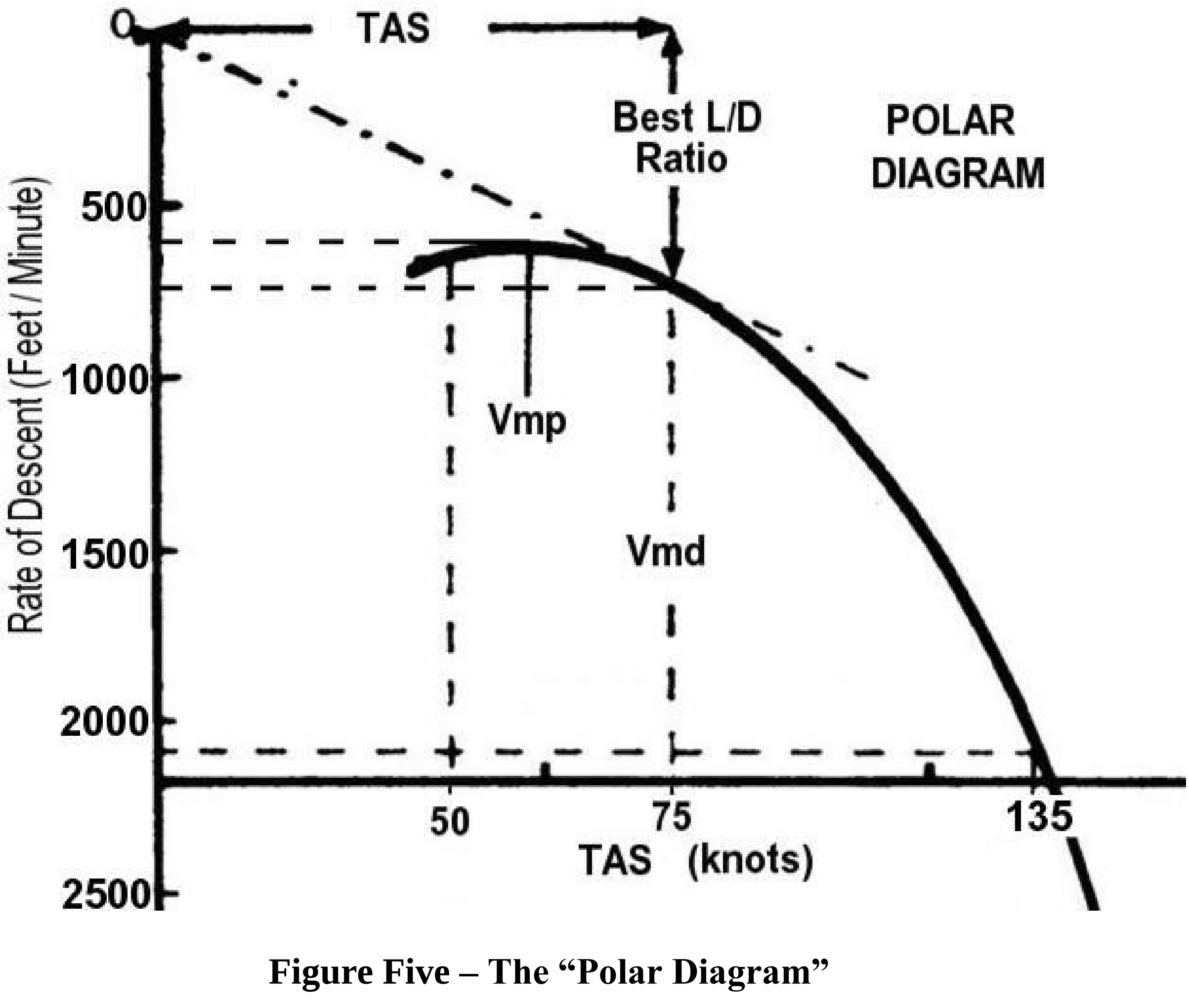


Figure Five – The "Polar Diagram"

As a result of these two changes, this new 'upside down' graph is given a new name. It is called a 'Polar Diagram'. Now a surprising amount of useful information can be obtained from a Polar Diagram, including the best speeds to fly with or against the movement of the air mass (both horizontal and vertical) and the best speed to fly with changing weight (both real and apparent). Those 'rules of thumb' I introduced you to during the lesson on gliding, are derived from the Polar Diagram. Annex's A and B to this supplement delve further into the use of Polar Diagrams.

Okay, I am going to take a step back now to explain two statements I made earlier in this supplement. I said "sailplanes are normally operating at a low airspeed and high angle of attack". From the forgoing charts you should now be able to see why sailplanes operate most efficiently when they are slow. They operate at Vmd (best L/D) for range and Vmp (minimum sink) for endurance. I also said "induced drag is the greatest inhibitor of sailplane performance". Check out the following graph (Figure Six). It is a repeat of one I used in the lesson on gliding, but it is worth repeating; it is the power required curve superimposed on the ZLD, LID and Total Drag curves.

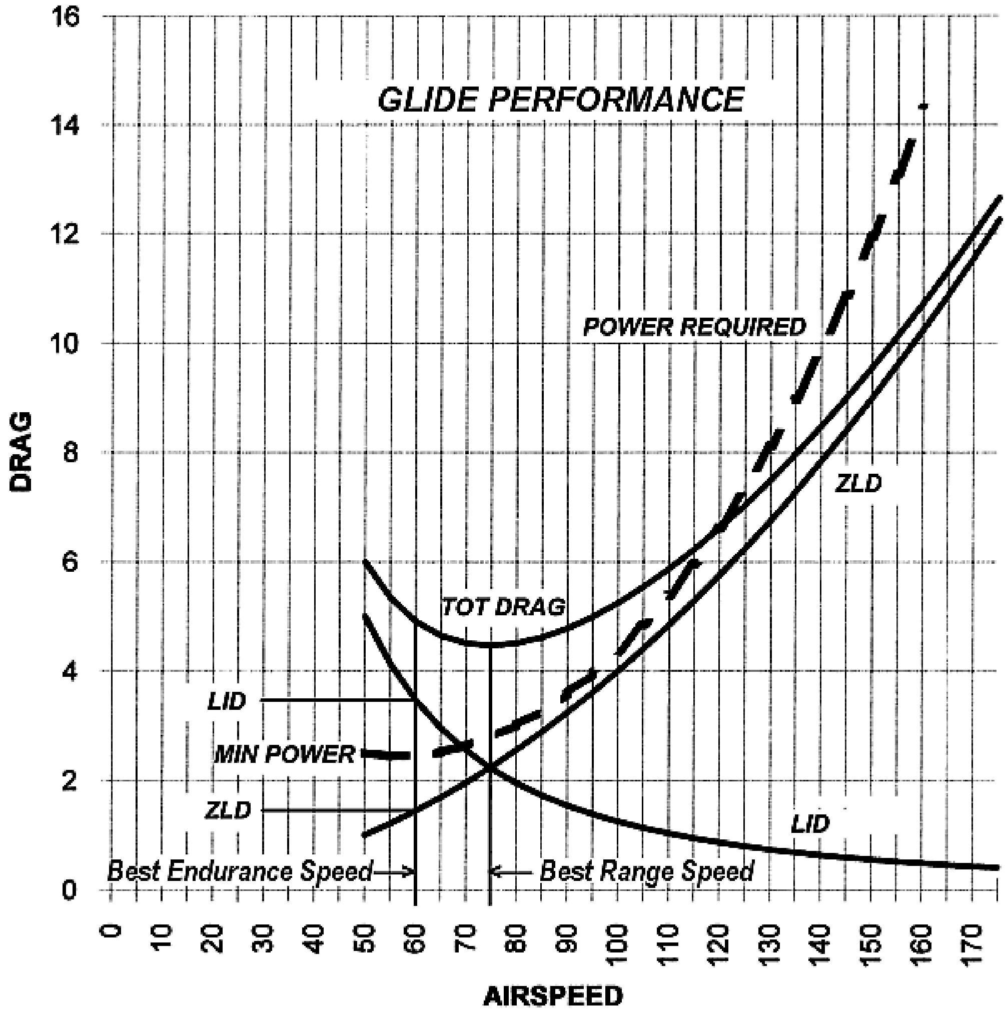


Figure Six – Glide Performance Graph

Note that at best L/D ratio (Vmd) the LID and the ZLD are the equal, but at minimum sink speed (Vmp), LID is about twice ZLD, that is, LID is 2/3 of the Total Drag! So all of the polishing and 'gap sealing' done around the fuselage of a sailplane, to reduce ZLD, will be to no avail, if LID isn't optimized by keeping that high aspect ratio wing working as efficiently as possible.

Annex A. The Polar Diagram

Annex B. Polar Diagram Comparison

Annex A

The Polar Diagram

The Polar Diagram is a graphic plot of airspeed versus rate of descent for a particular aeroplane when gliding. Sailplane pilots use the information that the Polar diagram provides to help them extract the maximum efficiency from their aircraft in every combination of atmospheric, weight and manoeuvre situations. A basic understanding of the Polar diagram would not harm powered aeroplane pilots either.

The Polar curve is a parabolic (exponential) curve similar to the power curve of a powered aeroplane except that it is plotted 'upside down' as this appears more correct when dealing with rates of descent when gliding. The following diagram (Figure One) shows at typical Polar curve for a modern sailplane. Note that the speed scale has been moved to the top of the diagram so that the zero points of both axes coincide. You will also note that the Polar curve is a little 'flatter' than the one shown in the main text and that the rate of descent scale is in hundreds not thousands of feet per minute. This is because a sailplane has much less total drag than a powered aeroplane at all speeds. The operating airspeeds are slower too because sailplanes tend to be lighter than powered aeroplanes of a similar size (although not always).

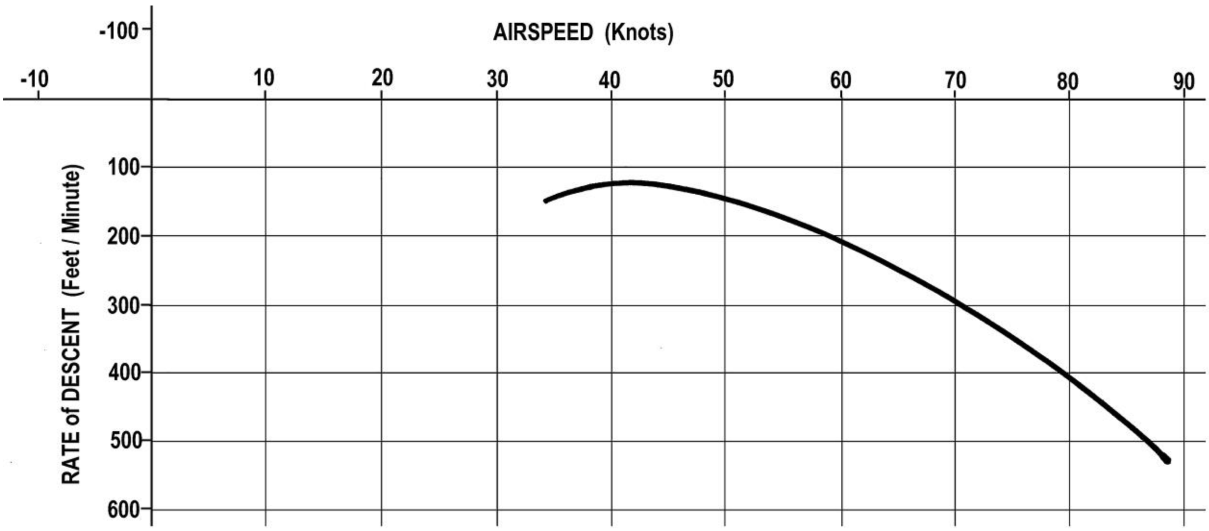


Figure One – Glider Polar Diagram

The airspeed at which 'Minimum Sink' (least rate of descent) is achieved is found by drawing horizontal and vertical lines from the peak of the Polar curve to the rate of descent scale and airspeed scale, whilst the speed to achieve the best glide angle (best L/D) is determined by drawing a line from the 'zero zero' origin such that it touches the Polar curve at a tangent, and then drawing a vertical line from this point to the airspeed scale. These two constructs are shown in the following two diagrams (Figures Two and Three).

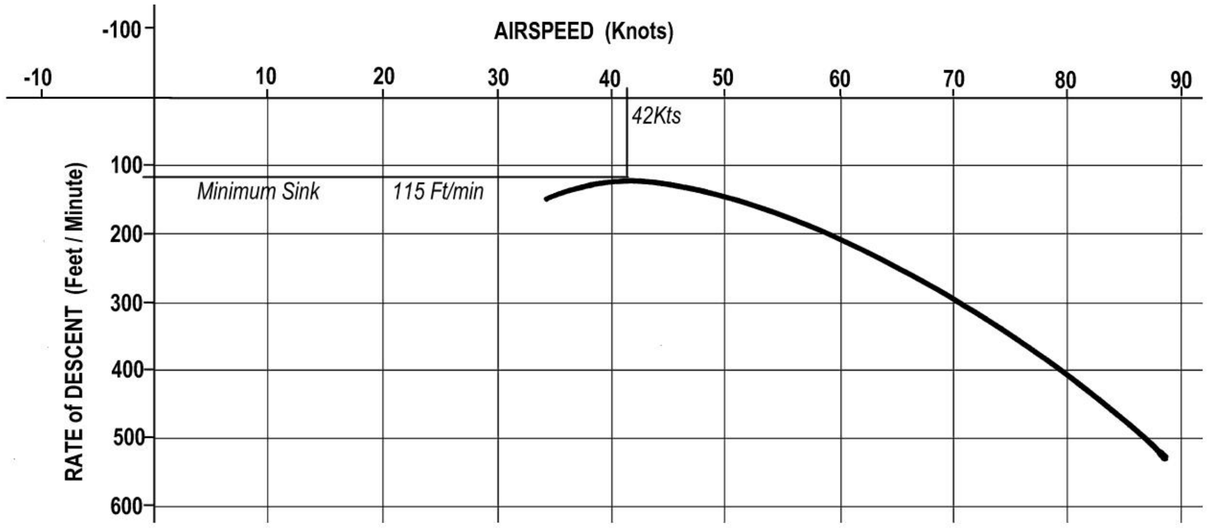


Figure Two – Minimum 'Sink' Speed

In Figure Two above you can see that the minimum sink rate is 115ft/min and the airspeed to attain this is 42kts.

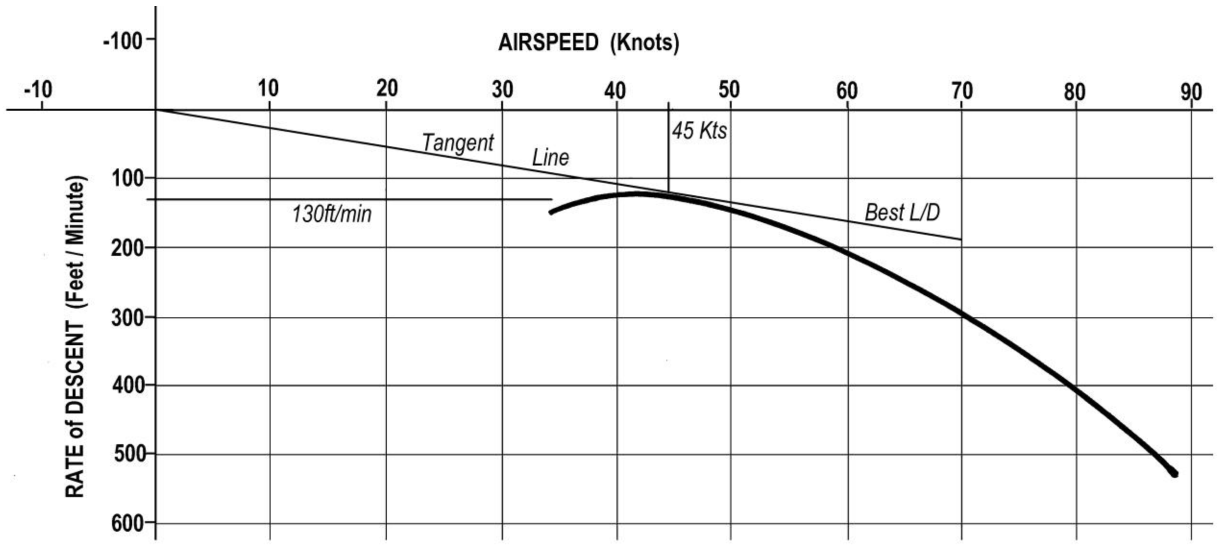


Figure Three – Best Range/Glide Angle Speed

In Figure Three the tangent line touches the Polar curve at 45kts, so 45kts is the speed to glide at for best range. By drawing a horizontal line from this point you can also see that the rate of descent has increased to 130ft/min.

Interestingly, the angle this tangent line makes below horizontal gives the pilot a representation of the glide angle of the aircraft. It is possible to imagine a little aeroplane gliding down that line, and it is also possible to imagine the glide angle if the line crossed the curve at any other point, that is, if the aircraft was flown at any other speed. Looking at the Polar diagram in this way makes it obvious that at any other speed the glide angle is worse. I have found that many student pilots have difficulty understanding how the glide angle varies with speed because they cannot visualize the situation. The Polar diagram is an excellent means of overcoming this visualization problem (See Figure Four).

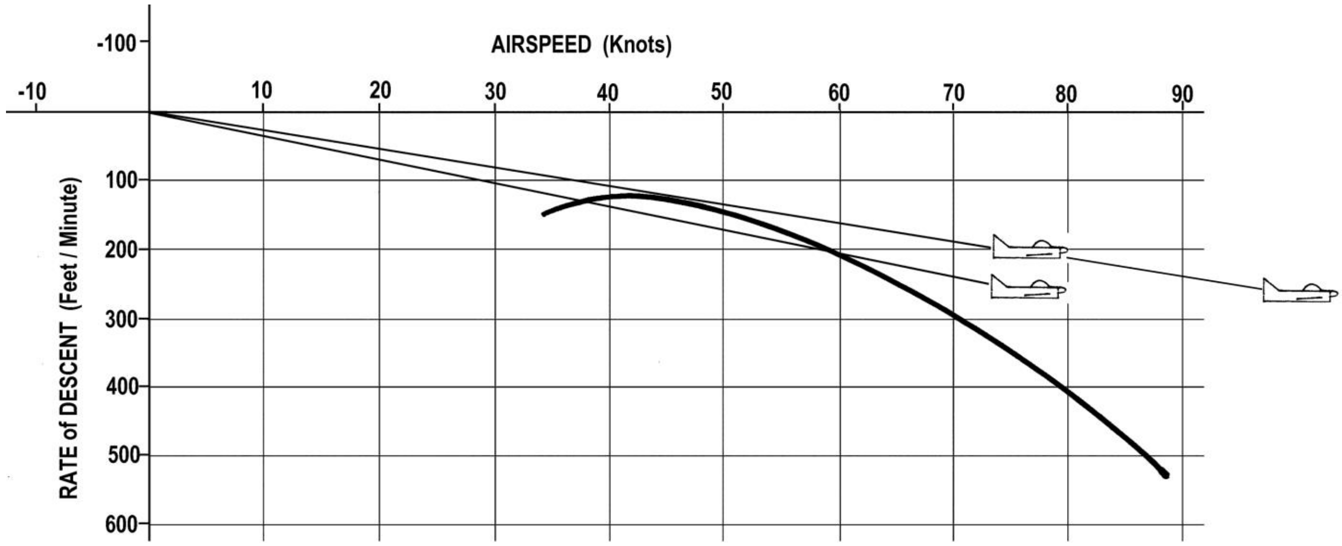


Figure Four – Visualizing the Glide Angle

You can easily see from the foregoing diagram that gliding at 60kts (and 37kts) produces a steeper glide angle and a significantly reduced glide range.

What about weight variations? How are they represented on the Polar Diagram? An increase in weight causes the polar curve to move down and to the right. The flight manuals of most sailplanes will show two Polar curves superimposed on the one graph, one for the lightest weight and the other for maximum weight as shown in the following diagram (Figure Five).

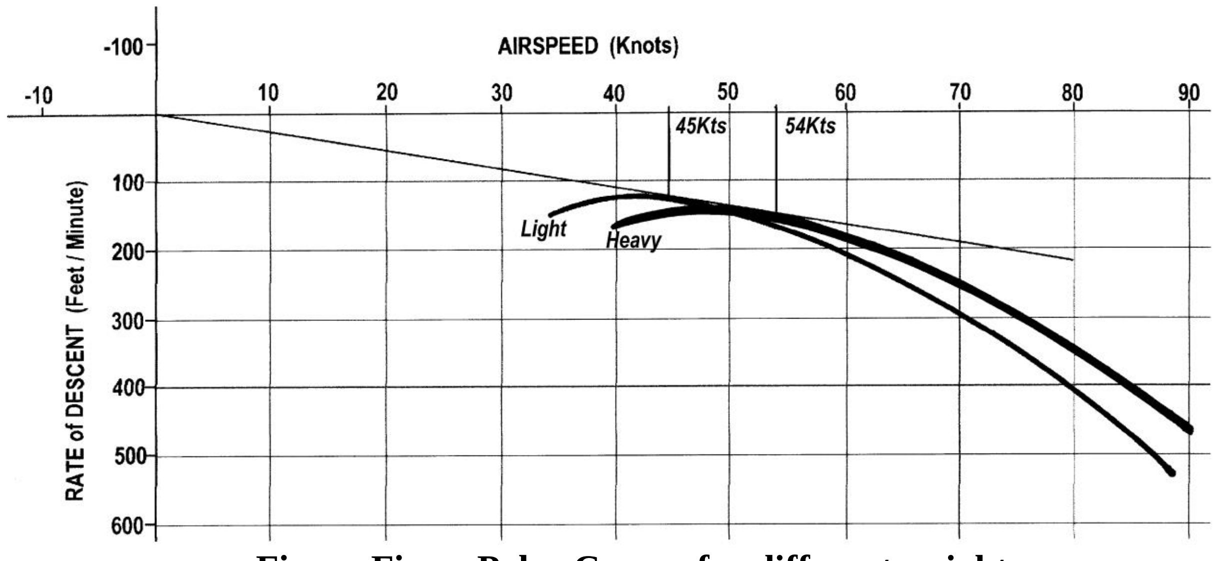


Figure Five – Polar Curves for different weights

The 'Heavy' Polar curve shown here represents a 40% increase in weight. Note that the gradient of the tangent line does not change, which means the glide angle and glide range do not change, but the speed to attain this has increased from 45kts to 54kts, a 20% increase. The rate of descent has also increased by 20%. This is where that 'rule of thumb' comes from that I mentioned in the lesson on Gliding. ***"Increase the glide speed by a percentage equal to half the percentage weight increase".***

Also note that the speed for minimum sink has increased from 42kts to 51kts, which is the same percentage, it is the same for the minimum sink rate too. Many high performance gliders carry water ballast to increase their weight and therefore their best range glide speed when the atmospheric conditions offset the increased rate of descent. The water can then be progressively dumped as these 'uplifting' atmospheric conditions diminish.

So we now have a graph which gives us the optimum speeds to glide through the air, but what about the sailplane's performance relative to the ground? Obviously if the air is not moving then the 'over the ground' performance will be the same as the 'through the air' performance, but what if the air mass is moving relative to the ground? If we are gliding in the same direction as the horizontal movement of the air mass (commonly referred to as a 'tail wind') then the range over the ground will be improved, and if we are gliding against its motion (commonly referred to as a 'head wind') the range will be reduced. But will it be necessary to adjust the glide speed in these two situations to achieve optimum performance over the ground? Yes. You have probably been wondering why, on the previous diagrams in this Annex the axes of the graphs have been extended beyond the 'zero zero' origin point; well, it is to enable us to determine the best glide speeds when the air mass is in motion.

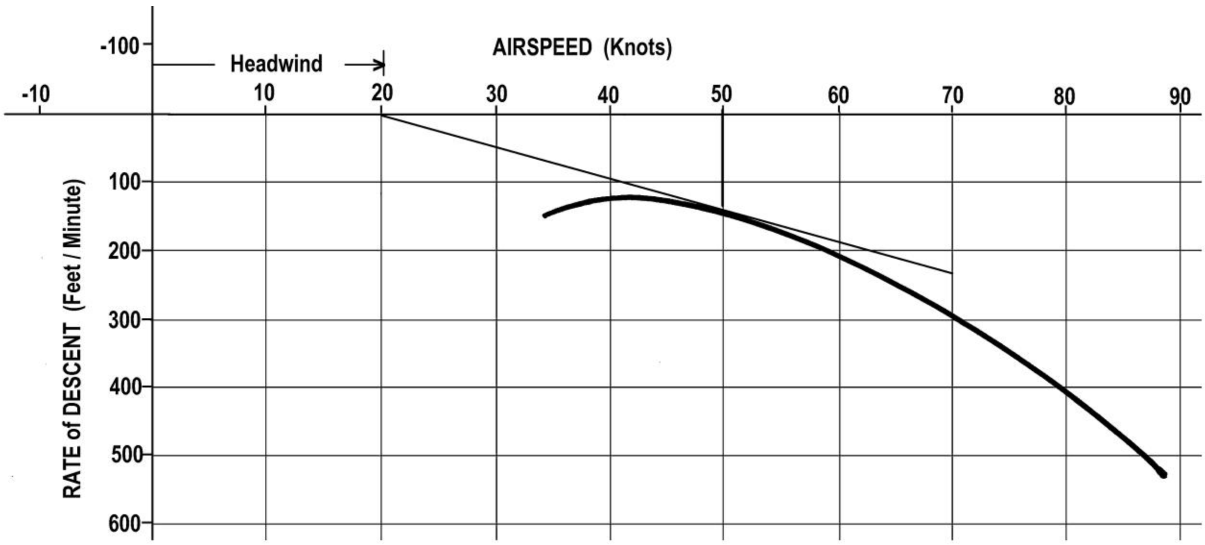


Figure Six – Gliding into a 'Headwind'

On the preceding diagram (Figure Six) I have adjusted the origin from which the tangent line is drawn, by an amount equal to a 20Kt 'headwind', (this is the zero **groundspeed** point). You can see that it touches the Polar curve at 50Kts, 5Kts faster than the 'still air' speed, which is an amount equal to 25% of the 'wind' speed. This is the speed to glide at in these conditions to get optimum glide range over the ground. This is where that 'rule of thumb' I mentioned in the lesson on gliding comes from. ***(Adjust airspeed by 25% of the 'wind' speed.)*** The reverse applies if the sailplane is experiencing a 'tail wind'. Check out Figure Seven.

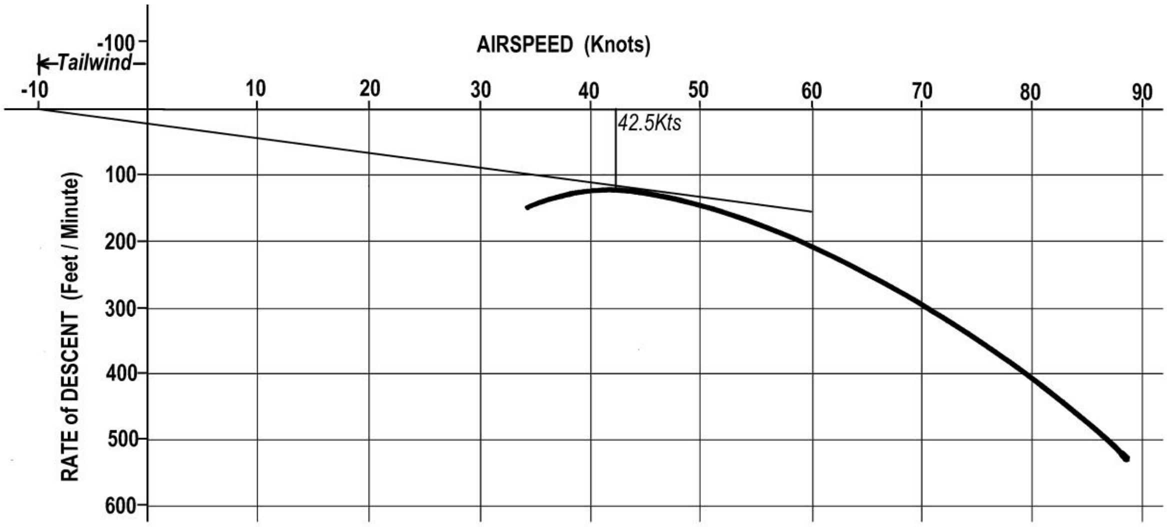


Figure Seven – Gliding with a 'Tailwind'

In Figure Seven I have drawn the tangent line from the 10Kt 'tailwind' point and you can see that it touches the Polar curve at 42.5Kts, which is a reduction of glide speed equivalent to 25% of the 'wind' speed once again. As the 'tailwind' gets stronger the tangent line will get 'flatter' and the optimum range glide speed will reduce until with an 'infinite tailwind' it equals the minimum sink speed. Minimum sink speed is as slow as you need to glide, regardless of the strength of the 'tailwind'.

Annex B contains a diagram comparing the Polar curves of a typical sailplane and a typical light powered aeroplane. There is an obvious glide performance difference between them but you can see that the rule of thumb for correcting airspeed for 'wind' works equally well on both.

What about movement of the air mass vertically? This direction of movement is not obvious to an observer standing on the ground because he or she cannot feel it like wind on the face, but when airborne it is felt as turbulence. In a powered aeroplane turbulence is regarded as an uncomfortable nuisance, but in a sailplane it is regarded as a source of renewable energy. The vertical movement of air has two fundamental causes, the first is thermal activity which results in rising bubbles of hot air and the second is wave motion caused by the air mass moving horizontally over obstacles like hills and mountain ranges. It each case, wherever there is rising air, not too far away is descending air, so the 'trick' to successful soaring is to find the rising portion and avoid the 'sinking' portion.

When a sailplane encounters the rising portion of a wave the pilot can slow down to minimum sink speed to better utilize this 'lift' (it's a bit like stopping at a petrol station to refuel), or, if there is already enough 'gas in the tank', the pilot can speed up and allow the rising air to offset the increased rate of descent. But when 'sink' is encountered the aim is to get through it as efficiently as possible. You guessed it - we can also use the Polar diagram to determine the best speed to fly through this sinking air. Check out Figure Eight.

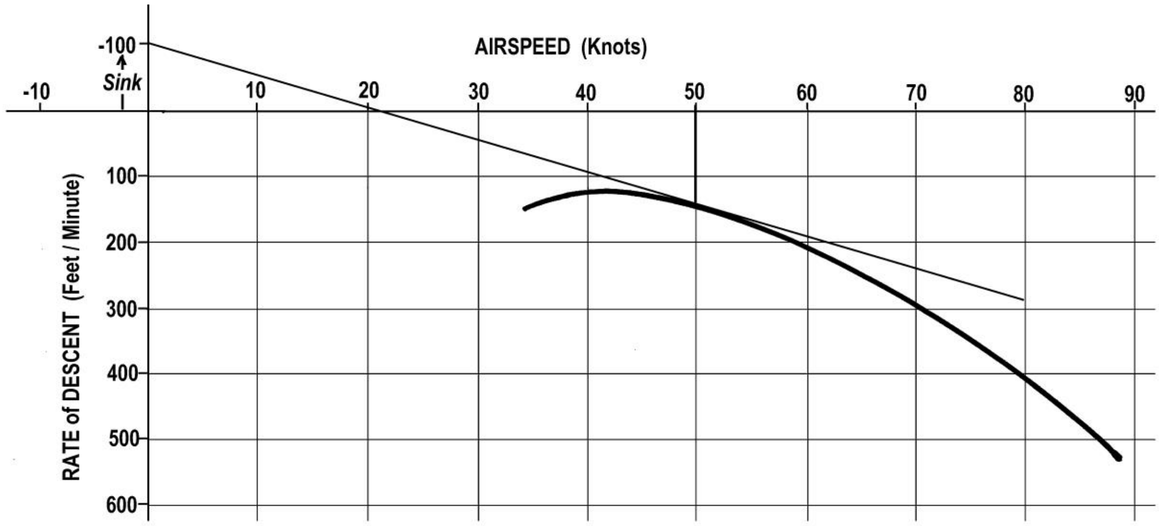


Figure Eight – Gliding in 'Sinking Air'

By adjusting the origin of the tangent line **up** the vertical axis by an amount equal to the rate the air mass is sinking (which is easier than dropping the whole curve down) the line now touches the Polar curve at the optimum speed to fly through this sinking air. In the example above, the air is sinking at 100ft/min so the speed to fly is 50kts. Let's take a minute to analyze that some more. If the rate of sink at 45kts though the air mass is 130ft/min then the rate of sink relative to the ground is 230ft/min. Therefore in one minute the sailplane will have lost 230ft. By increasing speed to 50kts (an 11% increase) the sailplane will have traveled the same distance in only 53 seconds and its rate of sink relative to the ground will have increased to 250ft/min (a 9% increase), but in 53 seconds it will have only lost 220 feet. So its glide angle and therefore its range relative to the ground are slightly improved by gliding faster in these conditions.

Obviously the origin of the tangent line can be positioned to account for both vertical and horizontal movement of the air mass simultaneously. In the following example (Figure Nine), when gliding in 100ft/min sink and 20kts 'headwind', a glide speed of 60kts should be used.

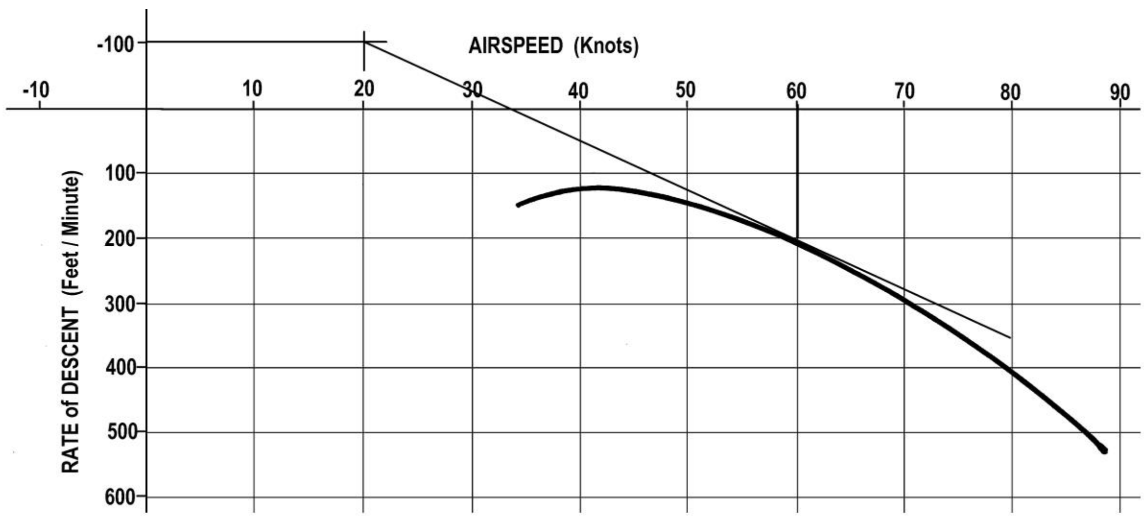


Figure Nine – Gliding with a 'Headwind' and 'Sink'

In the next example (Figure Ten), when gliding in 100ft/min sink and 10kts 'tailwind', use a glide speed of 48kts.

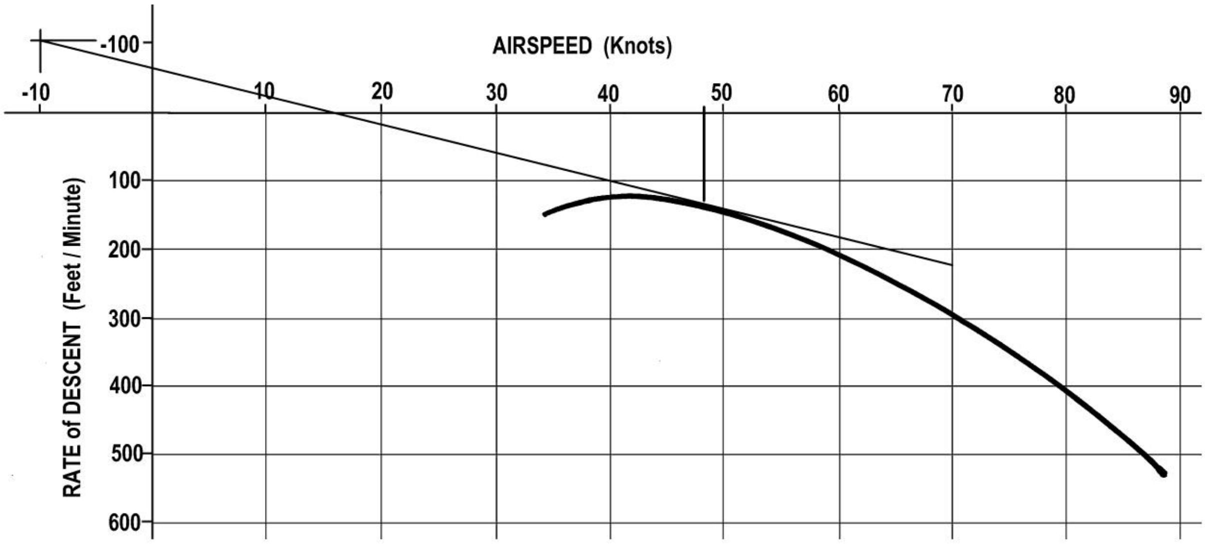


Figure Ten – Gliding with a 'Tailwind' and 'Sink'

Now you are probably wondering how the devil a sailplane pilot can be constantly figuring all of this out in the air every few minutes whilst flying the aeroplane and looking for the telltales of these elusive waves and thermals. Once upon a time the pilot had to somehow do all of this in his or her head, utilizing those rules of thumb I have mentioned, or some manual 'gizmo'. This was a big part of the challenge of the sport. Nowadays all high performance competition sailplanes carry a natty little electronic computer, pre-programmed with the aeroplane's Polar data, which receives inputs from the airspeed indicator, altimeter, variometer, accelerometer and the GPS, then 'crunches the numbers' and presents the pilot with the optimum speed to glide minute by minute in all combinations of vertical and horizontal air mass movement. (It even suggests speeds to fly based upon the statistical probability of 'future lift'!) It doesn't find the rising air but it does pretty much everything else.

When soaring the waves along mountain ridges a sailplane can be flown in a reasonably straight line for some distance so all I have said so far applies, but rising thermal bubbles require the pilot to interrupt his journey for a while and fly in circles within the bubble to gain potential energy from it (it really is like stopping at a gas station to refuel) and as we have learned in previous lessons, turning causes additional drag. Polar diagrams can be used in this situation too.

When circling within the bubble (called 'Thermalling') the apparent weight of the sailplane increases just as we have seen in the lessons on turning and manoeuvring, so the Polar curve shifts down and to the right just as it did for a 'real' weight increase. Here is a diagram (Figure Eleven) that I used previously but showing the minimum sink speeds. (After all there is no point in gliding for range when going around and around in circles!)

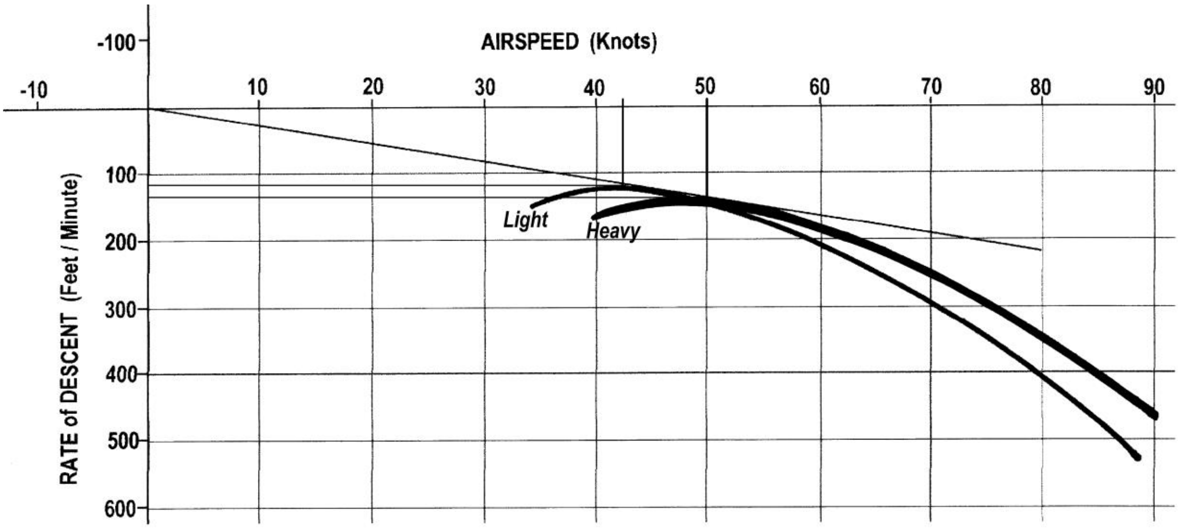


Figure Eleven – Minimum Sink Speeds when Turning

As I said previously this diagram shows the Polar curve position when weight is increased 40%. This 40% increase in weight is also experienced as an apparent weight increase in a 45º banked turn (1.4G). So when thermalling at 45º bank the minimum sink speed increases by 20%. That is, from 42kts to 50kts, and the rate of descent increases by the same proportion from 115ft/min to 138ft/min.

At angles of bank above 45º some discrepancies creep into this rule of thumb. As we have learned from the lesson on stalling, Vs increases by √G, so at 60º bank and 2G, Vs has increased by a factor of 1.4 **and so have the rest of the 'V speeds' on the Polar curve**, but the 50% rule of thumb suggests an increase of 1.5. At higher angles of bank the discrepancy is even greater, but no problem. Do you remember the simple relationship of bank angle and stall speed I explained in the lesson on stalling, to give the pilot a quick 'readout' of stall speeds at the standard bank angles? Here it is again.

"Just remember 10%, 20%, 40% increase in stall speed for 30º, 45º, and 60º bank respectively, whatever aeroplane you are flying, be it a Cessna or a Jumbo Jet!"

This applies to the whole polar curve too, for both speed and descent rate. So once you know Vmp and Vmd for your sailplane you can quickly calculate how they increase in a turn. (The aforementioned electronic computer uses accelerometer data to perform this computation.)

Often angles of bank in excess of 60º are needed to stay within the rapidly ascending core of a thermal bubble. Even though the sailplane's rate of descent through the air mass increases significantly at these high bank angles, the extra 'lift' from this core can more than offset its descent rate. It takes considerable skill to find and manoeuvre the sailplane within a thermal core like this, and this is where the aerodynamics of sailplanes gives way to the art of thermalling, so I will say no more on the subject.

Annex B

Polar Diagram Comparison

The following diagram (Figure One) compares the Polar curve of a typical modern sailplane (glide ratio 40:1) with that of a typical modern light training aeroplane (glide ratio 10:1). Tangent lines for still air and a 20kt headwind have also been included, from which you can see that the 'add 25%' rule applies to both aeroplanes.

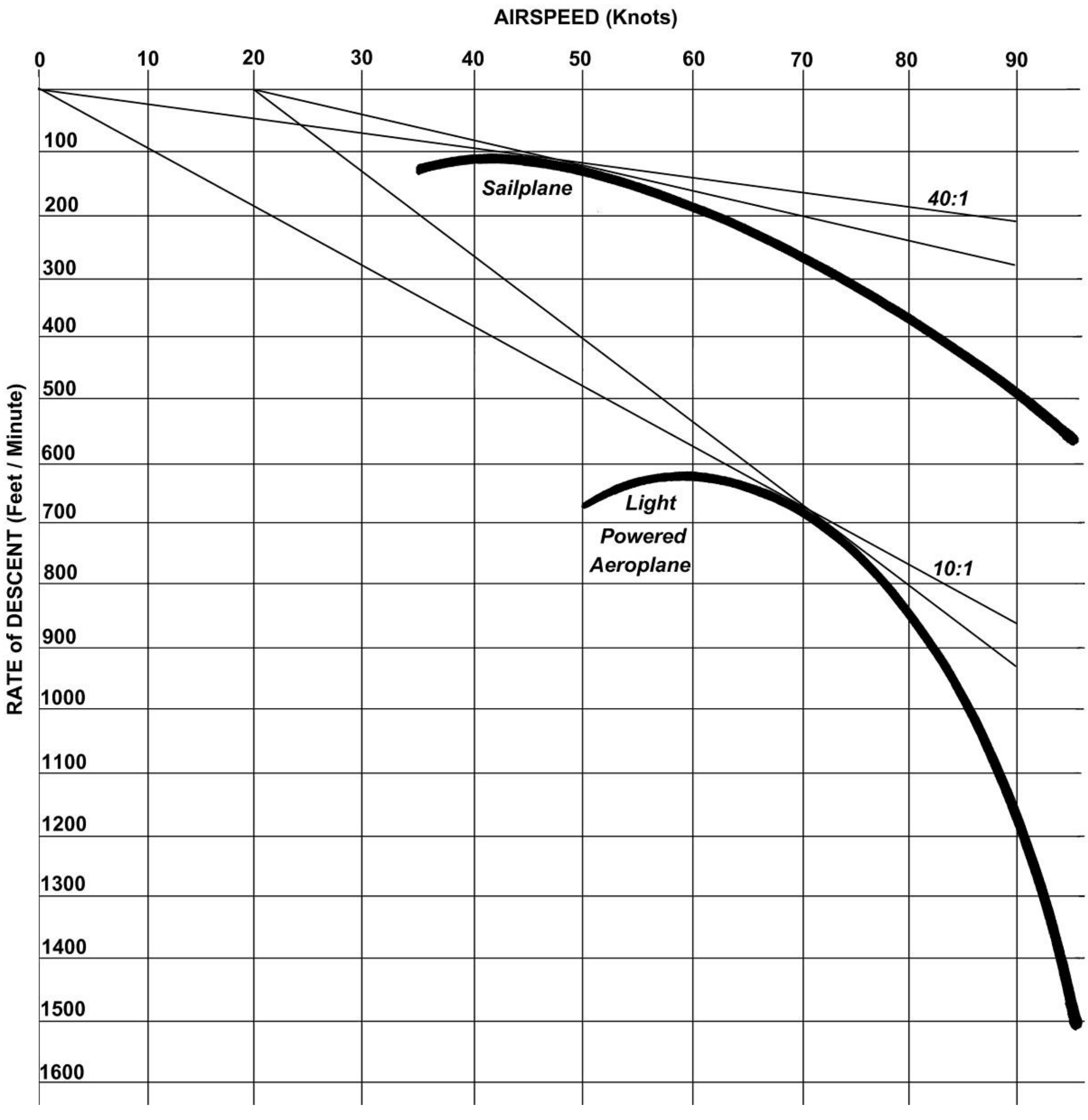


Figure One – Polar Diagram comparison

You may recall that we used the technique of adjusting the 'zero zero' origin on the power graph in the lesson on Power to determine the power required at various IAS/TAS relationships too. Interesting huh! It is a pity that the manufacturers of light training aeroplanes do not include a glide performance Polar diagram in the aircrafts flight manual. It is a most informative graph.

FLYING INSTRUCTORS

The first 50 hours of any student pilot's career is the most important of all of their training. During this time the student's basic motor skills and their understanding of, and attitude toward, flight, are instilled. There is an old adage which says, "Practice makes perfect". I disagree; practice makes permanent, good instruction makes perfect. Bad habits acquired in the first 50 hours will become permanent with practice and repetition and will ultimately come back to 'bite' them one day.

The demanding task of instilling the correct techniques, habits and attitudes at the outset of a student pilot's training, should only be done by the most skilled and experienced flying instructors, so that the student has the opportunity to start his or her flying career on 'the right foot'.

Is this what happens at most flying schools? Sadly not. This job is relegated to the junior instructors, whilst those with more experience concentrate on what they perceive to be the more demanding training sequences, like instrument flying and multi engine training, and whilst the chief instructor spends half his or her time doing the paperwork imposed by an increasingly 'out of touch' regulatory authority.

Now most junior flying instructors that I have met have been bright, intelligent, enthusiastic, well mannered young men. The sort of person you would let your daughter 'go out' with. The majority of these young instructors were only deficient in two things: they couldn't fly very well and they couldn't teach very well!

I know that with this statement many young instructors will fall backwards off their chairs or throw this book against the wall (or both) and vow to never let their students read it, but let me say this to them...... "It is not your fault". You are the product of a deficient system, and despite your best intentions your training and experience do not qualify you to teach ab initio students. Let your students read this book, it may help them get the start that you were probably deprived of.

In Australia it is possible to gain a Commercial Pilots Licence with only 150 hours of flying experience, and with a further 50 hours of 'training', to become a 'flying instructor'. This is like letting sixth grade primary schools students teach first and second grade! I know there is not a parent out there who would allow their children's schooling to be done this way, and yet they accept their sons and daughters being allocated a similarly inexperienced and poorly trained instructor when they sign them up for flying lessons.

Most other countries have similar deficient systems of creating ‘flying instructors’, and yet their regulatory authorities spend millions of dollars, and create mountains of regulations to ‘improve’ flight safety standards, whilst the bleeding obvious solution is right under their collective noses.

“Know your subject”. This statement is the cornerstone of any teaching situation. A flying instructor course should be about teaching experienced pilots, who know how to fly, how to impart their knowledge to a person who does not yet know anything about flying. How this is possible if the trainee instructor has little experience and hasn’t been taught much about flying to start with, escapes me. A flying instructor course should be a teaching course, not a flying course. In other words, being able to fly should be a prerequisite of the course, and yet I have had flight instructor trainees at other schools come to me for help in sorting out basic flying problems that they have whilst they are undergoing an instructor course elsewhere on the same airfield!

The basic ‘formula’ for teaching any motor skill is: Demonstrate, Direct, Monitor. First the instructor *demonstrates* the particular skill, then he/she *directs* the student in an attempt to recreate what has just been shown, and finally the instructor allows the student to repeat the skill several times whilst *monitoring* the accuracy of the performance. This ‘formula’ has been used in flight instruction for as long as there have been dual control aeroplanes and it works. However, most flight instructor courses concentrate primarily on the demonstration part of the process, a little on the direction part and not at all on the monitoring/critiquing part. Monitoring and critiquing involves the instructor being aware of all of the errors, often subtle, that students can possibly make, detecting those they do make during early practice, being able to analyse why they made them, and then being able to correct the error by further direction or by re-demonstrating a different way. This is the most demanding part of the job and where experience is essential. If an instructor cannot anticipate and detect subtle errors and know how to fix them, often using alternate demonstration techniques, the student will ultimately practice and make permanent incorrect flying techniques.

Instructor trainees spend a lot of time learning how to synchronize their mouth with their flying demonstration: learning their ‘patter’. Indeed it is possible to buy a book called the “Flying Instructors Patter Manual” in which there are pre-prepared ‘scripts’ of what to say whilst giving flying demonstrations! (Good Grief!) Once this patter has been mastered the trainee instructor considers that successful graduation is ‘in the bag’.

Have you ever walked through a shopping mall and seen an attractive lady demonstrating the latest kitchen gadget? She has a little boom microphone on a headset, connected to an amplifier, so that her voice can reach her passing audience whilst her hands are free to demonstrate the gadget. As she demonstrates, her mouth regurgitates a well rehearsed pre-prepared script (patter) over and over again. That is about where the average junior flying instructor's skills are, upon graduation. The kitchen gadget is simple and designed for dummies to operate. Aeroplanes aren't.

During the 23 years that I ran the Sydney Aerobatic School I received hundreds of unsolicited applications for work as a flying instructor with the school, from all over Australia. Most were accompanied by a resume of experience, and not one of those had more than 300 hours total flight time or any aerobatic experience! I actually interviewed a few that aroused my interest, but we never got past the interview. Now you are probably thinking that I must have been a particularly difficult 'SOB', and probably given them a very hard time during the interview. They might agree with you because I asked them difficult questions like 'how does induced drag vary with angle of attack', and 'what is the percentage increase in stall speed in a 45 degree banked turn'. I make no apologies for expecting my flying instructors to know the answers to these sorts of simple questions, and many more and difficult questions too.

I never got to the point of assessing their instructional skills…..why bother? They didn't know their subject.

My flying school offered experienced and capable flying instructors to the flying student who had just walked through the door for the first time. It wasn't long before the unique nature of what we were offering was spread by word of mouth, and as a result we quickly developed a waiting list of students. We were also the most expensive school on the airfield as I believed in paying my instructors a fair remuneration for their skills. This did not deter the majority of our students, who were well aware of the false economics of cheap products, especially when the continuance of their life was a factor. I used to have a motto hanging on the operations room wall which said:

> *Buying anything of quality is like buying oats! If you want good clean oats you must pay a fair price, but if you can be satisfied with oats that have already been through the horse, they come cheaper.*

I am still bemused by flying schools and aero clubs that cannot understand the simple economics of this. They pay their flying instructors 'peanuts' and continue to get what they pay for.

How was I able to expand my instructional staff and yet stick by my principles? Well initially I recruited some of my air force buddies whom I knew to be good instructors, but ultimately I had to train my own; but not just anyone who wanted to be taught by me, I only accepted those I believed competent enough to meet my criteria. The candidates had to demonstrate to me an excellent standard of flying ability, including being a competent aerobatic pilot. They had to be comfortable in the sky, and be able to handle anything an aberrant student could throw at him without being ‘phased’ by it (testing that aspect was a lot of fun for me). Then we embarked upon a course of instructor training almost twice as long as the ‘standard’ courses, which included training in aerobatic instruction, and emphasized monitoring and critiquing of student performance in all aspects (and attitudes) of flight.

Upon Graduation they were relegated to a minimum of six months of pure aerobatic instruction (and its associated remedial flight training) to graduates of other flight schools, in order to hone their error analysis and critiquing skills, before I would let them anywhere near a new ‘unspoiled’ ab initio student. It was a system which, I am pleased to say, worked very well.

The testing of my undergraduate flight instructors for their initial rating was the responsibility of the regulating authority. In each case the tester assessed them as flying and instructing to a standard equivalent to a working instructor of many years’ experience; indeed one tester actually apologized to me for not being able to issue them with a rating much higher than the legislation allowed him.

What is the answer to this dilemma of flight instructor/student pilot standards? Simple, make flying instructing a lucrative career in its own right, instead of just being a stepping stone for young commercial pilots to amass flying hours before moving on to an airline job. Increase the entry standards to an instructing course, increase the length and depth of the course, and then pay the newly graduated instructors an appropriate remuneration which reflects the additional skills that they bring to the flying school which employs them. Then, as they gain experience, increase the remuneration to make it worthwhile for them to stay in the profession.

Where should this change start? It should start with the regulating authority. Many years ago I was being assessed by a ‘test officer’ from the Australian regulating authority in order to be approved to assess flying instructors for the renewal of their qualifications. (Initial issues and upgrades were still the province of the regulatory authority in those days.) My tester assumed the role of a junior grade instructor and I had to assess his performance. Initially I thought he was having a big joke with me, so bad was the instructor he was simulating, so I let him continue on for a little longer than I would normally, but finally I could stand it no more so I stopped him and failed him on the spot! The tester, having resumed his regulatory role, criticized me for being too harsh and explained that he was not deliberately portraying a poor candidate - just a regular one from his experience which he would have passed! Whereupon I ‘failed’ him for allowing such poor instructional standards to survive, and suggested that he should find another line of work! As you can imagine this did not ‘go down’ with him very well and he decided to seek advice from his superiors about what to do with me.

After some time I was awarded an approval to test only my flying instructors for renewal of their ratings, as, he said, the regulatory authority believed that if I was allowed to test outside of my own school, I would single handedly shut down the entire industry!

Why have I written this chapter at the end of a book about how aeroplanes fly? I have written it for aspiring students who have not yet stepped inside their first flying school premises. I have written it to alert you to the fact that even though you are entering an alien environment and may feel ‘out of your depth’ you are still in control of the standard of flight instructor that you will allow to teach you. Familiarize yourself with the various instructor ratings and standards that apply in your country and then make an appointment to meet the chief instructor and question him about his staff and their experience level, and what standard of flight instructor he would allocate to train you. Talk to experienced pilots outside of the flying school about where they learned to fly, and what they thought of their training. Take your time and be as informed as you can be before taking the final step of committing your hard earned money to any one particular flying school. If more student pilots did this, the schools might get the message that they should provide a better service to their customers, and control their instructor standards accordingly.

When I was 17 I was instructed by a young junior flying instructor who I thought was God! I look back now and shudder to remember some of the things he didn’t (or couldn’t) teach me, but should have. Fortunately, shortly after gaining my Private Pilot’s Licence, I was rescued by the Royal Australian Air Force, who took me in and taught me to fly all over again, properly. So I experienced first hand both good and bad flying instruction in quick succession at an early age, and have carried that experience with me into every flight instructional situation ever since, both as ‘receiver’ and ‘giver’.

Flying is one of the greatest things you can ever learn to do. Don’t spoil your dream by accepting mediocre flying instruction. Too many people have, and they spend the rest of their lives flying on faith. Faith that the things they don’t understand, and don’t know how to control, will never happen to them.

Forget about faith; you don’t need faith to fly, you just need to learn how to fly…..PROPERLY.