SHA-SHIB GROUP OF INSTITUTIONS

Training Notes

Module 08- Basic Aerodynamics

SHA-SHIB GROUP

EMPOWERING KNOWLEDGE THROUGH VISION

FOREWORD

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- The information in this book is for study/ training purposes only and no revision service will be provided to the holder.
- While carrying out a procedure/ work on aircraft/ aircraft equipment you must always refer to the relevant Aircraft Maintenance Manual or Equipment Manufacturer's Handbook.
- For health and safety in the workplace you should follow the regulations/ Guidelines as specified by the Equipment Manufacturer, your company, National Safety Authorities and National Governments.

Knowledge Levels – Category A, B1, B2, B3 and C Aircraft Maintenance Licence

Basic knowledge for categories A, B1, B2 and B3 are indicated by the allocation of knowledge levels indicators (1, 2 or 3) against each application subject. Category C applicants must meet either the category B1 or the category B2 basic knowledge levels.

The knowledge level indicators are defined as follows:

LEVEL 1

- A familiarization with the principal elements of the subject.

Objectives: The applicant should be familiar with the basic elements of the subject.

- The applicant should be able to give a simple description of the whole subject, using common words and examples.
- The applicant should be able to use typical terms.

LEVEL 2

- A general knowledge of the theoretical and practical aspects of the subject.
- An ability to apply that knowledge.

Objectives: The applicant should be able to understand the theoretical fundamentals of the subject.

- The applicant should be able to give a general description of the subject using, as appropriate, typical examples.
- The applicant should be able to use mathematical formulae in conjunction with physical laws describing the subject.
- The applicant should be able to read and understand sketches, drawings and schematics describing the subject.
- The applicant should be able to apply his knowledge in a practical manner using detailed procedures.

LEVEL 3

- A detailed knowledge of the theoretical and practical aspects of the subject.
- A capacity to combine and apply the separate elements of knowledge in a logical and comprehensive manner.

Objectives: The applicant should know the theory of the subject and interrelationships with other subjects.

- The applicant should be able to give a detailed description of the subject using theoretical fundamentals and specific examples.
- The applicant should understand and be able to use mathematical formulae related to the subject.
- The applicant should be able to read, understand and prepare sketches, simple drawings and schematics describing the subject.
- The applicant should be able to apply his knowledge in a practical manner using manufacturer’s instructions.
- The applicant should be able to interpret results from various sources and measurements and apply corrective action where appropriate.

-: DGCA MODULARISATION :-

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CAR – 66 ISSUE II R 2

(LICENSING OF AIRCRAFT MAINTENANCE ENGINEERS)

DIRECTORATE GENERAL OF CIVIL AVIATION

TECHNICAL CENTRE, OPP SAFDURJUNG AIRPORT, NEW DELHI

Modules	Subject	A or B1 Aero plane with		A or B1 Helicopter with		B2
		Turbine Engine (s)	Piston Engine (s)	Turbine Engine (s)	Piston Engine (s)	Avionics
1	Not Applicable					
2	Not Applicable					
3	ELECTRICAL FUNDAMENTALS	X	X	X	X	X
4	ELECTRONIC FUNDAMENTALS	X	X	X	X	X
5	DIGITAL TECHNIQUES ELECTRONIC INSTRUMENT SYSTEMS	X	X	X	X	X
6	MATERIALS AND HARDWARE	X	X	X	X	X
7A	MAINTENANCE PRACTICES	X	X	X	X	X
7B	MAINTENANCE PRACTICES					
8	BASIC AERODYNAMICS	X	X	X	X	X
9A	HUMAN FACTORS	X	X	X	X	X
9B	HUMAN FACTORS					
10	AVIATION LEGISLATION	X	X	X	X	X
11A	TURBINE AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS	X				
11B	PISTON AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS		X			
11C	PISTON AEROPLANE AERODYNAMICS, STRUCTURES AND SYSTEMS					
12	HELICOPTER AERODYNAMICS, STRUCTURES AND SYSTEMS			X	X	
13	AIRCRAFT AERODYNAMICS, STRUCTURES AND SYSTEMS					X
14	PROPULSION					X
15	GAS TURBINE ENGINE	X		X		
16	PISTON ENGINE		X		X	
17A	PROPELLER	X	X			
17B	PROPELLER					

TRAINING NOTES MODULE: 08			
SUBJECT NAME: BASIC AERODYNAMICS			
UNIT NO.	OBJECTIVE	LEVEL	
		B1	B2
8.1	PHYSICS OF THE ATMOSPHERE International Standard Atmosphere (ISA), application to aerodynamics.	2	2
8.2	AERODYNAMICS Airflow around a body; Boundary layer, laminar and turbulent flow, free stream flow, relative airflow, upwash and downwash, vortices, stagnation; The terms: camber, chord, mean aerodynamic chord, profile (parasite) drag, induced drag, centre of pressure, angle of attack, wash in and wash out, fineness ratio, wing shape and aspect ratio; Thrust, Weight, Aerodynamic Resultant; Generation of Lift and Drag: Angle of Attack, Lift coefficient, Drag coefficient, polar curve, stall; Aerofoil contamination including ice, snow, frost.	2	2
8.3	THEORY OF FLIGHT Relationship between lift, weight, thrust and drag; Glide ratio; Steady state flights, performance; Theory of the turn; Influence of load factor: stall, flight envelope and structural limitations; Lift augmentation.	2	2
8.4	FLIGHT STABILITY AND DYNAMICS Longitudinal, lateral and directional stability (active and passive).	2	2

Module 08: Enabling Objectives and Certification Statement

Certification Statement

These Study Notes comply with the syllabus of DGCA, CAR – 66 (Appendix I) and the associated Knowledge Levels as specified.

REVISION LOG

Sr. No.	Issue / Revision No.	Issue / Revision Date	Pages Revised	Signature

TABLE OF CONTENTS

Introduction

The great dream of flying like a bird was in the mind of human since the dawn of intelligence. Recent historical research has uncovered that Leonardo da Vinci himself was possessed by the idea of human flights and he designed vast numbers of "Ornithopters" (Machines with flapping wings like a bird.) between 1486 and 1490.

The first successful human flight was reported at 1:54 PM on November 21st 1783, when a balloon carrying Pilatre de Rozier and the Marquis d Arlandes ascended in to the air and drifted five miles across Paris. The first flight with human passenger rose in to the air and lasted for 25 minutes. It was the first time in history that a human being had been lifted off the ground for a sustained period of time.

All early thinking of human flight were centered on the imagination orf birds. Thus the thought of mechanical flight had been oriented toward the flapping wings of ornithopters, where the flapping motion was supposed to provide both lift and propulsion.

However Sir George cayley (1773-1857) is responsible for breaking unsuccessful line of thought ; he separated the concept of lift from propulsion, that culminated in the Wright Brother's success in 1903. It was the first concept to include a "fixed wing" for generating lift. Sir George cayley is considered to be the true inventor of the airplane.

Flex Du Temple, the French Naval Officer in 1874 and Alexander F.Mozhaiski, the Russian in 1884 achieved the first and second assisted powered takeoffs in history, but neither experienced sustained flight.

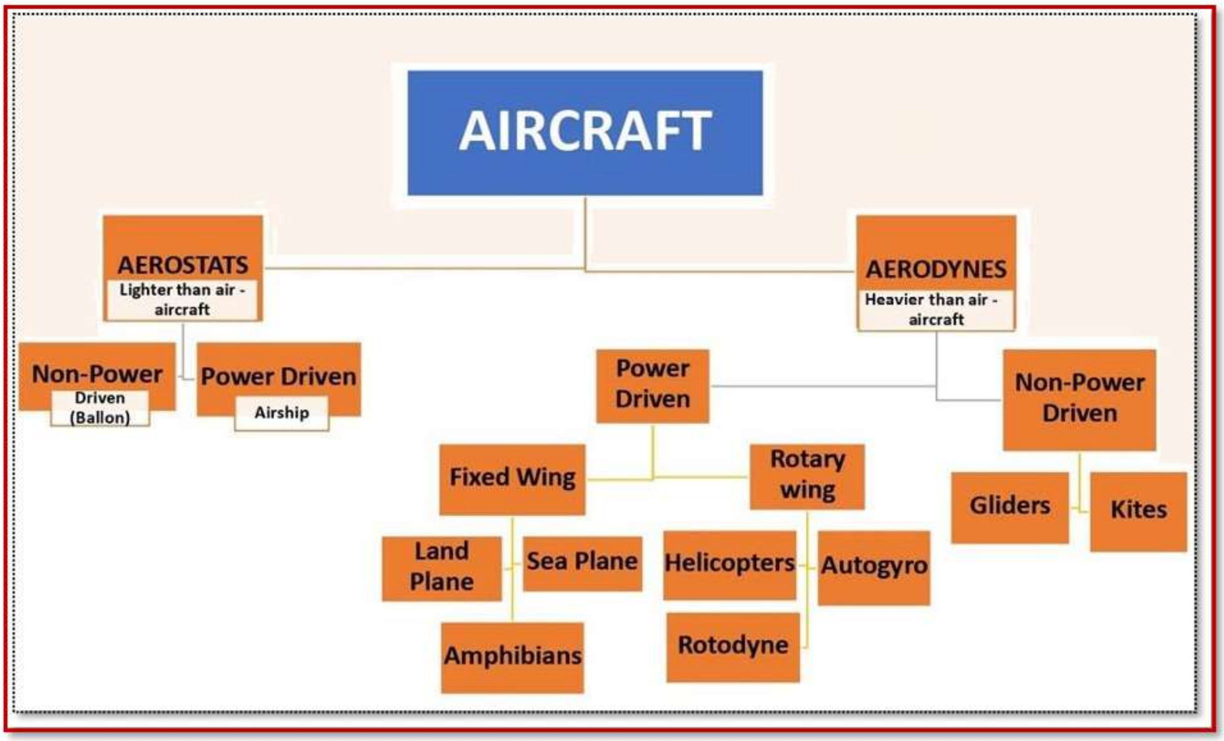
Otto Lilienthal (1848-1896) designed and flew the first successful controlled gliders in history. Lilienhal was the first who recognised the need to get up in the air, fly around in gliders, and obtain the "feel" of an airplane before an engine was used for power flight. The "Wright Brothers" interest in flight did not crystallize until Wilbur first read some of Lilienthal's papers in about 1884 on Sunday August 9, 1896. Lilienthal was gliding from the Golenberg hill near stolen in Germany. A temporary gust of wind brought Lilienthal's monoplane glider to a stand still; he stalled and crashed to the ground. Lilienthal was carried away with a broken spine. He died the next day in the Bergmann clinic in Berlin. Lilienthal remarked several times that "sacrifices must be made". This epitaph is carved on his gravestone in Lichter felde cemetery.

The most historic moment in aviation history took place at about 10:35 AM On Thursday, December 17, 1903. An odd-looking machine made from spruce and cloth in the form of two wings powered by a 12HP engine Begins to move along a 60 ft. launching rail on level ground. Orville Wright lying on the bottom wing and Wilbur Wright runs along the right side of the machine supporting the wing tip so that it will not drag the sand. Near the end of the starting rail, machine lift into the air and flies unevenly, rising suddenly to about 10 ft, then ducking quickly toward the ground. This type of erratic flight continues for 12s ,when the machine ducks to the sand, 120 ft, from the point where it lifted from the Starting rail. It was the first in the history of the world in which a machine carrying a man has raised itself by its on power into the air in full flight had sailed forward without reduction of speed and had finally landed at a point as high as that from which is started.

CLASSIFICATION OF AIRCRAFT

An aircraft is a man-made contrivance moves through air. That is, a body must become airborne first, to become an aircraft or it's to be lifted from the ground. According to the generation of lift the aircraft is basically classified in to 'Aerostats and Aerodynes'.

Aerostats are those which derive lift by the buoyant principle, based on the Archimedes theory. They are also termed as "lighter than air aircraft". Balloon and airships are coming under this category. Balloon is a non-power driven aerostat while an airship is a power driven aerostat.



Aerodynes on the other hand derive lift by the aerodynamic principle. When a body move through air, it is acted upon by the aerodynamic forces. Stated otherwise, aerodynamic force is the force exerted by air on a body moving through it. Therefore 'Aerodynes' can generate lift only when there is relative motion between it and the surrounding medium Aerodynes are also called "Heavier than air-aircraft".

This was step-stone to a new era of aviation - starting with low subsonic speeds and later cruising at supersonic and hypersonic speeds. Aerodynes are further classified into power driven and non-power driven under power driven heavier than air-aircraft comes fixed wings and rotary winged aircraft.

Land plans, sea planes and amphibians are coming under fixed wing powered aerodynes. Land planes are those which can land on ground and take off from land only, where as seaplanes can take-off from the land on water only. On the other hand amphibians can take off from the land on either water or ground. Amphibians can thus be counted as a land plane as well as a seaplane.

Under rotary winged aircraft come helicopters, autogyro and rotodyne. In a helicopter, thrust and lift are produced by the rotor which is driven by the engine. In an "autogyro" thrust is provided by engine where as lift is produced by a wind milling rotor (which is not driven by an engine). This rotor starts wind milling due to the forward motion of the aircraft.

In a rotodyne, separate engines are there for thrust and lift. The lift is produced by a rotor as in the case of helicopters. A rotodyne and helicopter can hover (i.e. remain stationary in air without moving upward, downward or sideways - but of course with a rotating rotor). But an autogyro cannot hover, since its lift is contributed by the forward speed.

Non-power driven aerodynes are gliders and kites. They derive lift by the relative motion of it and the air.

PHYSICS OF ATMOSPHERE

1.1 The Atmosphere

Introduction:

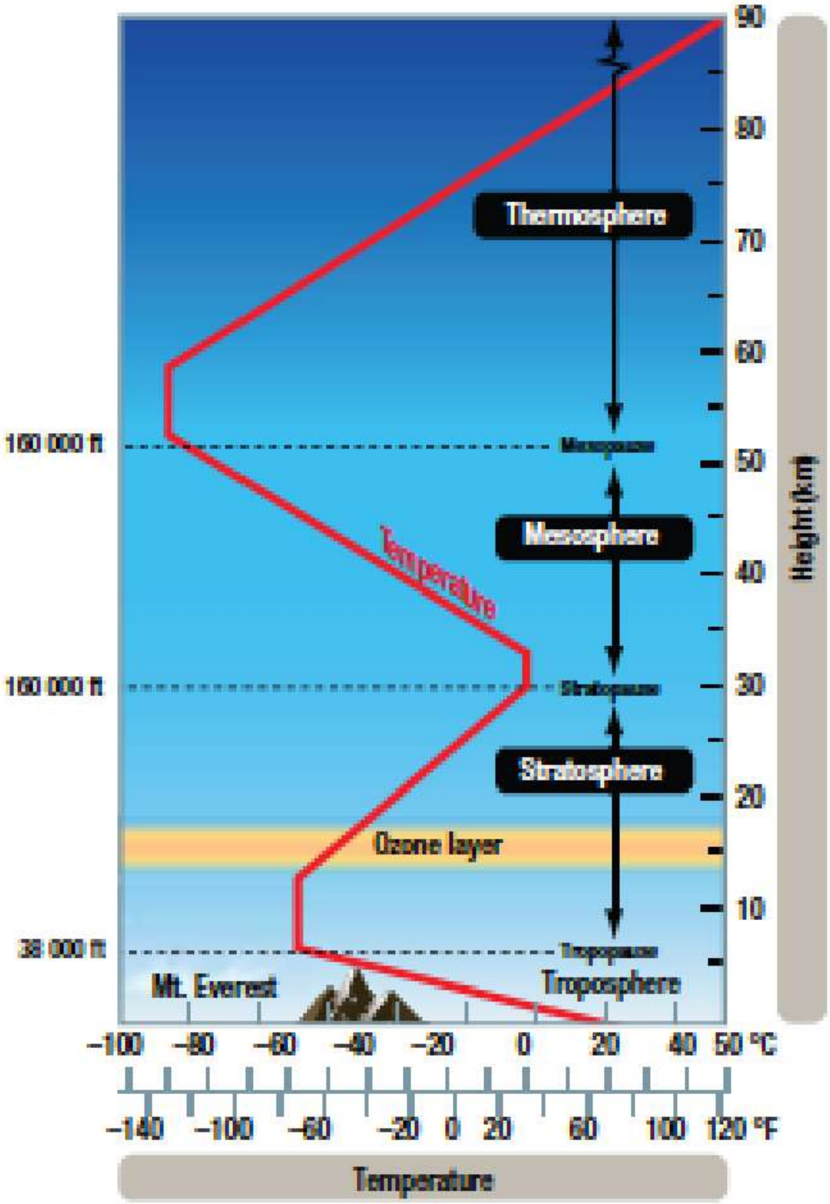
An aircraft as it passes through the air must generate enough lift force in order to fly and sustain flight, to overcome its weight by doing some work on the atmosphere that surrounds it.
It is important therefore, that in order for us gain an understanding of how an aircraft flies, that we first have some knowledge of the medium that an aircraft operates in, the atmosphere, as changes in the properties of the atmosphere will affect the way an aircraft flies.

1.2 Composition of Atmosphere:

The atmosphere that surrounds the earth, or air, as we know it, is made up by a number of gases principally nitrogen and oxygen. The exact make up of air in the lower levels of the atmosphere (by volume) being 78% nitrogen, 21% oxygen and 1% other gases (Argon and carbon dioxide).
These percentage values are consistent up to approximately 50 miles above sea level, although the concentration levels of air varies greatly with height, there being insufficient concentrations of air present in the atmosphere for example to sustain human life at the upper limits of the tropopause.

1.3 Various Layers of the Atmosphere:

The atmosphere is a region of gases that surrounds the earth up to a height of approximately 500 miles (800 Km) and is considered to consist of five distinct gaseous layers. These layers are known as the troposphere, stratosphere, mesosphere, ionosphere and the exosphere.
(a) The Troposphere - where temperature decreases with increase of height. In this region nearly all significant weather occurs.
The Tropopause - the upper limit of the troposphere where temperature stops decreasing with an increase of height. The tropopause is therefore the upper limit of significant weather, the first point of lowest temperature, and additionally it is the region for maximum wind strengths.



The height of the tropopause varies with Altitude, season of the year, and prevailing weather conditions with the result that it is usually higher in low Altitudes, in summer and in fine weather.

Typical heights for the tropopause are:

Altitude	Tropopause Height
Equator	16-17 km 53,000-57,000 ft
45°N/S	10-12 km 33,000-39,000 ft
Poles	7'1/2 - 9 km 25,000-29,000 ft

(c) The Stratosphere extends from the tropopause to approximately 50 km amsl, and is characterised by the temperature being steady or increasing with height.

(d) The Mesosphere extends from 50 km to 80 km. The temperature generally decreases with height.

(e) The Thermosphere or Ionosphere, where temperature increases with height.

1.4 Atmospheric Pressure and its effect on Density

Pressure in the atmosphere occurs because the gasses that make up the atmosphere are held in contact with the earth's surface by the force of gravity.

The closer we are therefore to the earth's surface, the greater is the gravitational effect, so the higher is the number of air molecules present and the greater is the weight or pressure.

Conversely as we climb in the atmosphere, due to the reduction in gravity, air thins out and the number of air molecules decreases, so the weight of air decreases and so will atmospheric pressure.

Thus, if a column of air 1-inch square was to extend from sea level to the extremities of the atmosphere, atmospheric pressure at any point could be found as it would equal the weight of the air molecules above it.
At sea level we find that the standard atmospheric pressure is equal to 14.69 PSI (1013.25 mbar) and decreases as we climb in the atmosphere at a non-uniform rate due to the reduced gravitational effect the further we move away from the surface. Atmospheric pressure becoming half its sea level value at about 18000 ft and approximately quarter of its sea level value at the tropopause (about 36,000 ft).
These changes in atmospheric pressure will affect the density of air, as if a given volume of air is considered, the higher we climb in the atmosphere, as the air pressure reduces due to the decrease in the number of air molecules the less air will be compressed, so its density will decrease. Conversely as we descend in the atmosphere, for the same given volume as pressure increases the higher will be the number of air molecules present, so its density will increase.
The density of air is therefore directly proportional to pressure, increasing or decreasing in line with atmospheric pressure.

1.5 Atmospheric Temperature and its effect on Density:

In the lower region of the atmosphere, the temperature of air depends on the amount of heat energy from the sun that is reflected back from the surface. Therefore the further away from the surface the air is the lower will be its temperature.
Temperature affects the density of air as at a constant pressure, the cooling of air decreases the amount of movement and spacing between air molecules allowing more molecules to be contained in a given volume increasing its air density. Conversely as air heated at a constant pressure the molecules tend to speed up and increase the spacing between them reducing the number of molecules in a given volume deceasing air density. The density of air is therefore inversely proportional to temperature. The international lapse rate for temperature in the atmosphere up to a height of 36,090 ft. is 1.98^{0}C per1000ft. After this height this rate is no longer valid as temperature then remains constant at at -56.5^{0}C where it then varies in different parts of the upper atmosphere, due to varying atmospheric conditions becoming hottest in the upper region of the thermosphere, just below the exosphere.

1.6 Humidity in the Atmosphere and its effect on Density:

Humidity is the amount of water vapour suspended in the air and is found up to a height of approximately 6 miles (9.6 km) in varying quantities.
The ability of air to hold water vapour increases with air temperature. The actual amount of water vapour in the atmosphere being dependent on the air temperature of the day and whether the air is near or has recently passed over a large area of water. So on hot days air can hold more water vapour, but even at cold temperatures there is always a certain amount of water vapour in the atmosphere at lower levels.

Humidity affects air density because water vapour is less dense than air. The density of water vapour under standard sea level conditions is 0.7600 Kg/m^3 whereas for perfectly dry air the density is 1.225 Kg/m^3. The density of air is therefore greatest when air is perfectly dry and least dense when it holds its maximum amount of water vapour, water vapour being only 5/8 the weight of dryair.
The actual amount of water vapour air can contain however is relatively small, ranging from a trace to a maximum of about 4 to 5% per unit volume at its saturation point, where it can hold no more water vapour. In expressing the amount of humidity suspended in the air, many forecasters will give it as a percentage of its saturated humidity, known as relative humidity. This is the ratio of the actual amount of water vapour suspended in air, to the amount of water vapour at which air would become saturated at a certain temperature. So if air humidity is given at 100% then it actually means that the air per unit volume contains approximately 4 to 5% water vapour.

1.7 Overall Altitude effects on Density:

As we have already stated, the main factors that will affect density, pressure, temperature and humidity will all decrease as altitude increases. Pressure decreasing as air thins out, temperature decreasing up to a certain height and humidity decreasing in line with temperature.

The effects these factors have on density however are different as density changes directly with change in pressure and humidity and inversely with changes in temperature. Overall however, since pressure is the dominating factor in controlling the mass per unit volume, density will overall decrease in line with pressure and decrease as altitude increases.

1.8 The International Standard Atmosphere (ISA)

As atmospheric conditions vary around the world due to changes in the properties of the atmosphere, it was internationally agreed to have a Standard Atmosphere covering temperature, pressure and density for varying altitudes, in order to compare aircraft performance and calibrate aircraft instruments. The International Standard Atmosphere (ISA) was agreed by the International Civil Aviation Organization (ICAO) and set at mean sea level with values of:

Pressure: 1013.25 millibar (mb) or 14.7 PSI or 29.92 inches of mercury or 76 cm of mercury

Density: 1.225kg/m^3 or 0.077 lbs/ft^3

Temperature: 15°C or 59°F or 288K

It is from these sea level values that all other corresponding values have been calculated and presented as the International Standard Atmosphere.

In calculating the values of the International Standard Atmosphere up to the tropopause, the equation of state for a perfect gas is used, and is given by the formula:

$P = \rho R T$

Where

P = Pressure ρ = Density

T = Temperature

R = Gas constant (for air = 2.872)

1.9 PHYSICS OF A MOVING FLUID

Introduction:

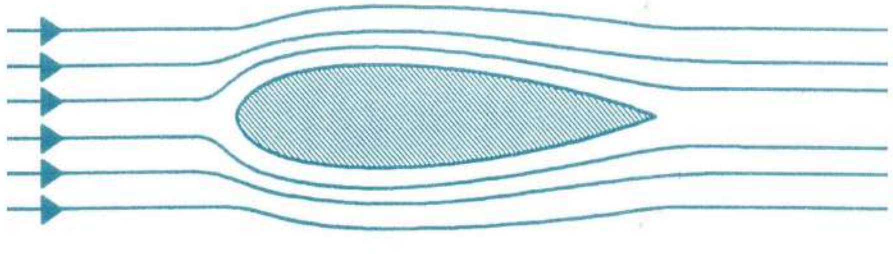
As we have already established the static properties of the atmosphere, its pressure, density and temperature. It is important that we now gain an understanding of how air acts when it is moving to fully understand how it affects an aircraft in flight.

Types of fluid flow:

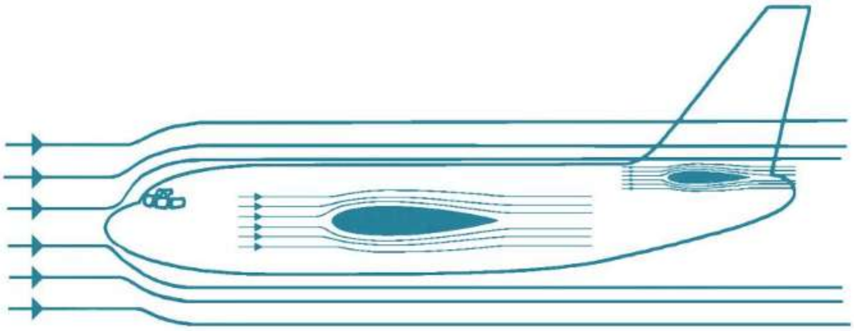
How the air of the atmosphere behaves when it moves over an object, such as an aircraft depends on a number of factors, such as the speed of the flow or the shape of the object it is passing over. The types of fluid flow experienced by air is either laminar or turbulent in nature, or when passing around an object a mixture of both.

1.10 Laminar airflow:

Laminar airflow, also known as linear airflow or streamline flow, exists when succeeding molecules of air follow a steady path. In this type of flow, the air flows smoothly over an object, with the



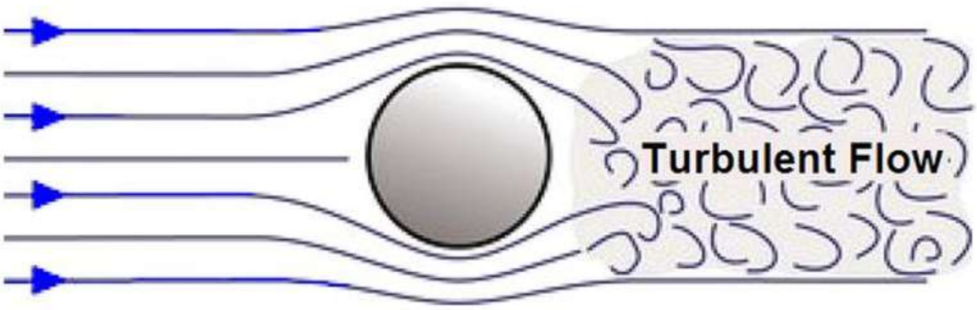
molecules following an orderly pattern, as they do not mix with other streamlines.
For an aircraft in flight, laminar or streamline flow produces an ideal flow pattern around an aircraft giving it the least amount of drag. In this type of flow there is no separation of the flow from the surface, so is desirable in most phases of flight.



To indicate the velocity of a flow around an object, the spacing between streamlines is used. Streamlines that are drawn close together indicate a high velocity, whilst streamlines with a wider spacing indicate a reduced velocity.

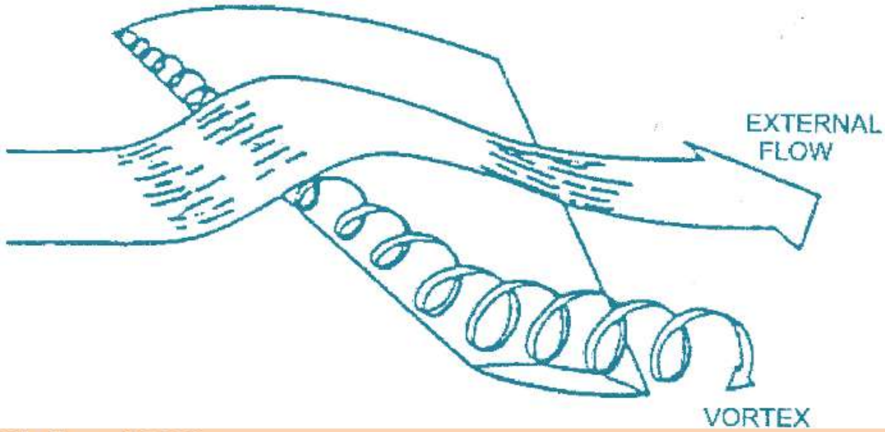
1.11 Turbulent flow:

Turbulent flow or unsteady flow occurs when succeeding molecules do not follow along a streamline but instead travel along a path different from that of the preceding molecule. In this type of flow, as the parameters are constantly changing with time, turbulent flow cannot be represented by streamlines.
For an aircraft in flight, turbulent flow over an aircraft will result in an increase in drag being produced so that more energy is required to maintain flight and is therefore undesirable in most phases of flight.



Controlled separated flow or leading edge Vortex Flow:

This flow is a halfway stage between laminar flow and turbulent flow and occurs when a sharp object such as a leading edge slightly separates the flow from the surface. The flow however does not turn turbulent, even though it has separated, but instead forms a vortex travelling along the leading edge. This type of flow is often found in swept and delta type planforms particularly at high angle of attack and because of the predictability and stability of the vortex it can be controlled to give a useful lift force.



1.12 Free Stream Airflow (FSA):

Free stream airflow is airflow that is significantly far away from a surface of a body not to be disturbed by it. The pattern of airflow round an aircraft at low speeds depends mainly on the aircraft's shape and its attitude relative to the free stream flow.

1.13 Viscosity:

As air is a fluid, when it is in motion, it will be subject to viscosity. This is the property of the fluid that tends to resist relative motion within the layers of a moving fluid.
In a streamline flow therefore, if different layers are moving, or sliding past each other at different velocities, the viscous forces between the layers will have a direct effect each other. The faster moving layers tending to slow down as they try to increase the speed of the slower layers.
The viscosity of a fluid however is dependent on temperature, but unlike liquids or fluids, the viscosity of a gas is directly proportional to temperature, so as an aircraft climbs in the atmosphere, the viscosity of air will decrease.

1.14 **Reynolds' Number:**

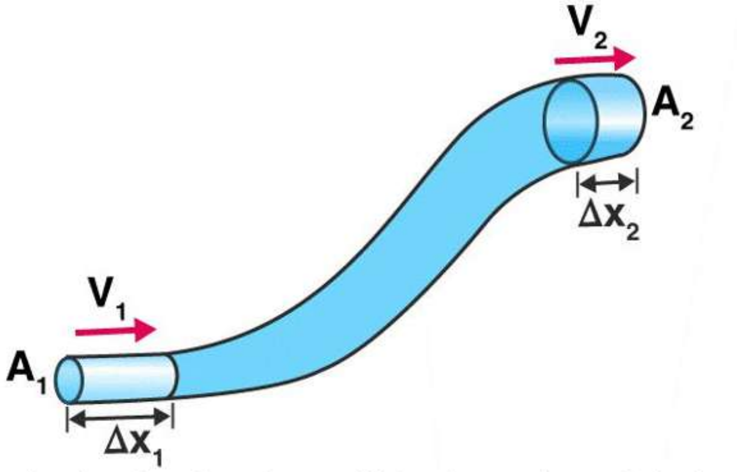
The change from laminar to turbulent flow was first discovered by a 19 Century physicist named Reynolds who was involved in experiments with flow of fluids in pipes. He discovered that the flow changed from streamlined to turbulent flow when the velocity of the fluid reached a critical value that was inversely proportional to the diameter of the pipe. Or simply put the larger the pipe the lower the speed at which the fluid became turbulent. He also discovered that this rule also applied to the flow past any body placed within the stream. For example if two spheres of different sizes were placed into the flow then the transition from laminar to turbulent flow would occur at a velocity that was inversely proportional to the diameter of the sphere and that the transition point would initially be at the point of maximum thickness relative to the flow.
Reynolds' experiments led him to produce a dimensionless formula that produces a number for a fluid passing over or through an object. The number produced determining the conditions and characteristics of the flow, which will be the same irrespective of individual factors.
Reynolds No = $\rho VL/\mu$
ρ = density
V = Velocity
L = Length (normally chord)
μ = Viscosity
Reynolds' Number is therefore a measure of the ratio between the viscous forces and inertial forces of the fluid. His formula has been well confirmed over the years and it is an established fact that if the same Reynolds number can be achieved for the airflow over a scale model as a full size aircraft in flight, then the flow patterns over the model are similar to the flow patterns over a full size aircraft. This allows aircraft designers and engineers to use scale model in wind tunnel tests to produce the same flight characteristics of a real aircraft, as in aerodynamics it does not make any difference if the

surface is moving through the air or if the air is moving over the surface. This is because it is the 'relative velocity' of the airflow that is important in determining its airflow pattern over an object.

1.15 Equation of Continuity:

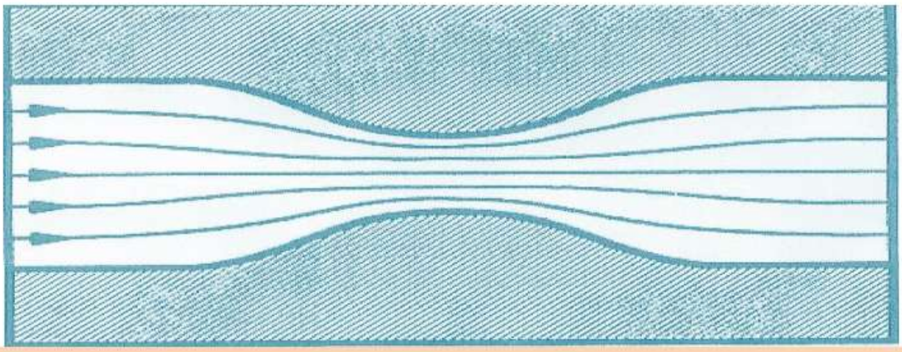
The equation of continuity states that when a fluid flow passes through a pipe its mass must remain constant, since mass can neither be created nor destroyed.

The equation applies only to streamline or steady flow and simply states that since mass cannot be created or destroyed, when air passes through a pipe its air mass flow is a constant.
Using this equation, if a flow passing through a pipe of varying cross-sectional area such as a venturi tube is considered. Then the mass airflow entering a pipe over a given time must equal the mass airflow leaving the system in the same time period. Let the fluid is incompressible, so its density will remain constant and can be removed from the equation, leaving:Mass airflow = AV = a constant
Or for different points along a tube as:
Mass airflow $=AV=A_1V_1=A_2V_{\surd}=$Constant OR



The mass flow at any point in the pipe therefore, will be the product of air density (ρ), cross-sectional area of the pipe (A) and air velocity(V).
Mass airflow = ρAV = a constant
This equation applies to both subsonic and supersonic airflow provided that the flow remains steady, but can be simplified for airflows travelling at low speeds up to approximately 0.4 Mach. This is because at speeds up to this point air is considered to be incompressible.

Using this equation, it can be seen that for an airflow passing through a pipe, the velocity of the flow is inversely proportional to the cross-sectional area. So a reduction in area causes an increase in velocity, with streamline converging as the velocity increases.



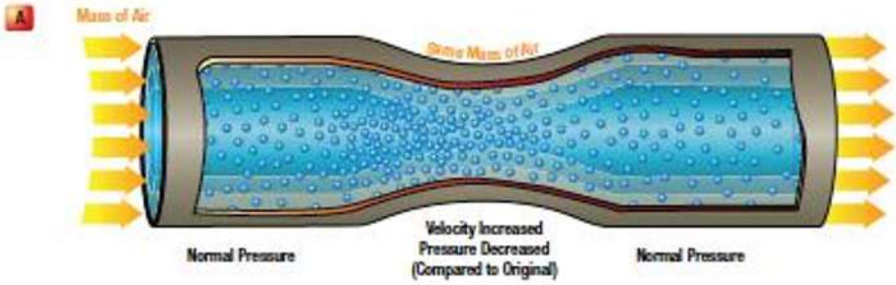
1.16 **Bernoulli's theorem:**

Bernoulli's Theorem expands the equation of continuity for a fluid flow to include the principle of the Conservation of Energy. His theorem states that, when a fluid passes through a pipe in a steady state, its total energy remains constant, as energy can neither be created nor destroyed.

For a fluid flow passing through a pipe therefore, the energy of the fluid entering the pipe in a given time would equal the energy leaving the pipe for the same time period.
In his original experiments, Bernoulli took into account all energy transfers for a fluid passing through a pipe. But for a perfect fluid however, he theorized that no energy would be lost to heat transfer or work done, so that the total energy of a fluid passing through a pipe could be considered to be a combination of the following:

- Potential Energy - energy due to height or position
- Pressure Energy - energy stored in a non-moving fluid and
- Kinetic Energy - energy due to movement of a moving fluid

For streamlined airflow, such as air passing over a streamlined object or through a pipe, the changes in height and therefore its changes in potential energy can be considered negligible and ignored. This simplifies Bernoulli's equation to the sum of the pressure energy and the kinetic energy.
i.e., Total Energy = Pressure Energy + Kinetic Energy = a Constant
In fluid flow, Bernoulli stated this equation in terms of pressure. The pressure energy being the non-moving pressure of the fluid called the static pressure and the moving energy of the fluid being called the dynamic pressure, which rearranges the formula for kinetic energy to include density, as in a fluid flow the energy will depend on the volume moved.
To rearrange kinetic energy into dynamic pressure , Kinetic energy = $\frac{1}{2} mv^2$,
where v = velocity
Deriving mass from the formula of density Density ρ = (m) mass/(V) Volume
$m = \rho V$
But since the density of a fluid is considered at a constant volume, V = 1, So mass (m) = ρ
Substituting this into the right hand side of the formula for Kinetic energy = $\frac{1}{2} \rho v^2$
The total energy of a fluid flow or total pressure therefore can be stated as:
Total Pressure(Pt) = Static Pressure(Ps)+Dynamic Pressure($\frac{1}{2} \rho v^2$)=Constant



For a fluid passing through the reduced area of a pipe, such as a venturi, the reduction of area causes an increase in dynamic pressure of the fluid and a decrease in its static pressure. Conversely when the cross-sectional area is increased there will be a reduction in dynamic pressure and an increase in static pressure.

NOTE: The total pressure can also be known or also referred to in other text books as its Total Head Pressure, Stagnation Pressure or Pitot Pressure. Dynamic pressure is commonly abbreviated to 'q' when no calculations are required or no factors within the formula change.

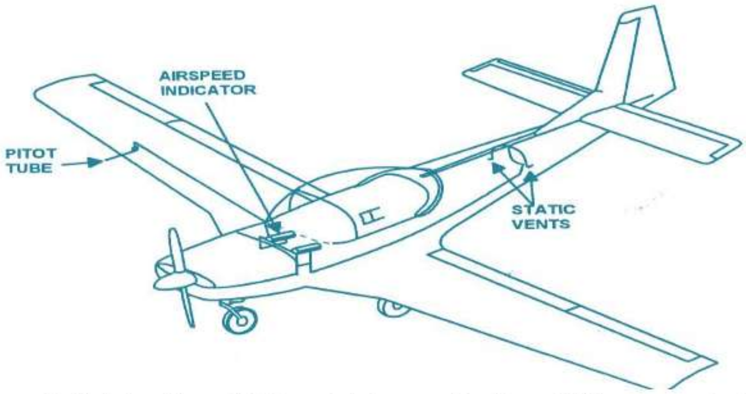
1.17 BASIC ATMOSPHERIC INSTRUMENTS

Introduction:

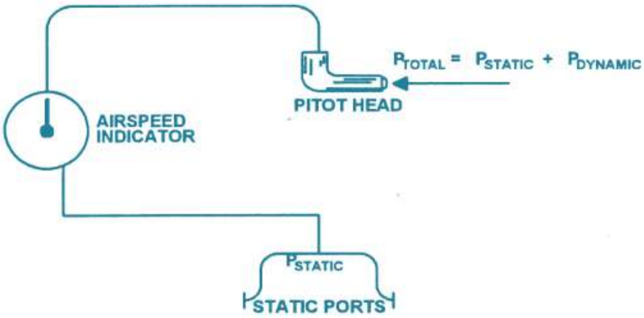
In order to fly an aircraft safely, a pilot flying needs some way of knowing how fast the aircraft is travelling through the air and the high they are. The basic instruments used for determining these measurements are the airspeed indicator (ASI) and the altimeter.

1.18 Airspeed Indicator (ASI):

The ASI is a simple instrument that operates by measuring the difference between two pressures taken from a pitot-static system. On a simple aircraft the system normally consists of two static vents positioned on either side of the fuselage and a pitot tube placed in a position pointing forwards towards the free stream airflow.



These two pressures are fed into the ASI, which reads the difference between the two measured



pressures and indicates dynamic pressure ($\frac{1}{2} \rho v^2$) in terms of airspeed.
To maintain the accuracy of the indicator, the instrument is checked when new and at regular intervals to ensure it does not have an error greater than 2 knots or 2 MPH. During calibration however, any errors found that are within limits are recorded at different points on the indicator scale and used as part of a correction scale to obtain calibrated airspeed.

1.19 Calibrated Airspeed (CAS):

Calibrated Airspeed (CAS), also called Rectified Airspeed (RAS) is IAS corrected for position error, which is the error due to the location of the pitot and static vents on the aircraft. As this error would be the same for all aircraft of the same type, these figures can be obtained by experimental data. The resulting pressure errors figures being published in the aircraft flight manuals and when combined with any instrument errors are recorded on a correction card, which is used by pilots to make the conversion between IAS and CAS.

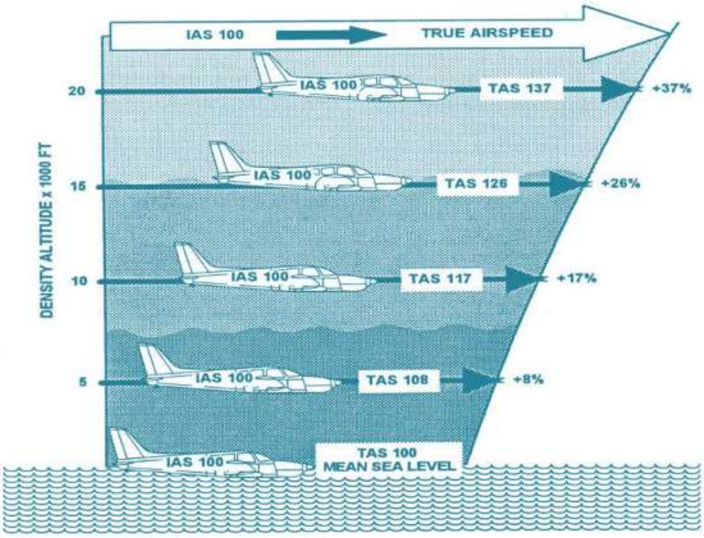
1.20 Equivalent Airspeed (EAS):

Equivalent Airspeed is IAS corrected for both position and compressibility errors. The latter error is due to compressibility of the air in front of the pitot head at airspeed greater than 300 knots (TAS). As this speed has universal implication the correction factor uses a standard atmosphere and is the ratio of ambient density to standard density.

1.21 True Airspeed (TAS):

True airspeed (TAS) is the actual speed of the aircraft relative to the air passing over it and is often required when making navigational calculations.
In flight, as the airspeed indicator and the correction figure where obtained under standard sea level conditions, the ASI and it correction figures, will only give the true airspeed of the aircraft at sea level conditions. To obtain an accurate airspeed at any other height therefore, the actual atmospheric conditions must be considered, as air density will reduce altering the dynamic pressure. In fact

indicated airspeed reduces at the square root of the atmospheric density.
Alternatively, if an aircraft was to climb at a constant IAS, then as density decreases, with increasing altitude, TAS will gradually increase due to IAS being obtained from the dynamic pressure ($\frac{1}{2} \rho v^2$).



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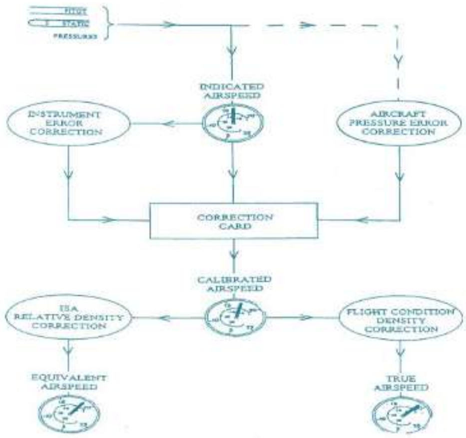
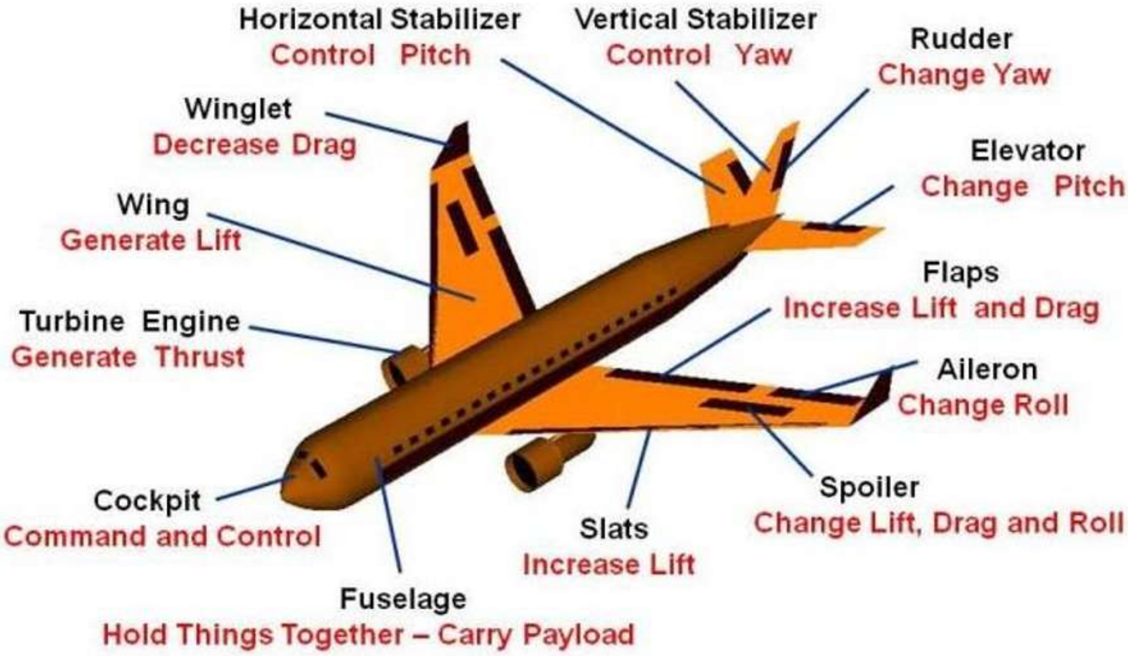
and TAS= EAS/$\sqrt{\sigma}$ where σ, the relative density = $\frac{\rho h}{\rho 0}$ where ρ_h is the density of at an altitude 'h' and ρ_0 is the density of at an altitude '0', i.e., at sea level.
Therefore, TAS= EAS at sea level. [since $\sigma = \frac{\rho h}{\rho 0} = 1$]
At altitudes, TAS > EAS at altitudes. [since $\sigma = \frac{\rho h}{\rho 0} < 1$ at altitudes]
Generalising, **TAS ≥ EAS**



The flowchart shows the steps required to make the appropriate airspeed conversion.

FLIGHT AERODYNAMICS

2.1 Components and Terminology



Basic Aircraft Components:

2.2 The Fuselage: The fuselage forms part of the main structure of the aircraft to which the wings and tail section are attached. The fuselage also provides the space for the crew, passengers and cargo to be carried and is designed to be as aerodynamically efficient as possible.

2.3 The Wings: The wings or mainplane of an aircraft are designed to generate sufficient lift to support the weight of the aircraft in flight. In most passenger aircraft they are also designed to carry the weight of the engines and fuel and must be capable of taking local loads well in excess of the total aircraft weight, which can exist during maneuvers

2.4 The Tail Section: The tail section consists of a vertical fin and horizontal tail plane. The function of these surfaces is to provide stability and maneuverability of the aircraft and will be explained in later sections.

The Control surfaces: These surfaces control aircraft movement and are categorized as either primary or secondary. The ailerons, elevator and rudder are termed primary; the spoilers, flaps and other high lift devices being termed secondary control surfaces.

2.5 PRIMARY CONTROL SURFACES

The primary control surfaces of an airplane include the ailerons, rudder, and elevator. Secondary control surfaces include tabs, flaps, spoilers, and slats. The construction of the control surfaces is similar to that of the stabilizers ; however, the movable surfaces usually are somewhat lighter in construction. They often have a spar at the forward edge to provide rigidity and to this spar are attached the ribs and the covering. Hinges for attachment are also secured to the spar. Where it is necessary to attach tabs to the trailing edges of control surfaces, additional structure is added to provide for transmission of the tab loads to the surface.

(i) Aileron

Ailerons are primary flight control surfaces utilized to provide lateral (roll) control of aircraft; that is they control aircraft movement about the longitudinal axis. They are usually mounted on the trailing edge of the wing near the wing tip.
Large jet aircraft often employ two sets of ailerons, one set being approximately midwing or immediately outboard of the inboard flaps, and the other set being in the conventional location near the wing tips. The outboard ailerons become active whenever the flaps are extended beyond a fixed setting. As the flaps are retracted, the outboard aileron control system is "locked out" and fairs with the basic wing shape. Thus, during cruising operations at comparatively high speeds, only the inboard ailerons are used for control. The outboard ailerons are active during landing or other slow flight operations.

Other aircraft have the ailerons operating asymmetrically; that is, the upward-moving aileron moves further than the downward moving aileron. This asymmetrical operation is used in some aircraft designs to reduce the amount of rudder pressure required when making turns. This reduces what is know as "adverse aileron yaw", which is caused by the downward-moving aileron creating an increase in aerodynamic drag, and results in the airplane yawing away from the direction of the desired turn. Aircraft having this arrangement are sometimes said to have differential ailerons.

(ii) Elevators

Elevators are the control surfaces which govern the movement (pitch) of the aircraft around the lateral axis. They are normally attached to hinges on the rear spar of the horizontal stabilizer. The construction of an elevator is similary to that of other control surfaces, and the design of the elevator may be unbalanced or balanced aerodynamically and/or statically.

(iii) Rudder

The rudder is the flight control surface that controls the aircraft movement about its vertical axis. The rudder is constructed very much like other flight control surfaces with spars, ribs and skin.
Rudders are usually balanced both statically and aerodynamically to provide for greater ease of operation and to eliminate the possibility of flutter. It should be noted that some light-aircraft rudders do not use any balancing method.

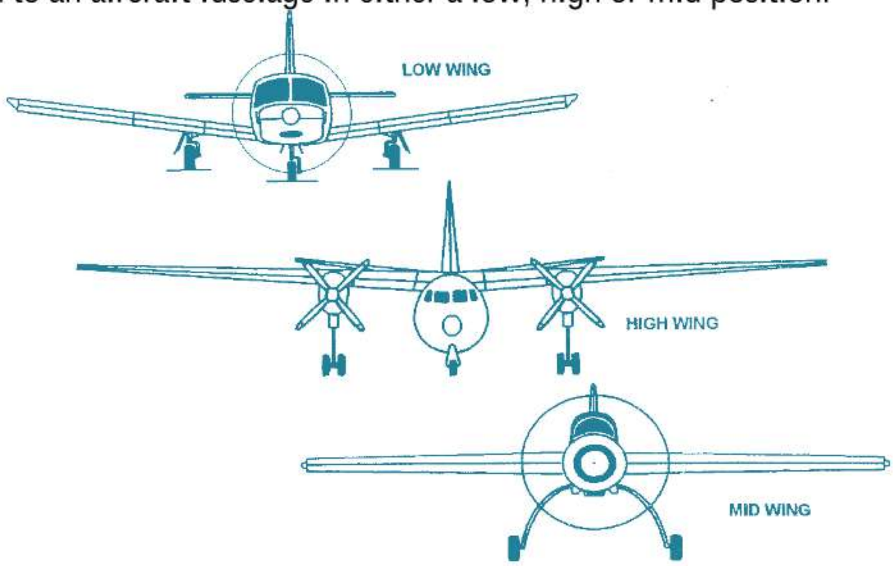
Rudders for transport aircraft vary in basic structural and operational design. Some are single structural units operated by one or more control systems. Others are designed with two operational segments which are controlled by different operating systems and provide a desired level of redundancy.

A single-unit rudder is capable of being operated by three different hydraulic systems in the aircraft. A rudder with an upper and a lower segment of which each segment can be operated by a different hydraulic systems.

The rudder with of two segments consists of upper and lower, and each segment consists of a forward and aft section. The forward rudder sections are attached to hinge brackets mounted on the rear spar of the vertical stabilizer. The aft rudder sections are supported by hinge brackets attached to the rear spar of the forward sections. The aft rudder sections are hinged to the forward sections and connected by pushrods to the vertical stabilizer structure. This provides aft-section displacement proportional to forward-section displacement, thus increasing the aerodynamic efficiency of the rudders. Trim and control tabs are not required with this type of rudder design because their functions are performed by the aft sections of the rudder.

2.6 Wing Position Terminology

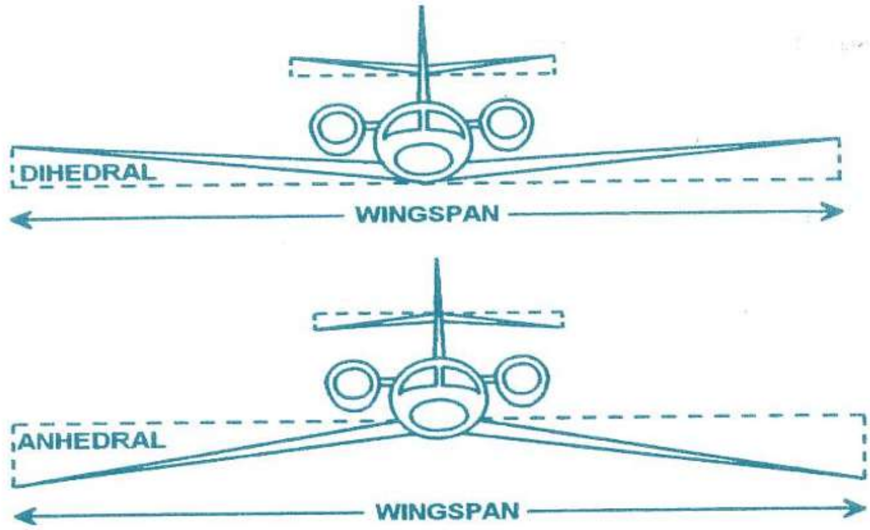
Wings are attached to an aircraft fuselage in either a low, high or mid position.



The actual wing position on the aircraft is determined by some of the following design parameters:

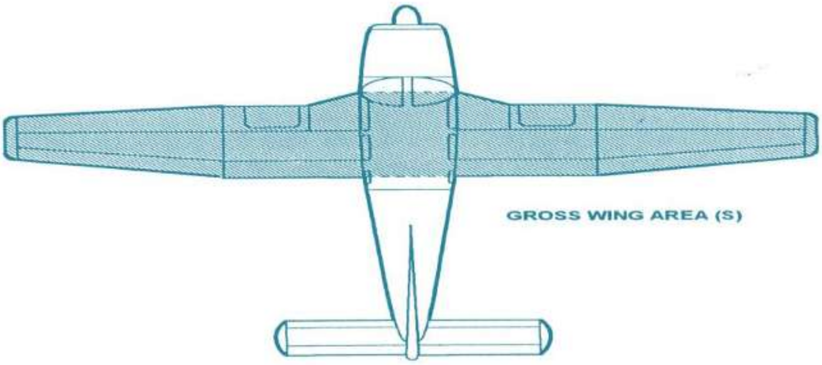
- Engine positioning and size or Propeller blade length.
- Undercarriage positioning.
- Short Take-off and Landing Capacity.

In practice the wings of an aircraft are inclined above, or below the horizontal. The inclination of the wings affects the stability of the aircraft and will be described later chapters. Wings inclined above the horizontal are termed dihedral, where as those inclined below the horizontal are termed anhedral.

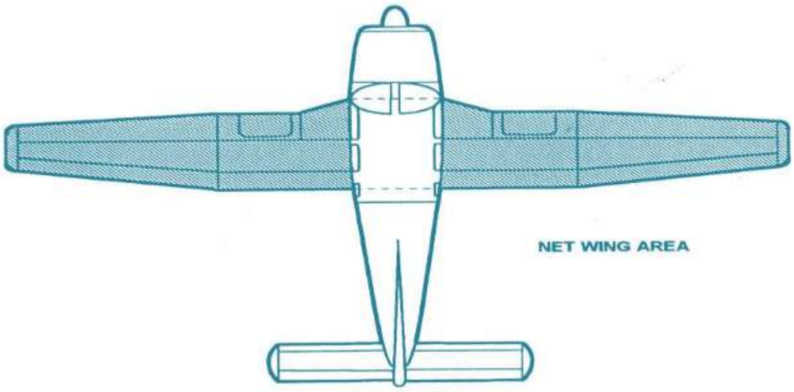


Wing Planform Terminology :The following terminology is associated with the wing planforms:

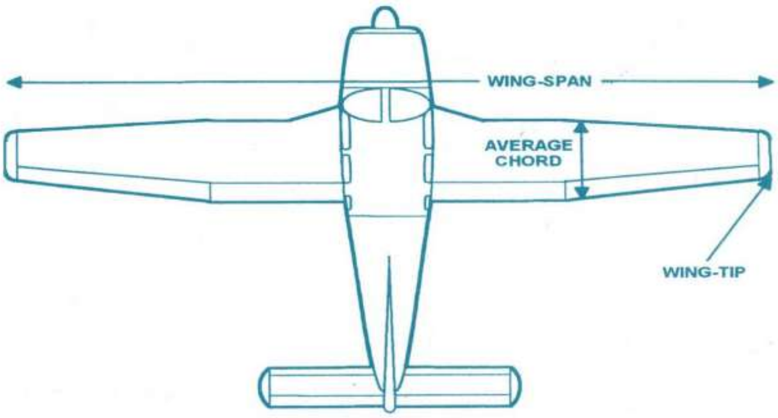
2.7 Gross Wing Area (S): The plan view area of the wing including the portion of the wing cut out to accommodate the fuselage.



2.8 Net Wing Area: The plan view area of the wing excluding the fuselage portion.



2.9 Wing span (b): The straight-line distance between wing tips.

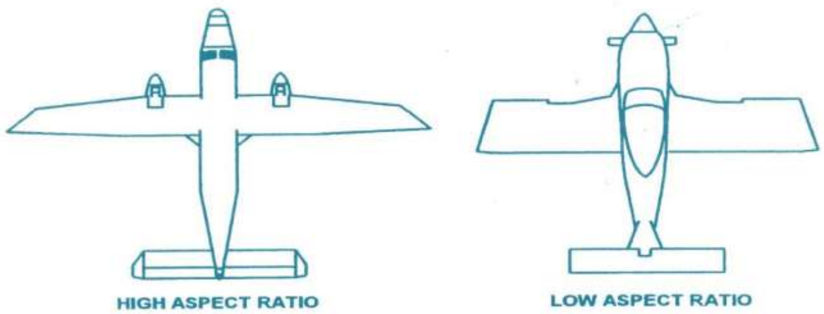


2.10 Average Chord (C_{av}): The average chord of the wing is the average length between the leading and trailing edge of the wing. The product of the span and average chord gives the gross wing area (S = b x C_{av}).

2.11 Aspect Ratio (AR): The ratio of the wingspan to the average chord, i.e., AR= $\frac{b}{\boldsymbol{Cav}}$ – (i)

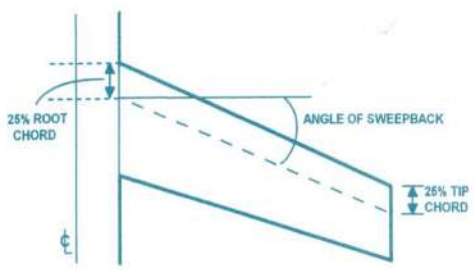
Further, AR= $\frac{b}{\boldsymbol{Cav}}.\times\frac{b}{b}=\frac{b2}{b\times\boldsymbol{Cav}}=\frac{b2}{s}=\frac{(span)2}{wing\ area}$ -- (ii) (since, gross wing area , S = b x C_{av}).

Also, AR= $\frac{b}{\boldsymbol{Cav}}\times\frac{\boldsymbol{Cav}}{\boldsymbol{Cav}}=\frac{s}{(\boldsymbol{Cav})\mathbf{2}}=\frac{wing\ area}{(mean\ chord)2}$ --- (iii)

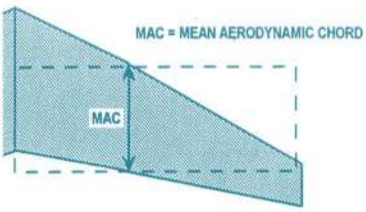


Long thin wings are of high aspect ratio, whilst short stubby wings are of low aspect ratio.

2.12 **Taper Ratio (λ):** The ratio of tip chord (C_{tip}) to chord root (C_{root})



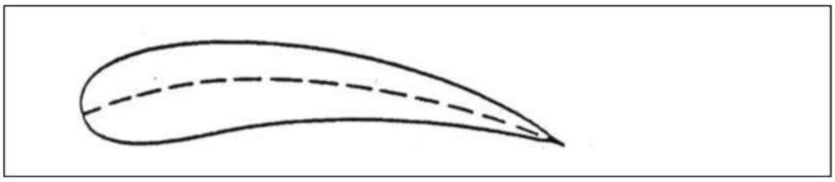
2.13 The Angle of Sweepback: Measured by the angle between a lateral axis perpendicular to the aircraft centreline and a constant percentage chord line along the semispan of the wing. This percentage is usually taken to be a quarter chord (25%) of the wing, as taken from the leadingedge.



2.14 Mean Aerodynamic Chord (MAC): The chord line drawn through the centre of area of the half span area.

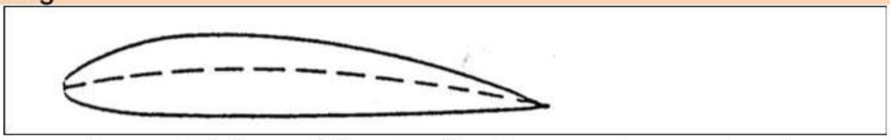
Wing shapes(Sectional Forms)

2.15 High Lift Wing:



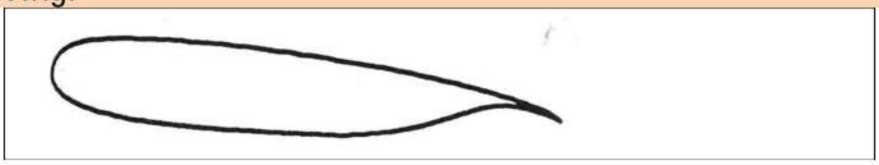
A high lift wing has a high thickness/chord ratio; a pronounced camber and a well-rounded leading edge. This type of wing produces high lift at low speeds. Its maximum thickness being found between 25 – 30% of the chord line behind the leading edge.

2.16 General Purpose Wing:



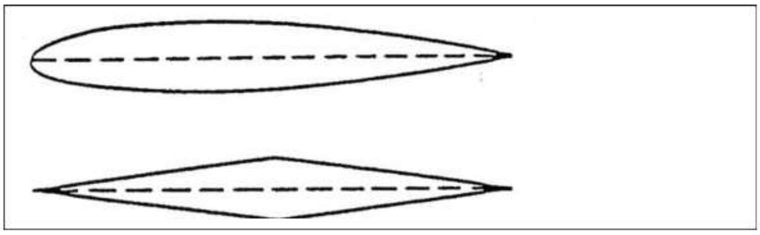
A general-purpose wing has a lower thickness/chord ratio, less camber and a sharper leading edge than a high lift wing. The maximum thickness of the wing is still found at about 25 – 30% of the chord line behind the leading edge. This type of wing produces less drag than a high lift wing at higher speed.

2.17 Supercritical Wing:



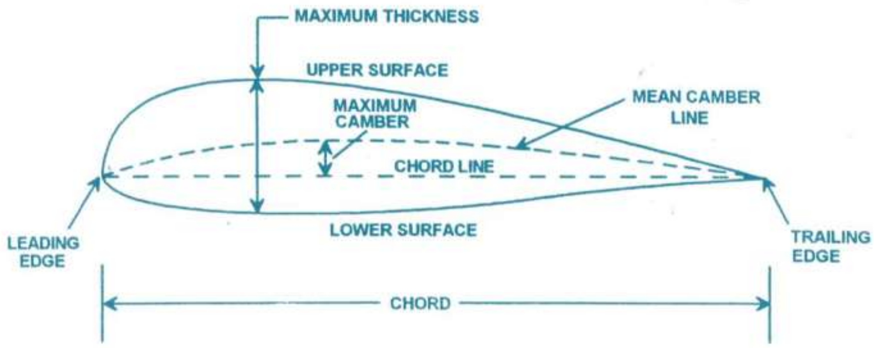
A supercritical wing has a very slight curvature on the upper surface and has its point of maximum thickness positioned close to the trailing edge. This type of wing is
found on many modern transport aircraft as it gives low drag characteristics near supersonic or transonic speeds.

2.18 High speed Wings:



High-speed wings are normally symmetrical shaped wings that have their point of maximum thickness at the 50% chord point.

The wing has a very low thickness/chord ratio normally between 5 -10% and has normally no camber and a sharp leading edge. This type of wing gives a very low drag characteristic at transonic and supersonic speeds, but has however poor lift capabilities at low speeds.



Wing Section Terminology

2.19 Chord Line: As stated earlier, chord line is a straight line joining the leading and trailing edges of a wing.

The Chord: The length of the chord line is used as a reference for all other dimensions relating to the wing.

2.20 The Mean Camber Line: A line drawn at an equal distance between the upper and lower surfaces of an aerofoil.

2.21 Maximum Camber: The maximum distance between the mean camber line and the chord line. It is one of the variables that determine the aerodynamic characteristics of awing.

2.22 Maximum Thickness: The maximum distance between the upper and lower surfaces.

2.23 Maximum Thickness Chord Ratio: The Slimness Ratio, which is the ratio of maximum thickness to chord, is normally expressed as a percentage. For subsonic wings the ratio is generally about 12 – 14%.

Aerodynamic Terminology

2.24 Free Stream Flow: The region of air where pressure, temperature and relative velocity are unaffected by the passage of the aircraft through it, free stream flow is also known as Relative Air Flow (RAF).

2.25 Total Reaction (TR): The Resultant of all the aerodynamic forces acting on the wing or aerofoil section, which acts perpendicular to the chord line.

2.26 Centre of Pressure (CP):The point on the chord line through which the TR is considered to act.

2.27 Fineness ratio: The ratio of the chord length of a non-lift producing body to its thickness.

2.28 Wing Loading: The weight per unit area of the wing.(i.e.,W/A)

2.29 Load Factor (g or n): The ratio of total lift produced to the weight of the aircraft.(i.e.,n=L/W)

2.30 CANARD WINGS:

A canard type configuration is one which has a fore-plane located forward of the wing instead of , in the most conventional, aft position. On an aircraft with a long slender fuselage with engines mounted in the tail and a CG position well aft, this layout has the obvious geometric advantage of a longer moment arm. This enables the stability and trim requirements to be satisfied by a fore-plane of smaller area. The trim drag problem also will be mitigated because, at high speeds, an up-load will be required on the fore-plane to trim the aircraft.

However, there are certain disadvantages with this layout:

a) Stalling Problems: On a conventional rear-tailplane configuration, the wing stalls before the tailplane and longitudinal control and stability are maintained at the stall. On a canard layout, if the wing stalls first, stability is lost, but if the fore-plane stalls first, then control is lost and the maximum value of C_L is reduced. One possible solution is to use a canard surface and a wing trailing edge flap in combination, with one surface acting as a trimming device and the other as a control. Alternatively, an auxiliary horizontal tailplane at the rear may be used for trim and control at low speed.

b) Interference Problems: The airflow from the fore-plane interferes with the flow around the main wing and vertical fin a canard layout. This can cause a reduction in lift on the main wing and can also result in stability problems. The interference with the vertical fin may lead to a marked reduction in directional static stability at high angles of attack. The stability may be improved by employing twin vertical stabilizers .

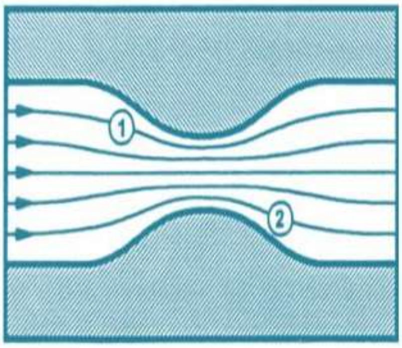
2.31 LIFT

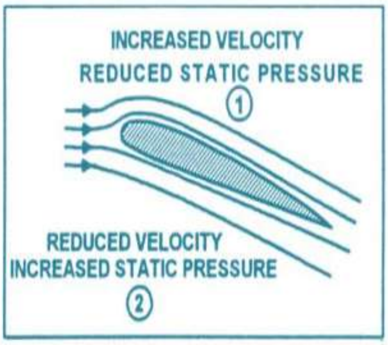
Introduction

In order to fly, an aircraft must generate a force that is at least equal to its weight to maintain level flight, and a force greater than the weight in order to manoeuvre. This force is called lift and acts perpendicular to the relative airflow (RAF).

Airflow and Lift

Whenever an aircraft moves through the air, or if an object is placed into a moving airstream, the air moving around the aircraft, or the object, will undergo a change in direction, which causes a change in its velocity. As this will either speed up or slow down the airflow passing over an object, it will also affect its static pressure, as explained by the equation of continuity and Bernoulli theorem.
Using Bernoulli's theorem, the definite relationship between velocity and the static pressure can be used to explain how lift is generated. This is because it can be proven that for an airflow passing around an aerofoil section, the flow will resemble the flow passing through a venturi tube, due to its wings geometrical shape.



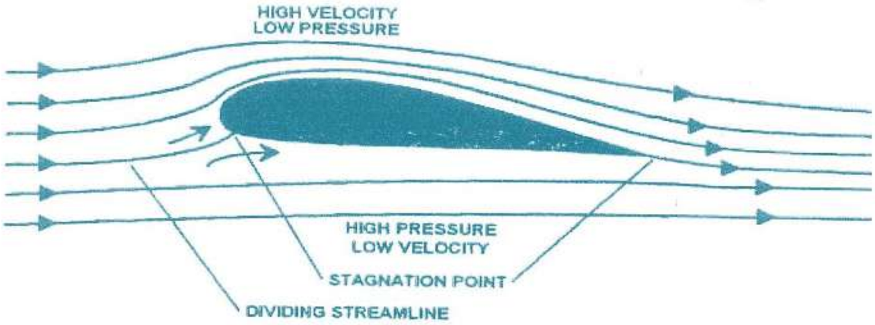


The convergent part of the tube resembling the upper surface of the wing as the velocity increases and static pressure decreases. Whilst the divergent part resembles the lower surface of the wing as the velocity is travelling at a lower speed than the upper surface so its static pressure is increasing.
These changes in velocities over the upper and lower surfaces results in a pressure differential occurring between the two surfaces that will produce an upward force known as lift.

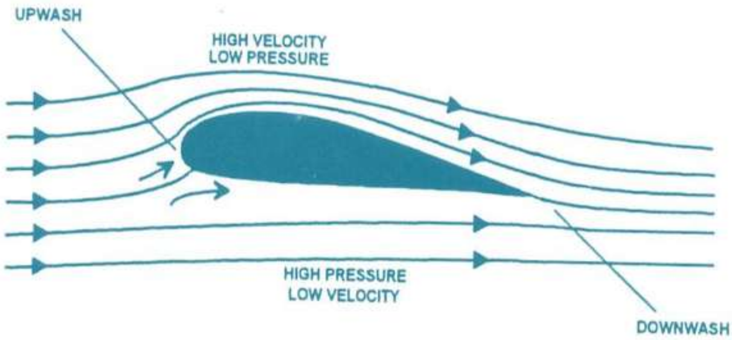
Airflow around an aerofoil

For an aerofoil surface that is placed into an airstream, the air approaching the airfoil will develop a dividing stream, which separates the flow between the upper and lower surfaces.
In order to separate the flow, the dividing stream as it approaches the aerofoil is slowed down by the surface and momentarily comes to a rest near the leading edge, forming a stagnation point. At this point the velocity of the airflow is reduced to zero and the static pressure reaches its maximum (Bernoulli equation), this is knownas stagnation pressure of the airflow and is above that of ambient pressure.

A further stagnation point will also exist at the rear of the aerofoil, due to the pressure gradient over the aerofoil, but this point will be dealt with later in the sections dealing with stalling, as it affects the air at the rear of the aerofoil.



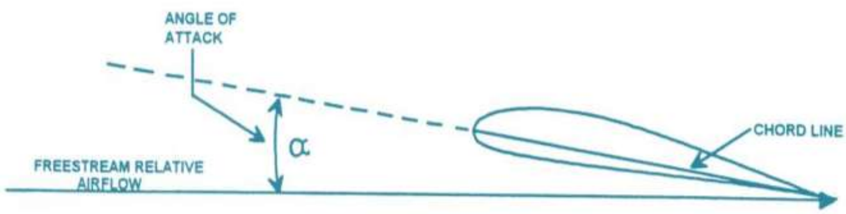
On a typical aerofoil section, the forward stagnation point occurs just below the leading edge of the wing, so that the airflow passing over the upper surface has to move forward first. In moving forward the air imparts an upward acceleration to the airflow passing over the upper surface, which along with the pressure differential (negative pressure gradient) associated with the upper surface helps draw the air locally upwards producing an upwash.



At the rear of the aerofoil the air leaving the upper surface will be moving faster relative to the air leaving the lower surface. This will tend to force the streamlines downwards producing a downwash.

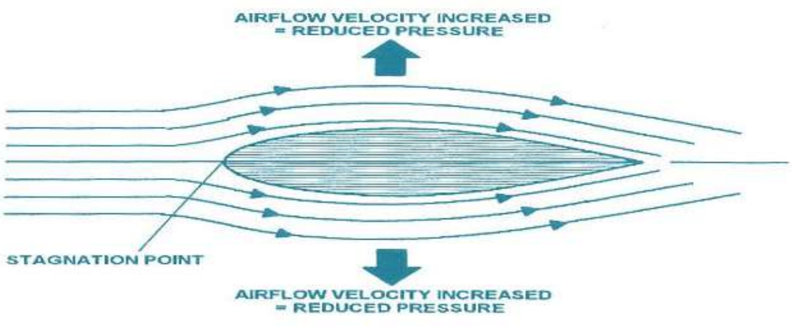
2.32 Angle of Attack (AOA)

The attitude that an aerofoil surface presents to an oncoming airflow is known as its angle of attack (α), and is the angle measured between the chord line of the aerofoil and the relative airflow (RAF).

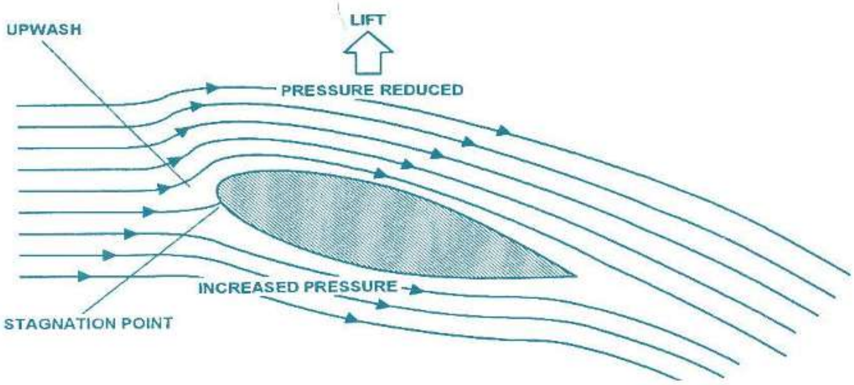


2.33 The Effect of Angle of Attack (AOA) on Airflow Around an Aerofoil:

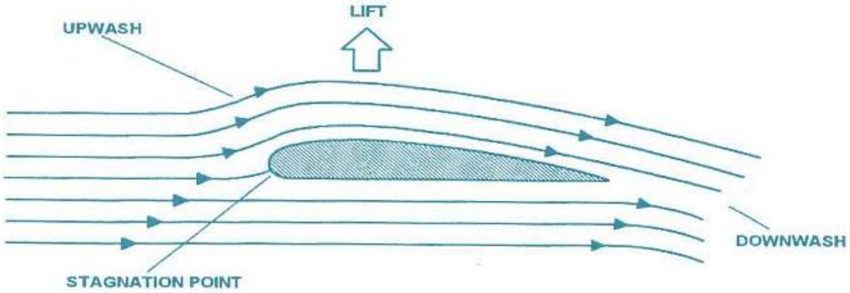
For a symmetrical aerofoil placed in a steady airstream, lift is only produced when the aerofoil has a positive angle of attack. This occurs because when a symmetrical aerofoil is placed at zero degrees AOA to the relative airflow, the stagnation point forms on the leading edge so that the change in



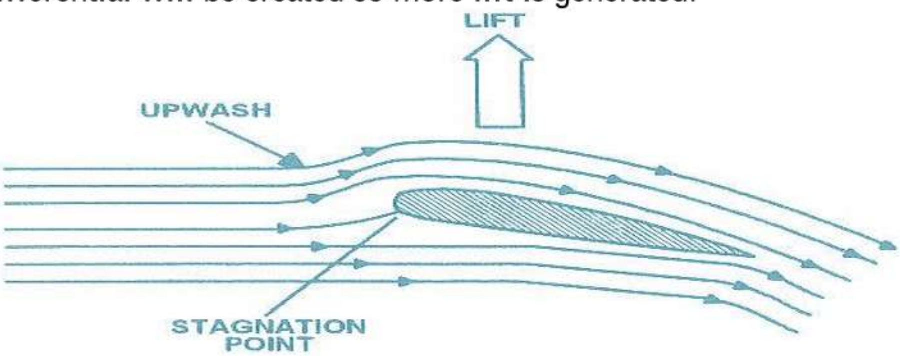
velocity above and below the aerofoil are equal so there is no pressure differential and no lift will be generated.
If the aerofoil is now given a positive AOA, the stagnation point will move below the leading edge causing an upwash to develop.



This brings about an increase in velocity of the air passing over the upper surface of the aerofoil compared to the air passing below the lower surface. In order to maintain the equation of continuity therefore, the air passing over the upper surface as it now has further to travel, must go faster.
The changes in velocity over the aerofoil therefore will change the static pressure above and below the surface producing a pressure difference between the two surfaces allowing lift to be generated.
On an asymmetrical aerofoil however, at zero degrees AOA, the stagnation point will form below the leading edge and an upwash will occur. This will therefore produce lift at this angle, as the air passing over the more curved upper surface will be travelling faster than the air passing below the aerofoil.



Increasing the angle of attack on an asymmetrical wing will now cause the stagnation point to move further along the lower surface creating more upwash and increasing the distance that the air over the upper surface has to travel. As this will further increase the velocity of the air over the upper surface, a larger pressure differential will be created so more lift is generated.

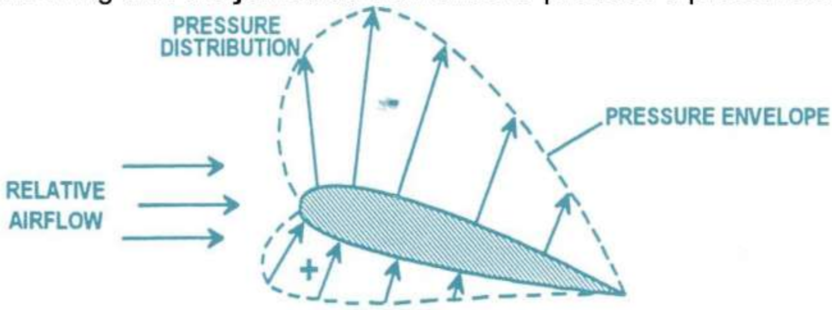


For an airflow passing over an aerofoil shape therefore, the angle of attack in conjunction with the actual shape of the aerofoil are the principal factors in determining how air moves around it and how lift is generated. As any changes to either of these two factors will affect how an airflow moves over an aerofoil and the amount of lift it generates.

2.34 Chordwise Pressure Distribution

For an aircraft in flight, although the whole aircraft contributes towards the lift and drag of the aircraft, it may be assumed that the wings since they are specifically designed to produce lift will produce the necessary lift for the whole aircraft.

A wing generates lift whenever an airflow passing over and under it, creates a pressure differential between the two surfaces due to local changes in its velocity and static pressure. These changes to the static pressure over the wing can be shown diagrammatically by a series of pressure vectors drawn from the surfaces of the wing that are joined at their ends to produce a pressure envelope.



By convention pressure above ambient is given a (+) sign towards the surface and those below ambient given a (–) sign and plotted away from the surface.

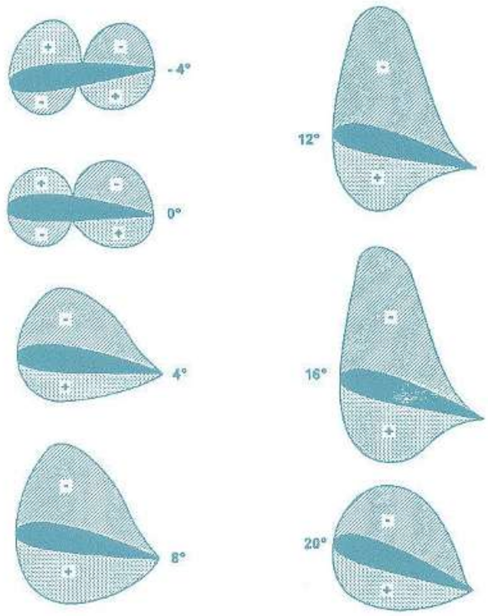
The length of the pressure vector is proportional to the difference between absolute pressure (P) and the free stream static pressure (P_0) ie ($P - P_0$). This is then converted to a pressure coefficient (Cp) by comparing it to dynamic pressure (q).

Instruments show that increasing the angle of attack will increase the pressure differential between the upper and lower surfaces, due to a greater decrease in pressure on the upper surface than the change in pressure on the lower surface and the pressure envelope increases in height and on an asymmetrical wing moves forward towards the leading edge.

The value therefore of the pressure coefficient at any stagnation point is +1

2.35 Variation of Pressure Differential With Changes of Angle Of Attack

For different angles of attack the size and position of the pressure envelope will alter and the actual pressure changes, during the design stage can be measured using manometers. These

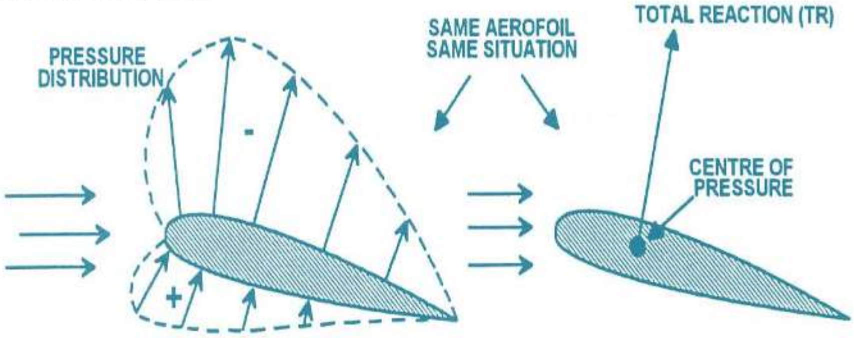


The size and direction of the vectors in the pressure envelope therefore indicates the amount of lift that can be produced and as can be seen from the above examples the envelopes and therefore lift increases up to a certain angle, known as the stalling angle of attack.

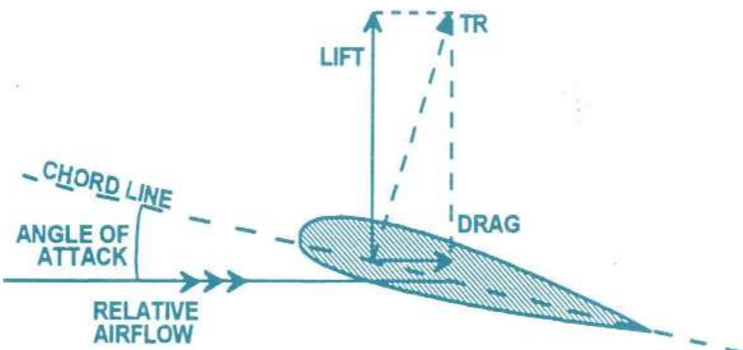
Beyond this angle, which is this is typically between 15 to 18^0 for a general aerofoil, the majority of flow over the upper surface breaks down into heavy turbulent flow, which causes an increase in pressure, and the relationship between velocity and static pressure no longer applies, since Bernoulli's theorem only applies to streamline flow.
On studying a pressure distribution diagrams it can be seen that at a certain angle of attack the pressure distribution is the same both above and below the aerofoil so no net lift will be generated. This is known as the Zero lift angle of attack, which for an asymmetrical aerofoil, will always be negative.
The zero lift angle of attack for most asymmetrical wings being approximately -4^0 angle of attack, but for a symmetrical aerofoil, this angle will always be 0^o angle of attack.

2.36 Centre of Pressure and Total Reaction Force:

In contrast to the complicated pressure plots of the pressure envelope, it is possible to show the overall effects of changes to the static pressure over a wing with a single force.
This single force is termed the total reaction force (TR) and acts through a single point on the chord line called the centre of pressure (CP). The force represents all of the forces acting over the wing and acts perpendicular to the chord line.



The direction of the total reaction force (TR) is the resultant of all the forces acting on the wing, its lift force that acts perpendicular to the relative air flow (RAF) and the drag force that acts parallel to the RAF. Therefore as both lift and drag vary in size, during flight, the lift force changing with changes in the angle of attack and the drag force changing with changes in speed and lift, the size and direction of the TR alters.

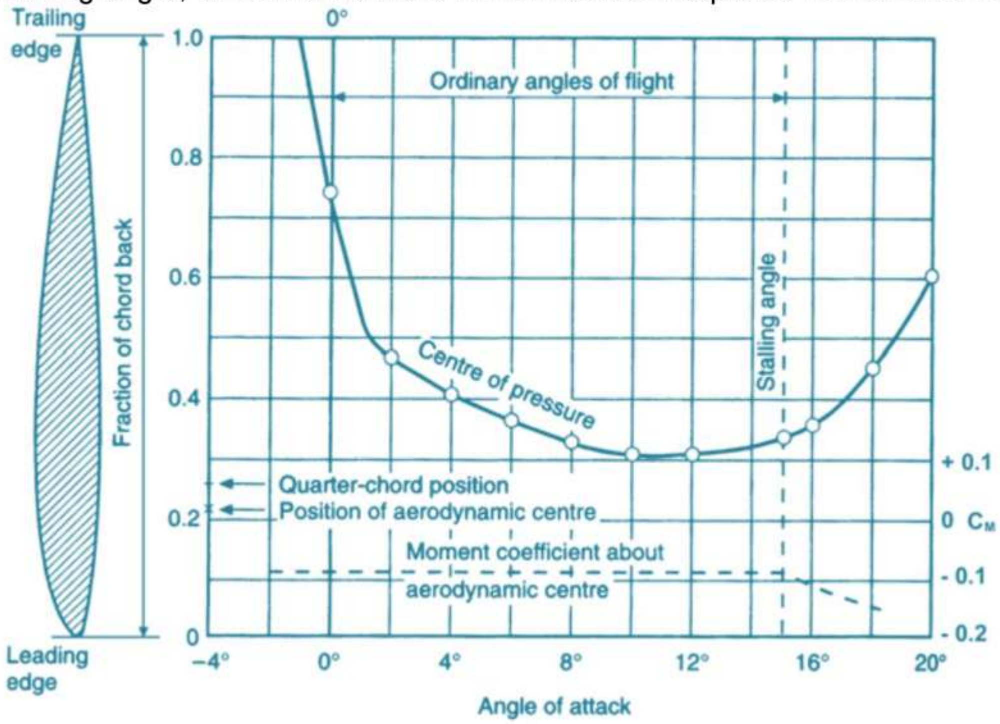


In level flight the CP is positioned on an asymmetrical wing about a quarter way along the chord line of the aerofoil section but moves along the chord line as the angle of attack changes.

2.37 Movement of centre of pressure with AOA

Increasing the angle of attack up to the stalling angle causes the CP and the low- pressure peak to move towards the leading edge (LE), but beyond this angle the low-pressure peak rapidly collapses causing the size of the TR to decrease and the CP to move quickly to the rearwards towards the trailing edge (TE), pitching the aircraft nose down. For a typical asymmetrical aerofoil, the range of CP movements over the normal working range of AOA is between the 25 to 30% of the chord line rear of the leading edge. However with a symmetrical aerofoil, there is virtually no CP movement over the working range of AOA at subsonic speed, and the CP stays approximately central as the TR tilts.

Note: As stated in the previous paragraph, when we increase the AOA, the CP moves forward and beyond stalling angle, it moves rearward which has been depicted in the following graph.

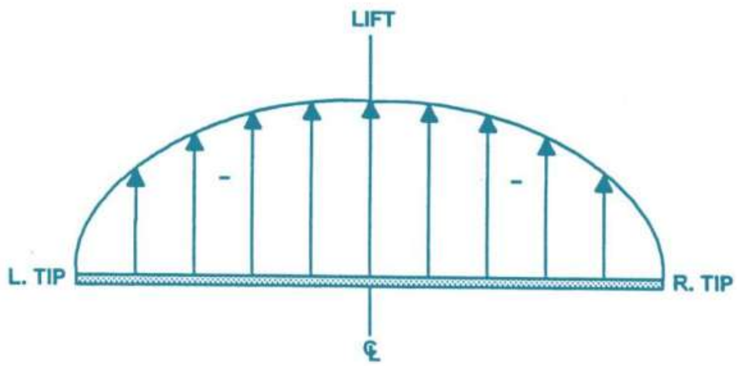


Movement of centre of pressure with AOA

2.38 Spanwise Pressure Distribution

So far, the pressure distribution around an aerofoil has only been considered in the chordwise direction. To fully understand how lift is developed over an aerofoil or wing, it is also necessary to consider its spanwise pressure distribution as airflow passes over a wing.

For an airflow passing over a wing with a positive angle of attack, a pressure differential between the upper and lower surfaces of the wing will produce lift. The greatest differential occurring at the root of the wing, where the largest proportion of lift is generated with the smallest differential at the wing tip; where the least amount of lift is generated.



Beyond the wing tips however, as air is nominally at atmospheric pressure, this causes a spanwise flow away from the fuselage on the lower surface and towards the fuselage on the upper surface. The airflow over the wing will therefore flow in both a chordwise and spanwise direction.

The effect of airflow moving in both a chordwise and spanwise direction is to create vortices at both the trailing edge of the wing and at the wing tips, creating a downwash behind the wing that reduces the overall lift and increases the drag on the aircraft.

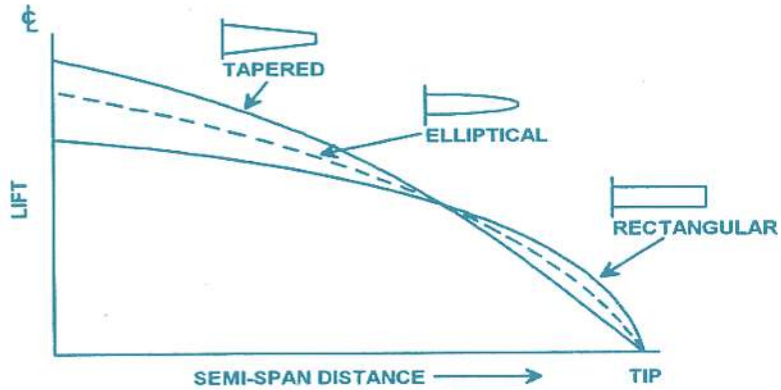
To recover the lost lift, due to a spanwise flow, the angle of attack must be increased to increase the lift over the wing. This will, however, cause a corresponding increase in spanwise flow and induced drag that this tilting of the lift force produces. The formation of trailing edge and wing tip vortices will be discussed later in the chapter covering drag.

2.39 Wing Shape and its Effect on Lift

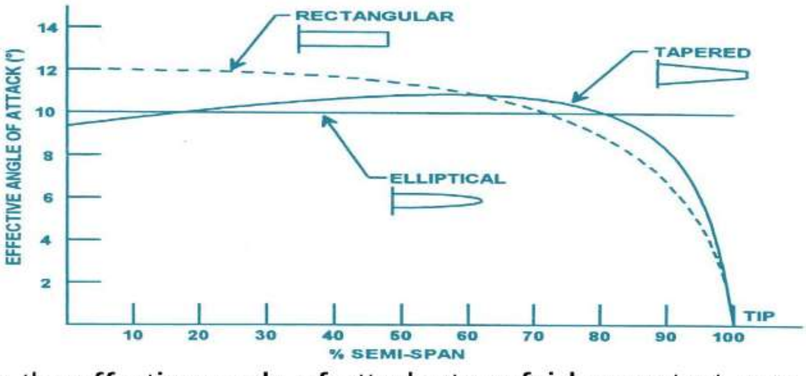
The shape of a wing affect the amount of lift generated as it has a major influence on the way air moves around it, in both a chordwise and spanwise direction.

In the chordwise direction, the pressure differential between the upper and lower surface will depend on its cross section shape ie its amount of camber, an asymmetrical wing producing more lift than a symmetrical wing for a given angle of attack.

In the spanwise direction, the planform shape of the wing affects the way lift is generated as it not only changes the area of the wing by changing in its chord length, but it also affects the way tip vortices are produced.



In a spanwise direction, the actual amount of lift developed by each section of a wing varies according to its angle of attack. In practice therefore, it is the wing section effective angle of attack that determines the amount of lift each section of the wing produces, which will depend on the strength of wing tipvortices.



On a rectangular wing the effective angle of attack stays fairly constant over the inner half of the wing but reduces rapidly over the outer half lift due to large wing tip vortices produced by having a large wing tip chord. By comparison a tapered wing with a reduced wing tip chord produces only small wing tip vortices. This allows this wing to have an increasing effective angle of attack to approximately three quarters of its length, before decreasing over its last quarter.

The most effective wing however in producing virtually no wing tips vortices, is an elliptical wing, due to its constant downwash. This wing therefore has a constant effective angle of attack, but as will be explained later on is not commonly used due to manufacturing problems.

The effectiveness of a wing to generate lift therefore will depend on both its section and planform shape along with its angle of attack. These factors are combined with other factors to form a wings coefficient of lift.

It follows therefore that in flight, any changes in a wings coefficient of lift will be mainly due to changes in the angle of attack, as the section and planform shape is fixed.

2.40 Lift Formula

As already seen in this chapter, in order to calculate the actual lift produced by a wing a number of factors have to be taken into account including the:

- AOA.
- Shape of wing and planform.
- Condition of wing surface.
- Reynolds'No.
- Speed of Sound(Mach No).
- Air density(ρ).
- Free stream air velocity squared(V^2).
- Surface wing area(S).

But as having to take all these factors into account every time, will make the calculation of lift difficult. So to simplify the calculations many of the factors are grouped together, making it easier to calculate.

It has already been established that the lift force produced by a wing will depend on the pressure differential between the upper and lower surface. So a basic formula for lift can be derived from the formula of Pressure.

Pressure = force/ area

Force (Lift) = pressure x area

But since the pressure over the wing depends on the velocity or dynamic pressure ($P_{dyn} = \frac{1}{2} \rho V^2$) of air over the wing, (Bernoulli's Theorem) and that the area that the pressure acts over is fixed in a certain configuration, substituting these two is into the formula for lift gives:

$\text{Lift} = \frac{1}{2} \rho V^2 \times S$

To take into account the remaining factors:

- AOA.
- Shape of wing and planform.
- Condition of wing surface.
- Reynolds' No.
- Speed of Sound (Mach No).

A coefficient, known as the coefficient of lift (C_L) is established and when inserted into the formula gives us a general lift formula.

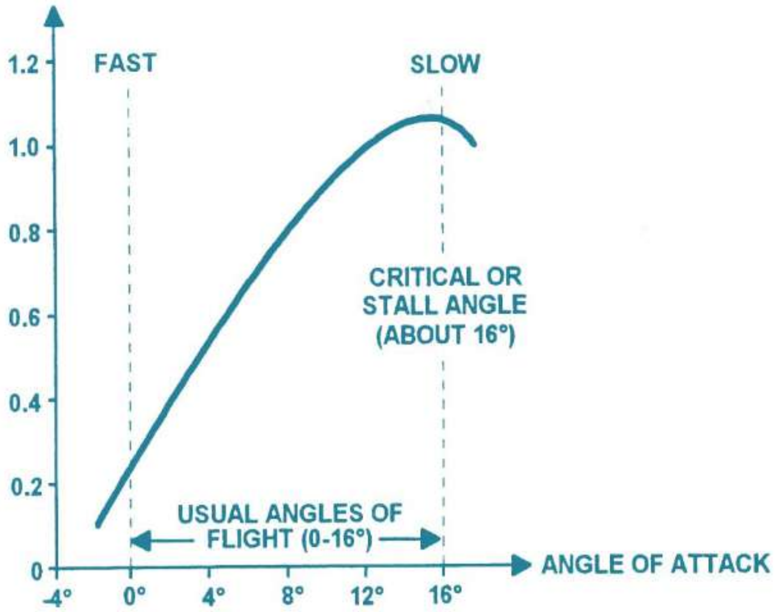
$\text{Lift} = C_L \frac{1}{2} \rho V^2 \times S$

This formula can also be rearranged in terms of the coefficient of lift (C_L)

Rearranging the formula this way shows that the coefficient of lift is a ratio between the lift force per unit area, at a single height or speed. Or that it is a ratio between the lift pressure and the dynamic pressure, which will vary with angle of attack.

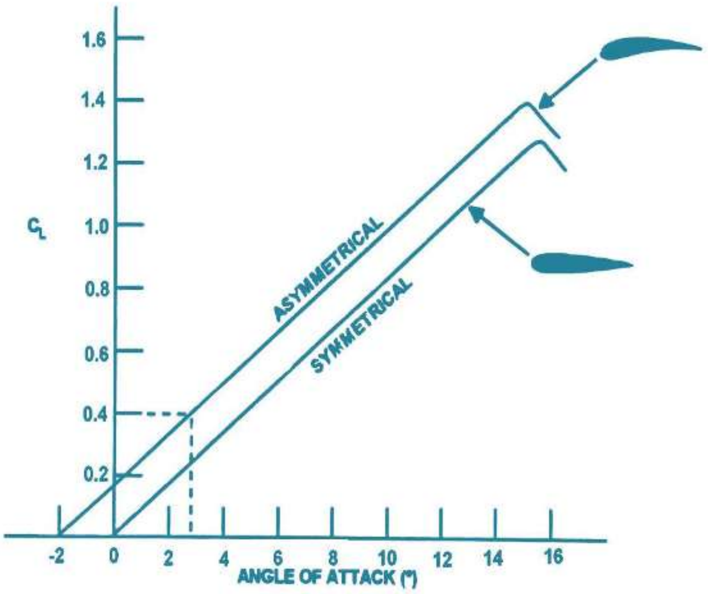
2.41 Variation of C_L with Angle of Attack

To establish the effect of changing the angle of attack has on the lift produced by a wing; a graph of the coefficient can be plotted against angle of attack. This is known, as a lift curve.



The lift curve for an asymmetrical wing shows that the greatest part of the curve is linear (a straight line) so that the value of C_L, and hence lift is directly proportional to the angle of attack in this region. At the far end of the curve between 12º and 16º AOA, the curve starts to lean over slightly indicating a loss of lifting effectiveness until it eventually forms a peak. At the peak the maximum value of C_L or $C_{L\ MAX}$ for the aerofoil is obtained, and hence the greatest lift for a given configuration.

The angle of attack at which the $C_{L\ MAX}$ is obtained is known as the critical or stalling angle AOA for the aerofoil. As beyond this AOA, as can be seen in the graph above, that lift decreases rapidly causing the CP to move towards the trailing edge causing a nose down pitching moment. The stalling of an aircraft in flight will be discussed in later chapters.



In practice each aerofoil possesses its own lift curve for each configuration, so it is possible to compare the performances of both asymmetrical and symmetrical type aerofoil.

In comparing these curves, the lift curves show that an asymmetrical wing will produce more lift at any given angle of attack, than a symmetrical one of the same surface area, but has a lower stalling angle. The curves also show that the zero lift angle for an asymmetrical wing is always a minus, whereas for a symmetrical aerofoil zero lift angle is always zero.

2.42 HIGH LIFT DEVICES (Lift augmenting devices)

As aircraft have got larger and heavier, it has become necessary for aircraft to incorporate some form of supplementary lifting during the landing and takeoff phase. The most common lift augmentation

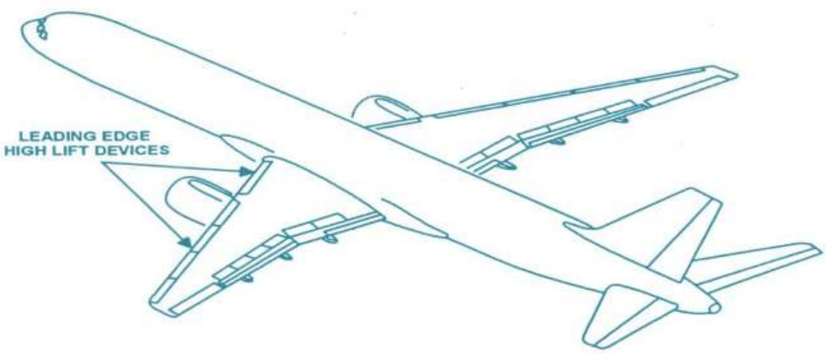
devices falling into either one of two categories:
- Leading edge devices.
- Trailing edge devices.

2.43 Leading edge devices

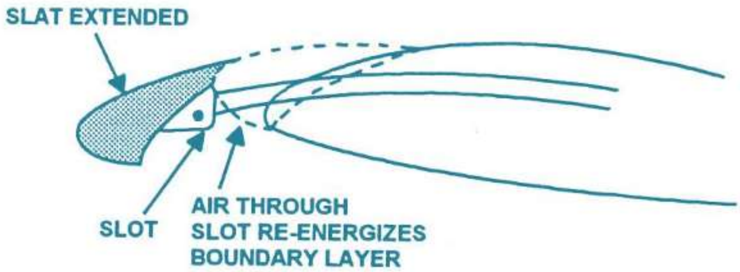
The requirement for leading edge devices is to cause an increase in velocity of the airflow over the upper surface of the aerofoil in order to delay separation of the boundary layer. The result of this delayed separation allows an increase in stalling angle of attack, which allows the centre of pressure (CP) to move further forward towards the leading edge, increasing the lift at lower forward airspeeds and giving the aircraft a nose up pitching effect.
The devices used to achieve this are:
- Leading edge slats.
- Leading edge flaps.

2.44 Leading Edge Slats

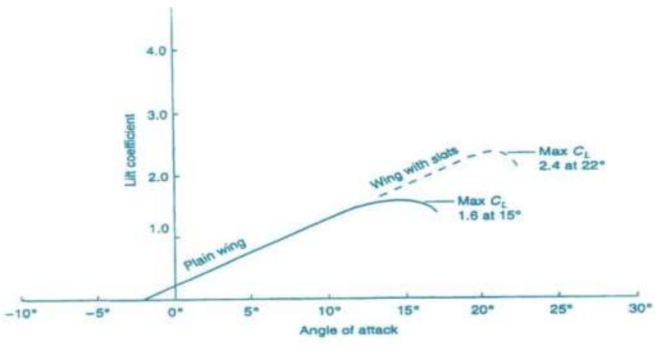
Slats are small auxiliary aerofoils attached along the leading edge of the wing.



When selected the slat extends to form a slot between the slat and the leading edge upper surface of the wings. This allows air to pass through the slot from the high- pressure area under the wing into the low-pressure area above the wing, thereby accelerating the flow by the venturi effect, re-energising the boundarylayer.



The re-energised boundary layer over the front part of the wing helps maintains a smooth flow of air over the upper surface, delaying the transition from laminar to turbulent and pushing back the separation point. This will substantially increase the coefficient of lift (C_L) and delaying the stall to a much higher angle of attack.



When the slat is closed (retracted) the slot is closed and the slat forms the leading edge of the wing.

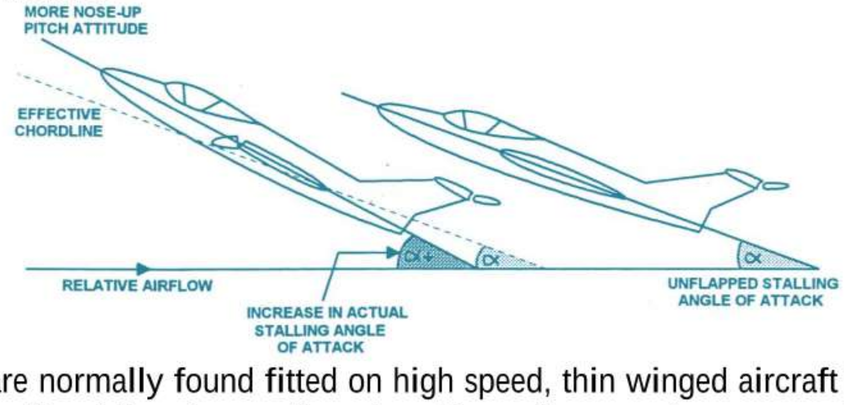
TYPES OF SLOTS

Although there is a large variety of high-lift devices nearly all of them can be classed as slots.
Slots may be subdivided into -
i. Fixed slots
ii. Controlled slots
iii. Automatic slots
iv. Blown slots
The extra lift enables us to obtain a lower landing or stalling speed, and this was the original idea. If the slots are permanently open, i.e. fixed slots, the extra drag at high speed is a disadvantage, so most slots in commercial use are controlled slots, that is to say, the slat is moved backwards and forwards by a control mechanism; and so can be closed for high-speed flight and opened for low speeds. In the early days experiments were made which revealed that, if left to itself, the slat would move forward of its own accord. So automatic slots came into their own; in these the slat is moved by the action of air pressure, i.e. by making use of that forward and upward suction near the leading edge. shows how the force on the slat inclines forward as the stalling angle is reached. The opening of the slot may be delayed or hastened by 'vents' at the trailing or leading edge of the slat respectively and there may be some kind of spring or tensioning device to prevent juddering, which may be otherwise likely to occur.

Before leaving the subject of slots - for the time being, at any rate - there are a couple of interesting points which may be worth mentioning. Firstly, the value of the slot in maintaining a smooth airflow over the top surface of the wing can be materially enhanced by blowing air through the gap between slat and wing; this may be called a blown slot. Secondly, what might be called the 'slot idea' may be extended to other parts of the aircraft. Specially shaped cowlings can be used to smooth the airflow over an engine, and fillets may be used at exposed joints, and other awkward places, to prevent the airflow from becoming turbulent.

2.45 Leading Edge Flaps

Leading edge flaps like slats are used to improve the lifting capability of the wing at low airspeeds, but unlike slats they do not create a slot when they are lowered.
The effect of deploying a leading edge flap increases the stalling angle of attack by changing the effective chord line against the relative airflow that increases the camber of the wing and its coefficient of lift, generating more lift over the front part of the wing, allowing the aircraft to pitch more nose up before it stalls.

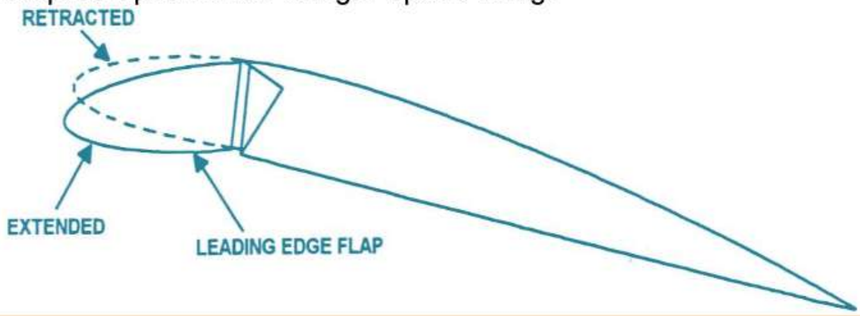


Leading edge flaps are normally found fitted on high speed, thin winged aircraft instead of slats, due to the thickness or profile of the wing, as they do not have the room to accommodate the mechanisms required for the installation of leading edge slats.
The main types of leading edge flaps are:

- Drooped leading edges.
- Krueger flaps.

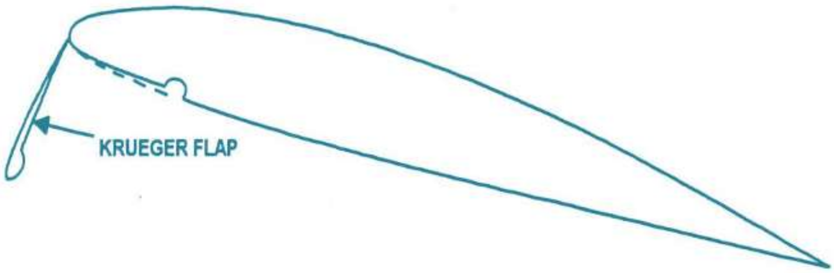
2.46 Drooped Leading Edges:

Drooped leading edge flaps normally cover the complete span of the leading edge and are lowered to increase the camber when the aircraft is approaching its stalling angle. At high speeds the flap is retracted to give the required profile for a high- speed wing.



2.47 Krueger flaps

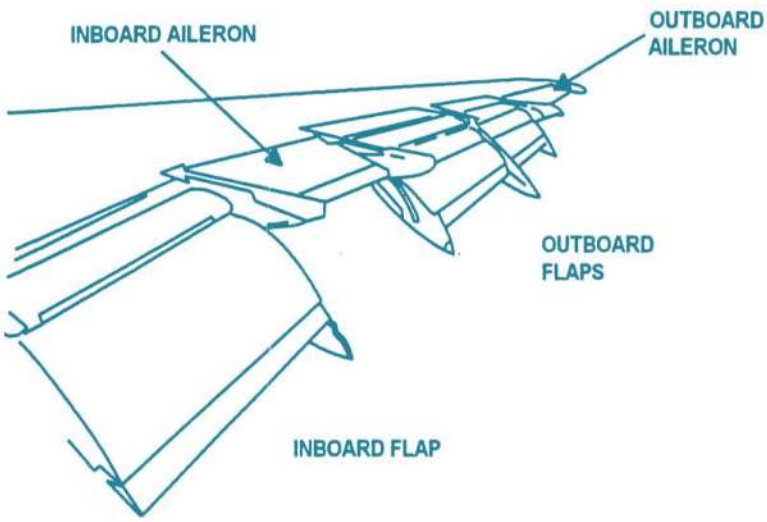
Krueger flap are similar to drooped leading edges in that when they are lowered they change the camber over that section of the wing. Unlike leading edge flaps, Krueger flaps do not normally extend the length of the leading edge but are fitted in certain sections. When retracted a Krueger flap form part of the under wingsurface.



2.48 Trailing Edge Devices:

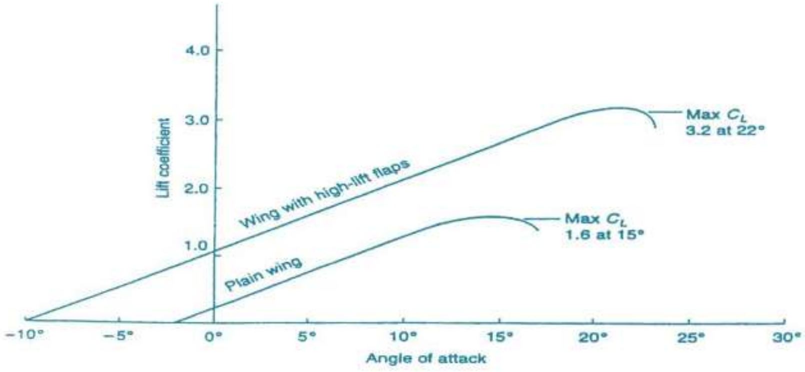
The trailing edge devices used to increase the lift over the wing are known as trailing edge flaps. These devises like leading edge flaps increase the camber of the wing when deployed, by changing the effective chord line.

The actual position of trailing edge flaps on an aircraft, is determined by the positioning of other control surfaces along the trailing edge, but will normally be positioned at the root of the wing, or split between the root and the centre section where the majority of the lift of the wing is generated.



On deployment, trailing edge flaps will increase the lift coefficient but will also increase the drag

coefficient, so are normally deployed in stages. Small-scale deployment at take- off and climb out, where at low speed they provide extra camber giving a small increase in the coefficient of lift, that is greater than the increase in the coefficient of drag. On landing, trailing edge flaps are fully deployed to give a large increase in the maximum coefficient in lift but also increases the drag, which helps retard the aircraft to shorten the landing distance.
To maintain level flight when flaps are fully deployed, the increase in drag is balanced by increasing engine thrust.



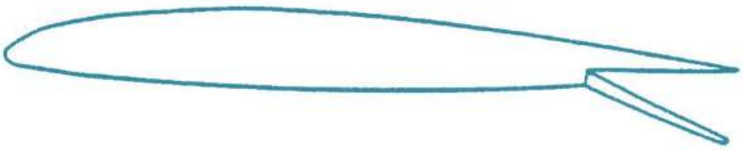
Types of trailing edge flaps:

2.49 Plain flaps

Plain flaps are hinged to rear of the wing, but unlike flying control surfaces they only normally move downwards. In common with all flaps they are fitted inboard at the root of the wings and both port and starboard flaps move symmetrically at the rate to avoid producing a rolling moment.

2.50 Split flap

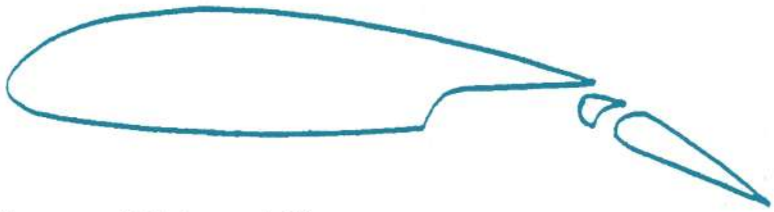
On a split flap only the lower aerofoil surface is hinged. The protrusion of the flap into the airflow causes the air to flow over the top surface at an increased velocity. Although split flap present some structural problems, these flaps are useful as there is very little movement of the centre of pressure when they are deployed.



2.51 Extension Flaps

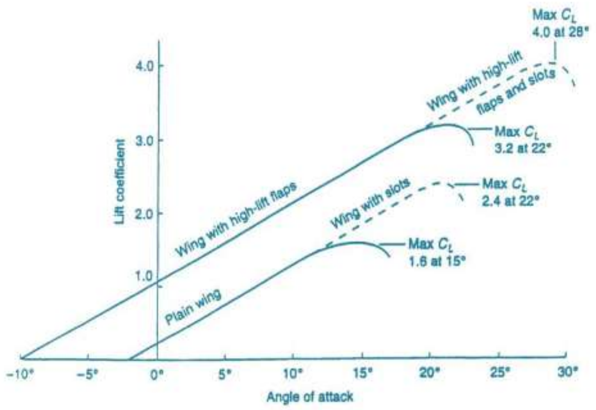
There are a number of variations of this type of flap, from a single extension flap to a flap with up to three extending elements. Extension flaps also commonly known as Fowler flaps expose slots when they are lowered, which accelerates the air over the upper surface of the extended flap segments to delay separation.
With extension flaps, not only is the coefficient of lift directly increased by the increase in camber and angle of attack, but the wing area is also increased which increases the overall lift.
A drawback with deploying extension flaps is that by increasing the wing area, the centre of pressure moves rearwards tending to give the aircraft a nose down pitching moment, which would require greater rearward movement of the control column on take- off and greater sensitivity by the pilot on landing.

To prevent this happening in most aircraft an input to the pitch trim system, either mechanical or electrical, is a standard feature, which adjust the pitch of the aircraft accordingly as the extension flap is deployed.

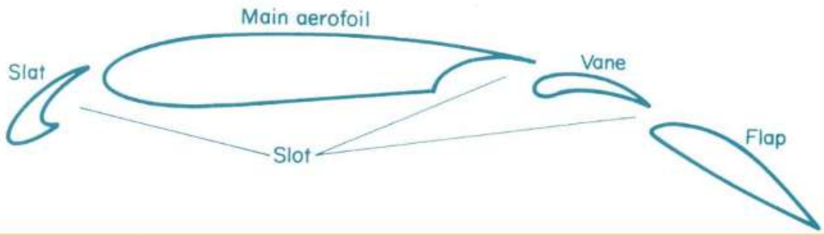


2.52 Combination of Flaps and Slats on Lift

The ultimate system, which can result in an increase in the lift coefficient of as much as 120% on that part of the wing to which they are fitted is a combination of slotted extension flaps and leading edge slats.



Deploying a combined system can also prevent a pronounced nose- up or nose-down attitude that occurs when deploying either slats or flaps alone. This is because as leading edge slats tend to move the centre of pressure forward and extension flaps the centre of pressure rewards. With careful design around any particular section therefore, as both these devices are extended, the movement of the centre of pressure can be reduced so that there are practically no adverse pitching moments in a critical phase of flight.



2.53 SECONDARY CONTROL SURFACES

Because aircraft often are capable of operating over a wide speed range and with different weight distributions, secondary flight controls, also called auxiliary flight controls, have been developed. Some of these surfaces called tabs, allow the flight controls. Other surfaces fall in a group termed high-lift devices which includes flaps, slats and slots. These allow the lift and drag characteristics of the aircraft wing to be changed to allow-slow speed flight for takeoff and landing and high-speed flight for cruising. Still a third group of surfaces are used to reduce lift and generate drag.

This group includes spoilers and speed brakes.

The number and complexity of the secondary control surfaces on a particular aircraft depends on the type of operation

and flight speeds for which the aircraft is designed.

Tabs

Tabs are small secondary flight control surfaces set into the trailing edges of the primary surfaces. These are used to reduce the pilot’s work load required to hold the aircraft in some constant attitude

by "loading" the control surface in a position to maintain the desired attitude. They may also be used to aid the pilot in returning a control surface to a
neutral or trimmed center position.

(i) Trim Tabs

The term trim tabs describes small secondary flight-control surfaces set into the trailing edges of the primary control surfaces. Tabs are used to reduce the work load required to hold the aircraft in some constant attitude by "loading"the control surface to a neutral or trimmed-center position. Tabs can be fixed or variable, and the variable tabs can be designed to operate in several different manners.

(i)a. Fixed Trim Tabs

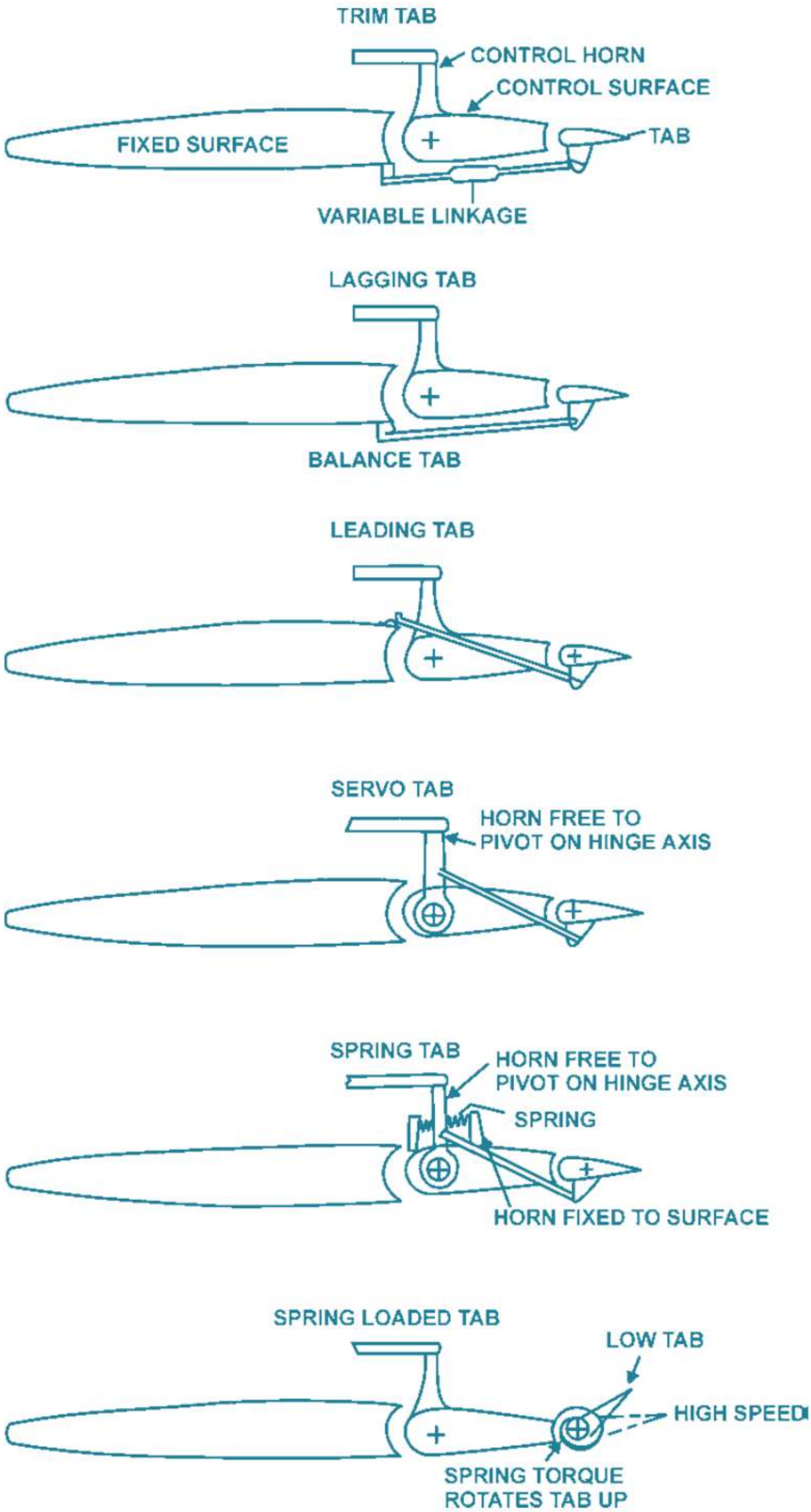
A fixed trim tab, is normally a piece of sheet metal attached to the trailing edge of a control surface. This fixed tab is adjusted on the ground by bending it in the appropriate direction to eliminate cabin flight control forces for a specific flight condition. The fixed tab is normally adjusted for zero control forces while in cruising flight. Adjustment of the tab is a trial and error process where the aircraft must be flown and the trim tab adjusted based on the pilot's report. The aircraft must then again be flown to see if further adjustment is necessary. Fixed tabs are normally found on light aircraft and are used to adjust rudders and ailerons.

(i)b. Controllable Trim Tabs

Controllable trim tabs are adjusted by means of control wheels, knobs, orcranks in the cockpit, and an indicator is supplied to denote the position of the tab. Controllable trim tabs are found on most aircraft with at least the elevator tab being controlled. These tabs are normally operated mechanically, electrically or hydraulically. When the trim-control system is activated, the trim tab is deflected in direction opposite to the desired movement of the control surface. When the trim tab is deflected into the airstream the air tries to push the tab back flush with the control surface. Since the control mechanism prevents the tab from being pushed back flush, the whole control surface is moved.

(ii) Servo Tabs

The servo tabs, sometimes referred to as the flight tabs, are used primarily on the large main control surfaces. A servo tab is one that is directly operated by the primary controls of the airplane. In response to movement of the cockpit control, only the servo tab moves. The force of the airflow on the servo tab then moves the primary control surface. The servo tab, , is used to reduce the effort required to move the controls on a large airplane.


TRIM TAB
CONTROL HORN
CONTROL SURFACE
FIXED SURFACE
TAB
VARIABLE LINKAGE
LAGGING TAB
BALANCE TAB
LEADING TAB
SERVO TAB
HORN FREE TO
PIVOT ON HINGE AXIS
SPRING TAB
HORN FREE TO
PIVOT ON HINGE AXIS
SPRING
HORN FIXED TO SURFACE
SPRING LOADED TAB
LOW TAB
HIGH SPEED
SPRING TORQUE
ROTATES TAB UP

(iii) Balance Tabs

A balance tab is linked to the airplane in such a manner that a movement of the main control surface will give an opposite movement to the tab. Thus, the balance tab will assist in moving the main control surface. Balance tabs are particularly useful in reducing the effort required to move the control surfaces of a large airplane.

(iv) Spring Tabs

The spring tabs, like some servo tabs, are usually found on large aircraft that require considerable force to move a control surface. The purpose of the spring tab is to provide a boost, thereby aiding in the movement of a control surface. On the spring tab the control horn is connected to the control surface by springs.

2.54 SPOILERS

Spoilers, also called "lift dumpers" are control surfaces which are used to reduce or "spoil" the lift on a wing. Spoilers are located on the upper surface of wings and are one of two basic configurations. The more common configuration on jet transports, is to have a flat panel spoiler laying flush with the surface of the wing and hinged at the forward edge.

When the spoilers are deployed, the surface rises up and reduces the lift. The other configuration shown in Fig is common among sailplanes and has the spoiler located inside the wing structure. When the spoilers are deployed they rise vertically form the wing and spoil the lift.

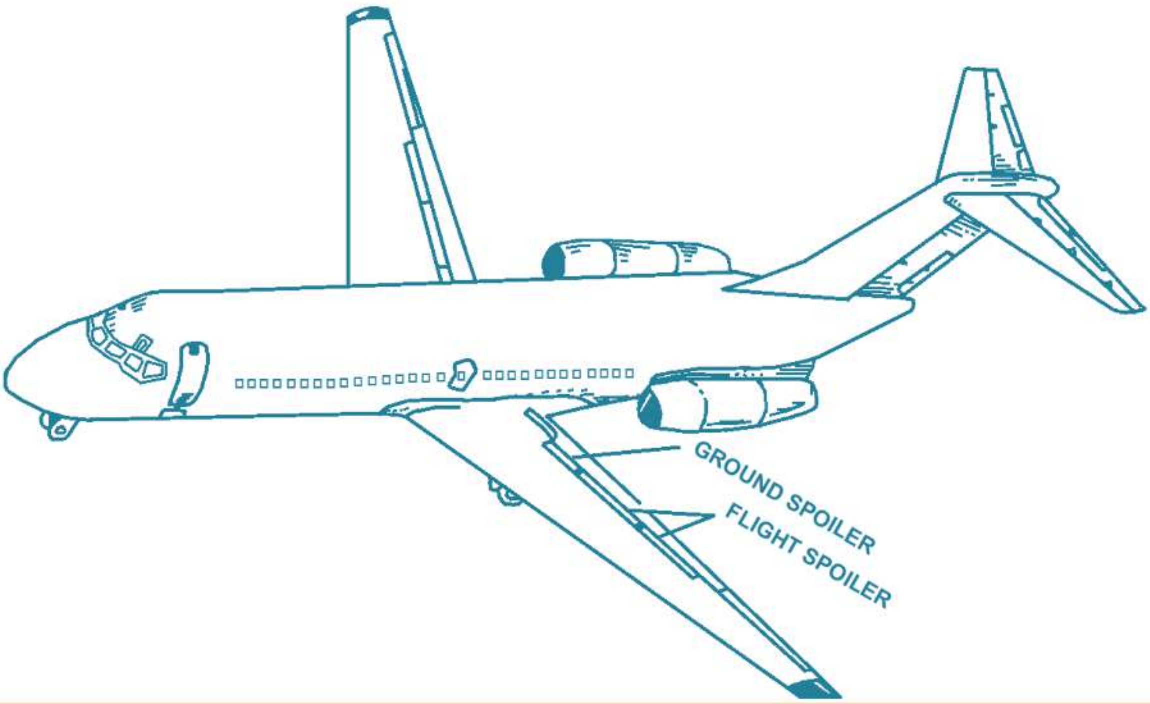
Flight spoilers are used in flight to reduce the amount of lift that the wing is generating to allow controlled descents without gaining excessive air speed. Depending on the aircraft design, the spoilers may also be operated by the pilot's control wheel or stick. When the pilot moves the control left or right for a roll movement, the spoilers on the wing toward the center of the turn (upward-moving aileron) move upward and aid in rolling the aircraft into the turn. In some aircraft
designs, the spoilers are the primary flight control for roll.

Some aircraft, such as sailplanes, have the spoilers arranged so that they rise vertically out of the wing.

Ground spoilers are only used when the aircraft is on the ground and are used along with the flight spoilers to greatly reduce the wing's lift upon landing. They also increase the aerodynamic drag of the aircraft's after landing to aid in slowing the aircraft.

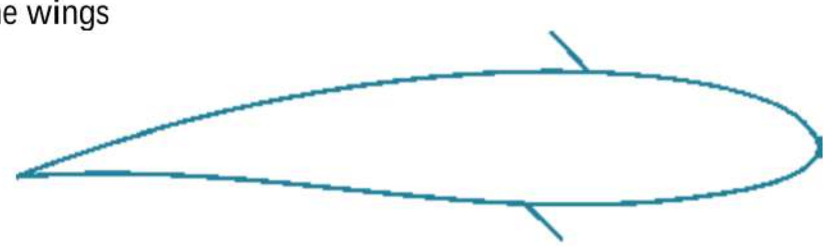
Spoilers can be controlled by the pilot through a manual control lever, by an automatic flight control system, or by an automatic system activated upon landing. The typical relative location of flight and ground spoilers are shown below.

Flight spoilers are normally located outboard of ground spoilers



Speed Brakes

Speed brakes, also called dive brakes, are large drag panels used to aid in control of the speed of an aircraft. They may be located on the fuselage or on the wings. If on the fuselage, a speed brake is located on the top or the bottom of the structure. If speed brakes are deployed as a pair, one is on each side of the fuselage. If located on the wings, speed brakes are deployed symmetrically from the top and the bottom of the wing surface to control the speed of the aircraft as well as to act as spoilers to decrease the lift of the wings



Speed brakes on a wing open on the top and bottom of the wing

On some aircraft designs, particularly gliders and sailplanes there may not be any clear distinction between a spoiler and a divebrake because one control surface may serve the purpose of both actions, i.e., to decrease lift and increase drag.

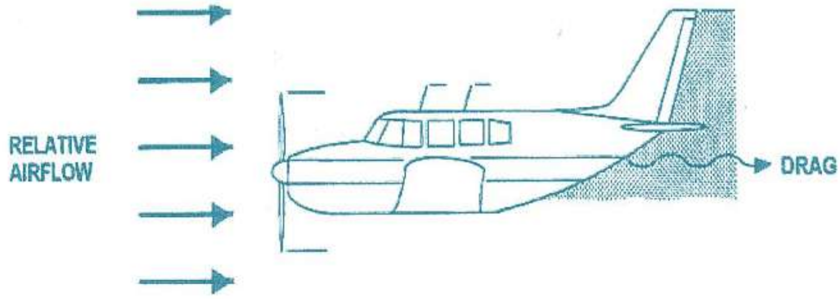
2.55 DRAG

Introduction

During the movement of aircraft through the air (ie flight), all parts of the aircraft exposed to the airflow will produce an aerodynamic force that opposes the forward motion of the aircraft.
This opposing force is known as DRAG, and it acts parallel to and in the same direction as the relative airflow (RAF).

Total Drag

For an aircraft in flight, drag is the resistance to forward motion that an aircraft experience as it moves through the air.



In steady level flight therefore, this resistance must be balanced by the thrust of the engine, so it

follows that for any given airspeed the lower the drag the less thrust is required to balance it.
Drag on an aircraft can therefore be considered as wasted energy, as the aircraft will have to expend thrust energy from the engines in order to overcome it. This makes aircraft that produce low levels of drag commercially attractive to aircraft operators, as the lower the drag, the lower is the amount of fuel used during a flight, so the cheaper it is to operate the aircraft.

2.56 Components of Total Drag:

In flight, the size of the drag that acts on an aircraft depends on a number of things including, shape, speed, type of manoeuvre etc. To help us understand what makes up the total drag on an aircraft it is usual and convenient to group these different components into categories so that total drag can be more easily studied and understood.
Some text books categorise the components of total drag as belonging to either one of two distinct groups, these being:

- Zero lift Drag, the drag produced when the aircraft is flying at the zero lift angle of attack.

And

- Lift dependent drag, the drag produced whenever an aircraft is producing lift. Other text books consider that the total drag is made up of either:

- Profile drag
- Induced drag
- Interference drag

In this course we will consider this latter grouping in explaining total drag, indicating which of the components make up either zero lift or lift dependent drag.

2.57 Profile Drag

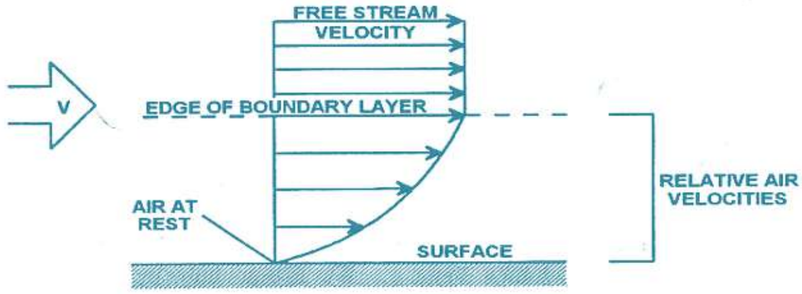
As an aircraft moves through the air, the amount of drag it creates depends upon on how easily the air moves around it. The shape or profile therefore, that an aircraft presents to the oncoming airflow is important as it influences the way the air moves around and will be a major factor in determining the amount of drag created.
The amount of profile drag created when the aircraft is flying at the zero lift angle of attack is also known as zero lift drag.
For an aircraft in flight, profile drag can be broken down into two forms of drag:

- Form drag
- Skin friction drag

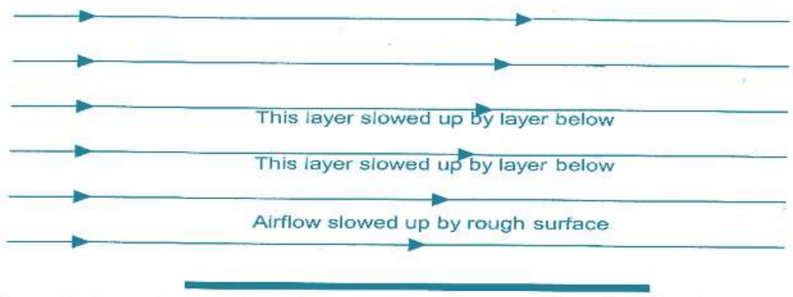
Before considering the makeup of profile drag in detail however, it is important to firstly consider the layers of air closest to the surface, known as the Boundary Layer. This is because it is the conditions of the air within the boundary layer that produces profile drag.

2.58 Boundary layer

In the boundary layer, as an airflow passes over aircraft and the wing in particular, it slows down due to the roughness of the surface and the viscous properties of the air itself. For the particles of air that are directly adjacent to the surface of the wing, viscous adhesion will adhere the air to the surface reducing its relative velocity to zero.



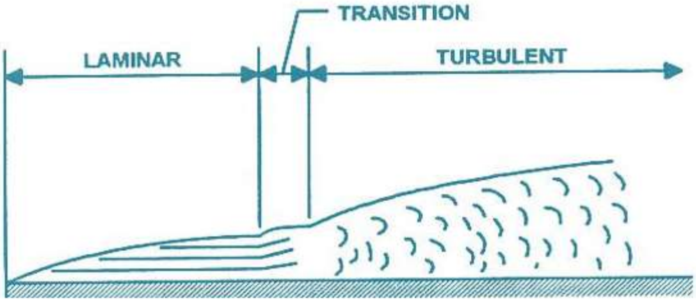
For other streamlines of air slightly further away from the surface, only the viscosity between different layers of air particles will cause the air to slow down, so it will not bring the air completely to rest. This means that the further away from the surface, subsequent layers of air will be slowed down but by lesser amounts.



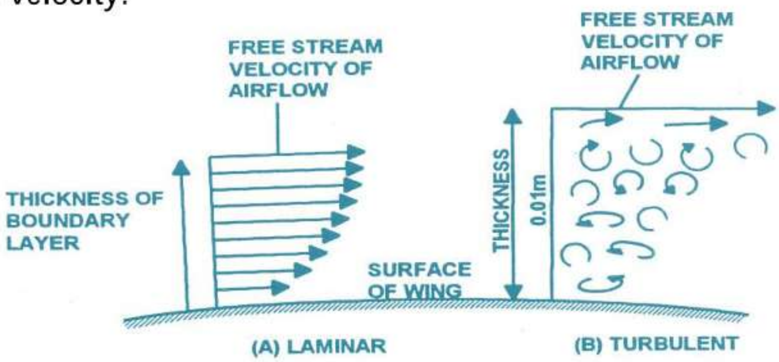
The velocities of the air within a boundary layer therefore, vary the further away the airflow is from the surface. The extent of the boundary layer being defined as the region of airflow flow in which the speed of the airflow is below 99% of the free stream velocity.

Conditions within the Boundary Layer

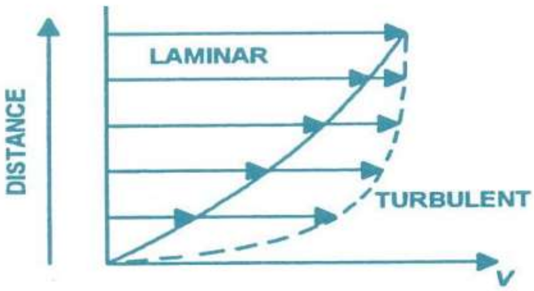
Within the boundary layer, the normal conditions are a mixture of both laminar and turbulent airflow. The usual tendency is for it to start by being laminar at the leading edge and then become turbulent as it passes over the wing, the change from laminar to turbulent airflow taking place in the transition region over the wing, at a point known as the transition point.



The thickness of the boundary layer is however, comparatively small only being about 10 mm in depth, starting from zero at the leading edge and increasing in thickness as it moves rearwards over the aircraft wing. After its transition to turbulent airflow the boundary layer thickens and grows at a more rapid rate, growing to approximately 10 times the thickness of the laminar boundary layer under the same free stream velocity.



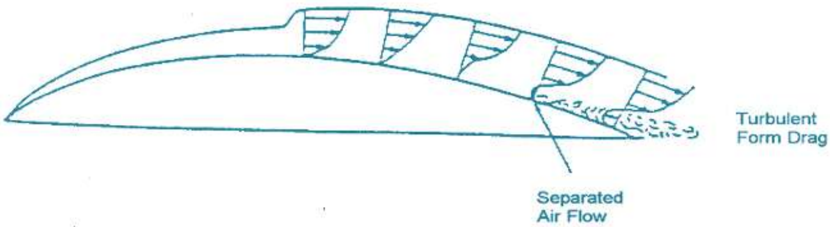
After the air becomes turbulent, as the airflow no longer follows an orderly pattern, its velocity increases as the air is constantly changing direction.

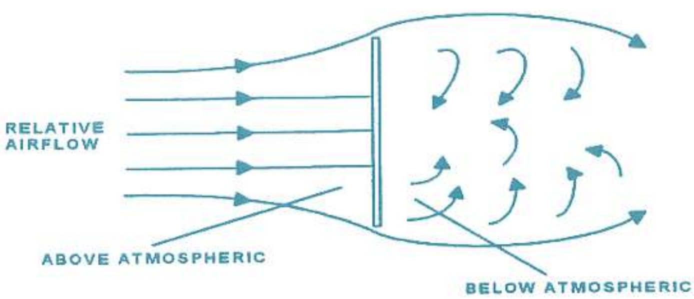


The kinetic energy therefore, of the airflow in the turbulent region is higher than in the laminar region at the same distance from the surface. This fact is extremely important, as the increased energy of the turbulent air will help delay separation over the wing by overcoming the adverse pressure gradient.

2.59 Form Drag

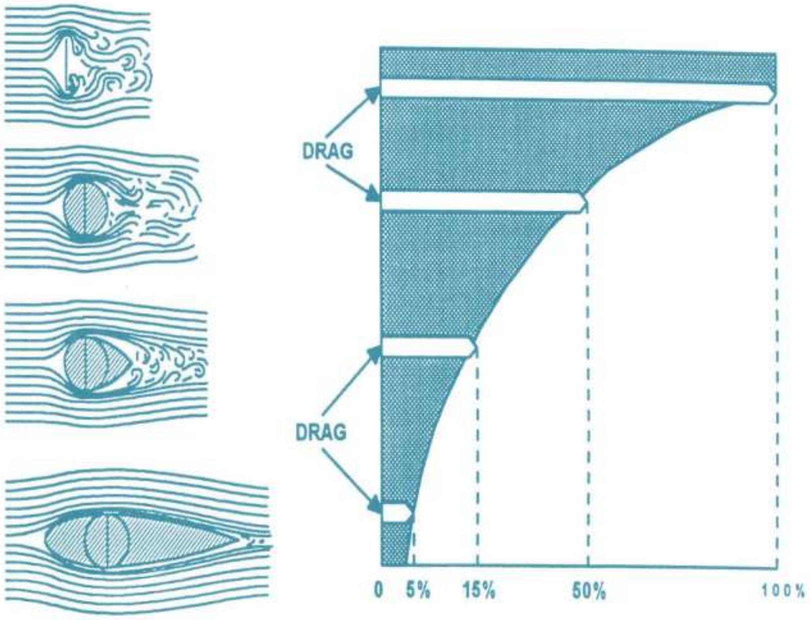
Form drag is the drag produced whenever the airflow that is passing over an object separates away from the surface becoming heavily turbulent. The separated flow behind the object producing a reduction in pressure that tries to pull the object back.
An extreme example of separated airflow and form drag can be seen when a flat plate is placed at right angle to the airflow.



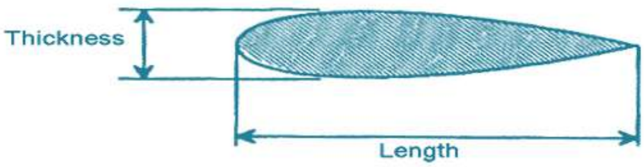


The pressure immediately in front of the plate is above atmospheric pressure, due to the formation of stagnation points, whilst behind the plate the pressure will be below atmospheric due to the formation

of vortices. This results in a sucking effect behind the plate pulling it backwards.
To reduce the amount of form drag produced by an airflow passing over an object therefore, it is necessary to make it less flat plate than the example above by streamlining. This reduces the rapid change of direction an airflow undergoes as it passes over an object, so that it stays attached longer delaying separation and reducing the amount of form drag produced.

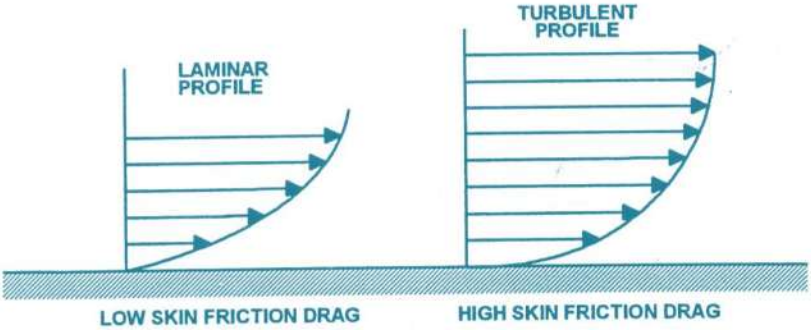


As can be seen from the above diagram, the amount of form drag reduces quite drastically when aerodynamic fairings are fitted to both the back and front of an object as it reduces the amount of separation. This increase of the length of the object to its thickness is known as the fineness ratio of an object and for a general-purpose aerofoil, that is travelling at low subsonic speed it will produce the least amount of form drag when an object has a fineness ratio of around 4.
1. This figure however can vary between higher speed wing designs without increasing the drag to any great extent.



2.60 Skin Friction Drag

The skin friction or skin friction drag of an aircraft is the drag associated with the retardation of air within the boundary layer, as the retarded air will try to drag the surface along with it In practice the extent of retardation and skin friction drag depends on the rate at which air adjacent to the surface is trying to slide relative to it. This produces a shear stress between adjacent air particles, which is directly proportional to the speed of the airflow. So the gradual velocity change associated with laminar airflow will produce a low shear stress near the surface that results in low skin friction drag. Whereas the rapid velocity change associated with turbulent boundary airflow will produce a high skin friction drag. It follows then that forward movement of the transition point increases the size of the turbulent region over the wing and increases the skin friction drag.



The viscous drag force between streamlines within the boundary layer are not sensitive to pressure and density variation and is therefore is unaffected by the variations in pressure at right angles (normal) to the surface of the body. Viscous drag forces are however, sensitive to temperature changes as the viscosity of a gas varies directly with temperature and will therefore increase and decrease with changes in altitude. The more viscous the air becomes the greater the retardation will be in the boundary layer, so the greater the skin friction drag.

Other factors Affecting Skin Friction Drag

Others factors that will affect the amount of skin friction over an aerofoil are:

- Surface condition and size of area.
- Forward speed of the aircraft.

2.61 Surface area

The size of the surface area will have an effect on the amount of skin friction drag produced, as the whole of the aircraft inflight will have an airflow passing over it, so each part the airflow touches will produce a boundary layer. It follows then, that by increasing the surface area of an aircraft it will increase the amount of boundary layer over the aircraft and produce a greater amount of skin friction drag.

The condition of the surface area will also have an effect on the amount of skin friction drag produced, as the laminar layer near the front of the aircraft is extremely sensitive to surface irregularities. Irregularities over the wing such as damage or contamination, which alter the smooth flow over the wing, will bring about an earlier or premature transition point increasing the amount of turbulent flow and skin friction drag.

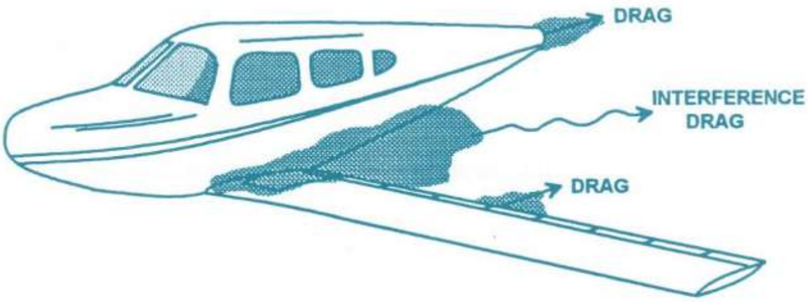
It should also be noted that contamination by ice, snow or frost, would not only result in an increased drag but also an increase in weight that requires an increased lift in order to maintain level flight.

2.62 Effect of Forward Speed on Skin Friction Drag

The effect of changing the forward speed of an aircraft affects the amount of skin friction drag produced, as an increase in the relative speed of the airflow over a wing will cause the airflow to change from laminar to turbulent at an earlier point. As this will cause a greater part of the aerofoil to be covered in turbulent airflow, it follows then that the skin friction drag will be greater.

2.63 Interference Drag

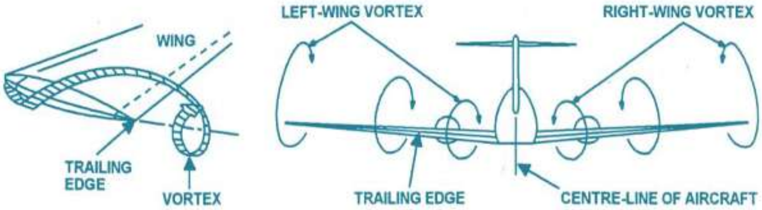
For an aircraft flying in level flight, the total drag acting on the aircraft is often found to be greater than the sum of the profile drag of individual components. This occurs because airflow over the aircraft is disturbed where various components are joined together, particularly between the wing and



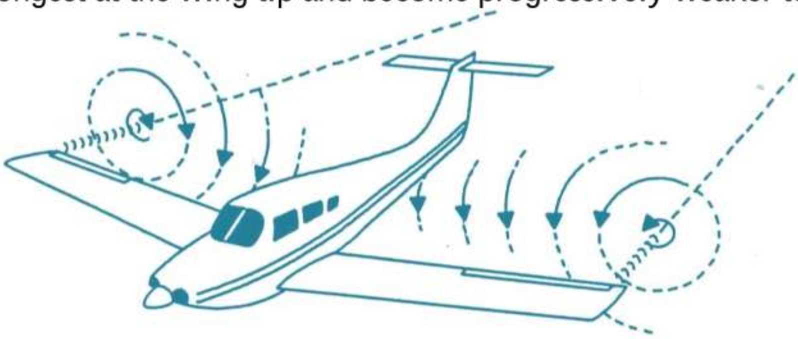
the fuselage. The disturbance leads to a modification of the boundary layers, either turning the local flow turbulent or causing local separation which produces additional drag known as Interference drag. For subsonic flight, the interference drag and total drag can be reduced by the addition of fairing or fillets, which smooth out the airflow.

2.64 Induced Drag

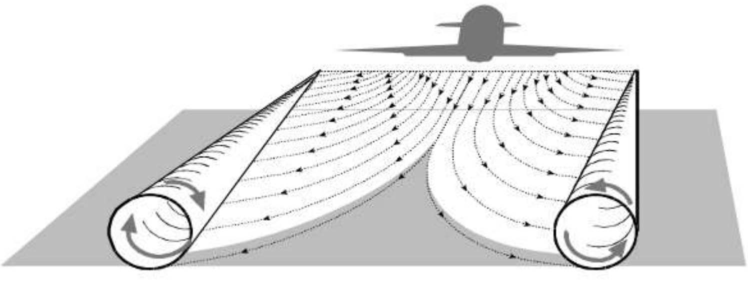
Whenever a wing is producing lift, a pressure differential exists between the upper and lower surfaces that will produce a spanwise flow and concentrated vortices at the extremities of the wing as air tries to flow from the lower to upper surfaces.



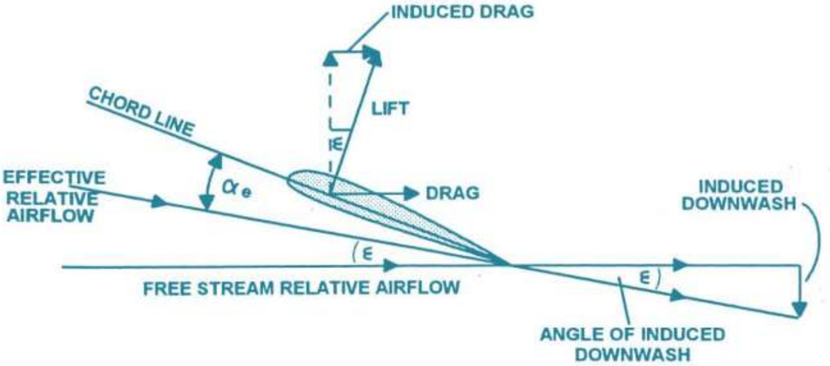
These vortices are strongest at the wing tip and become progressively weaker towards the centre line.



Behind the wing, the wing tip vortices induce a downwash to the airflow, which deflects the relative airflow down away from the horizontal through an angle known as the angle of induced downwash (ε).



This deflection of air behind the wing influences the relative airflow of the air approaching the wing deflecting it upwards by the same angle (ε). This in effect reduces the angle of attack on the wing reducing the overall lift, as the lift, which acts perpendicular to the local relative airflow, is tilted rearwards. To recover the lost lift, due to vortice formation, the angle of attack must be increased to increase the lift, which will increase the drag on the aircraft.

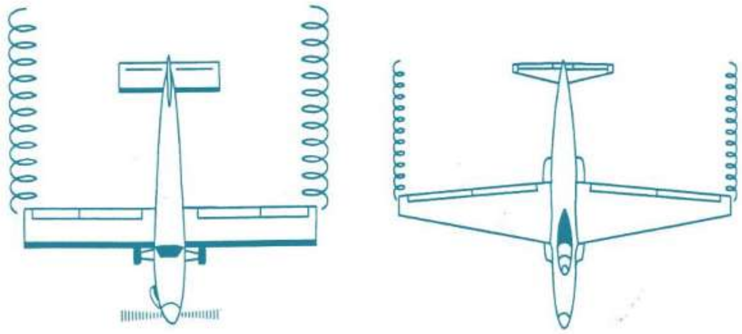


It follows then that the larger the vortex the greater the induced drag.
Factors Affecting Induced Drag
The main factors that affect vortex formation and therefore induced drag are:

- Wing plan form.
- Aspect ratio.
- Weight and speed.

2.65 Wing Plan form

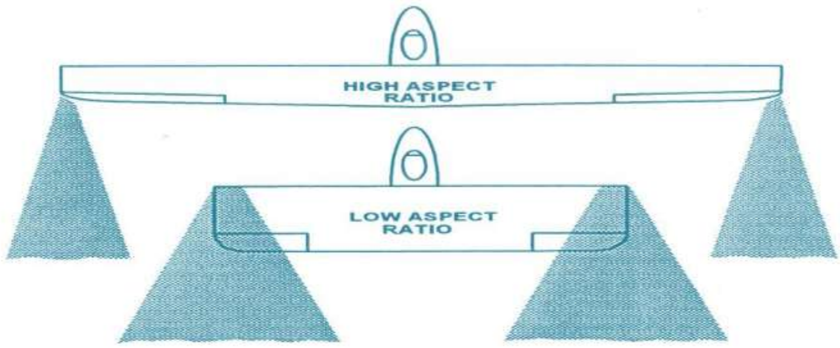
Wing plan form is the one of the principal factors affecting induced drag, as the size of the wing tip chord length directly affects the size of wing tip vortex. A rectangular planform with a large cord length at the wingtip will allow more air to flow from the lower to upper surface producing much larger vortices than a tapered one. So tapering a wing towards the tip it reduces the amount of air



flowing from the lower surface to the upper surface thereby reducing the size of wing tip vortices.
An elliptical planform has unique properties, as the downwash remains constant across the complete wingspan, but this type of wing gives manufacturing and structural difficulties so is not a design commonly used in modern commercial aircraft. A good compromise that maintains the aerodynamic efficiency as close as possible to the properties of an elliptical wing, is a straight tapered wing that is tailored by wing twist and section variation. This type of wing is the design found used in most modern commercial aircraft.

2.66 Aspect Ratio (AR) and Induced Drag

As discussed earlier,the aspect ratio of a wing is the ratio of its wingspan to its chord length and has an affect the amount of induced drag produced, as the higher this ratio is (the longer the wingspan is) the lower will be the pressure differential at the wing tips. This occurs because on a longer wing the spanwise pressure differential between the upper and lower surfaces can even each other out.



In fact, induced drag is inversely proportional to the aspect ratio, eg. if Aspect Ratio (AR) is doubled then induced drag is halved.

2.67 Weight , Speed and Induced Drag

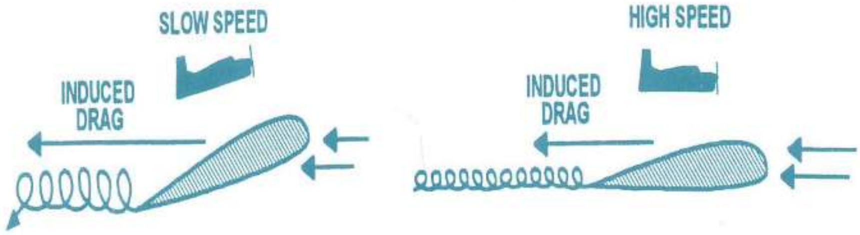
The weight and speed of an aircraft affects the amount of induced drag produced as both factors affect the amount of lift produced.

For an aircraft flying in level flight the amount of lift produced can be calculated from the formula.

$C_L = \frac{1}{2} \rho V^2 \times S$

It can be seen therefore that if the original speed is halved, then the dynamic pressure ($\frac{1}{2} \rho V^2$) of the formula will be reduced by four times. So to restore the lift required and maintain level flight, the coefficient of lift C_L must be increased four-fold by increasing the angle of attack. This however, increases the spanwise flow around the wing tips and the size of the wing tip vortices.

In level flight therefore, the size of the wing tip vortices and induced drag will be most significant at

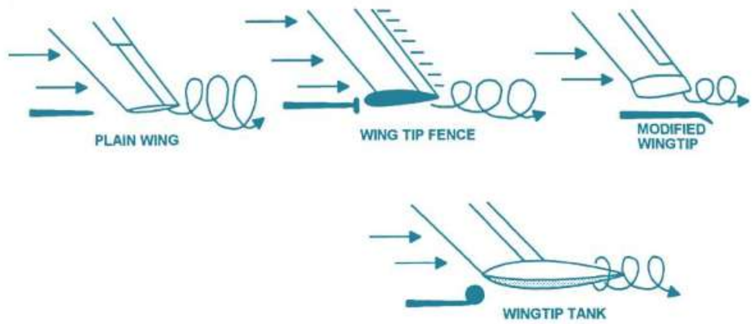


low speed where a high angle of attack must be used. Conversely at higher speed the size of the vortices and induced drag will be least, as to maintain the same level flight, the angle of attack must be reduced. Induced drag therefore is inversely proportional to the square of the speed.

It also follows, that for any given airspeed any increase in C_L that increases the overall lift eg during manoeuvres or due to weight increase will also increase the amount of induced drag.

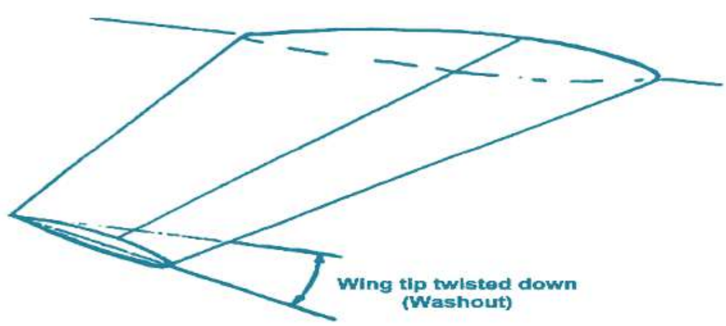
2.68 Methods of Reducing Induced Drag

In practice as induced drag is due to the formation of vortices at the wing tips, it is therefore advantageous to reduce this by using various design features like tapering the wing planform as above. Other methods include washout or wing tips modifications to minimize the size of wing tip vortices.



Washout

Washout is the twisting of the wing during manufacture so that the inboard sections of the wing at the wing root are at a higher angle of attack than that of the wingtip.



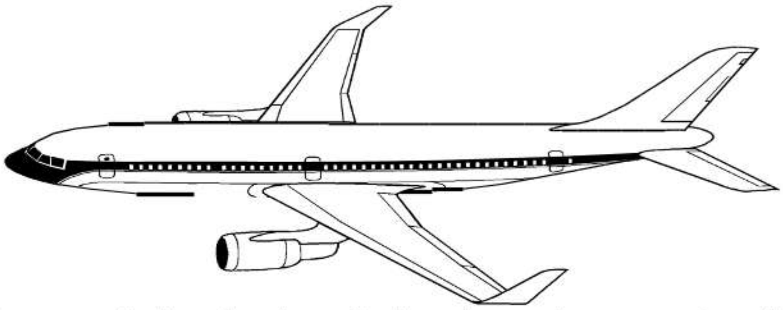
This allows the predominance of lift to be generated on the inner part of the wing minimising the pressure differential and leakage of airflow around the wing tip, reducing the size of the vortices when lift is being generated. Wash out design is normally incorporated in high swept wings.

2.69 Wing Tip Modification

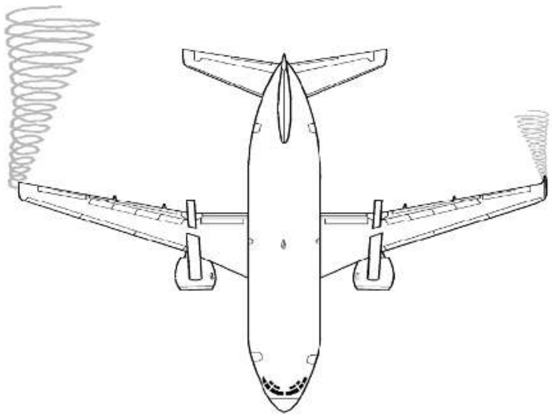
Another way the size of wing tip vortices and induced drag can be reduced is for the wingtips on the aircraft to be redesigning to include wing tip devices.

These devices reduce the flow of air from the lower to upper surface of the wing reducing the size of wingtip vortices and downwash behind the wing, which reduces the induced drag for a given angle of attack.

In a modern aircraft the most effective method of reducing induced drag is the introduction of winglets or blended wing tips.



These devices in addition to reducing the size of wing tip vortices, can also aid stability and in some designs increase the performance of the aircraft by producing additional lift and thrust.



2.70 Drag Curves

For an aircraft in level flight, if the interference drag is considered as part of the profile drag, since it is due to the design and shape, then the total drag acting on the aircraft can be considered as a mixture of profile and induced drag.

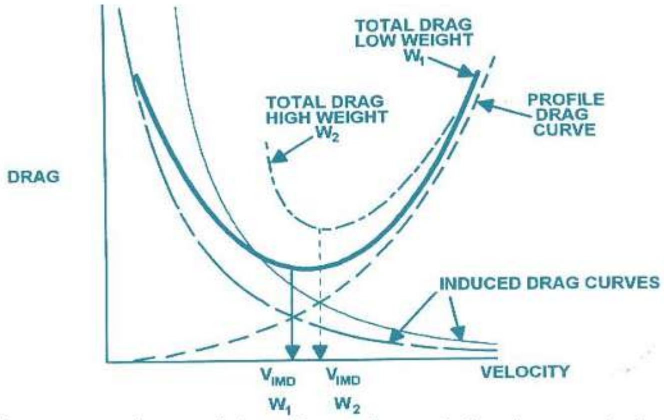
By plotting these two drags on the same axes of a graph, it is possible to establish a relationship between them, where the total drag can be found at any velocity by adding the two drags together.

The graph shows that the total drag on an aircraft becomes a minimum when the profile drag equals the induced drag. This point is known as the point of minimum drag and occurs at a velocity known as the indicated minimum drag speed (VIMD).

In flight therefore, as this speed will produce the minimum amount of drag it is also the normal cruising speed, as it is the most economical speed at which the aircraft can fly. The graph however, is only valid for an aircraft of constant weight and configuration, since altering the weight or configuration will change the amount of lift and drag produced, so for a new weight or configuration a new graph must be drawn.

For example in level flight at a certain height, as the lift produced must be equal the weight, if the weight is increased, then the lift requirements of the heavier aircraft will also be increased.

In level flight as this can only be achieved by either changing the angle of attack, or by increasing the speed of the aircraft, either the profile or induced drag will increase. As this will change the drag curve, a new drag curve must be drawn which will show that the lowest drag will occur by an



increase in speed. So whenever the weight of an aircraft is changed the minimum drag speed (VIMD) will change

Like lift the actual drag of an aircraft will depend on the following factors:

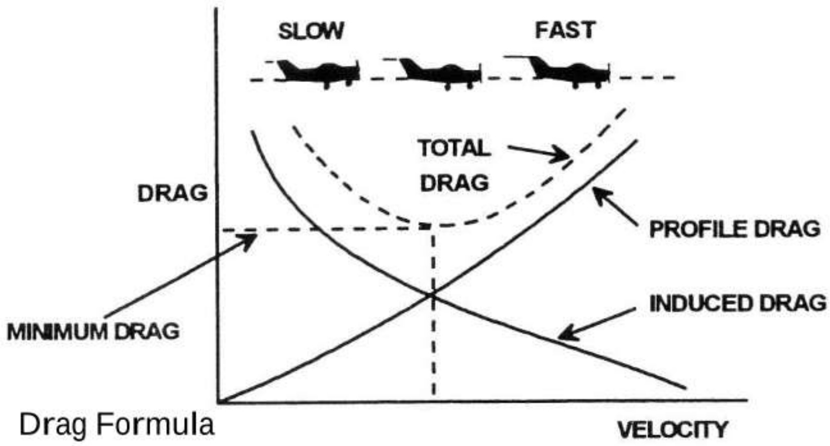
- AOA.
- Shape of wing and planform.

The general drag formula is therefore given as:

- Condition of wing surface.
- Reynolds' No.

Drag = $C_D \frac{1}{2} \rho V^2 S$

- Speed of Sound(Mach).
- Air density(ρ).
- Free stream air velocity squared(V^2).
- Surface wing area(S).



Drag Formula

But having to take all these factors into account each time would make drag calculations complicated. The drag equation like the lift equation therefore can be simplified by grouping different factors together.

As already established, the factors of density and velocity can be grouped together as dynamic pressure ($\frac{1}{2} \rho V^2$) that when combined with the surface area (S) will give a basic force. As this force will be the basic force opposing forward motion it will not give an exact value, as the total drag will vary the rest of the factors above.

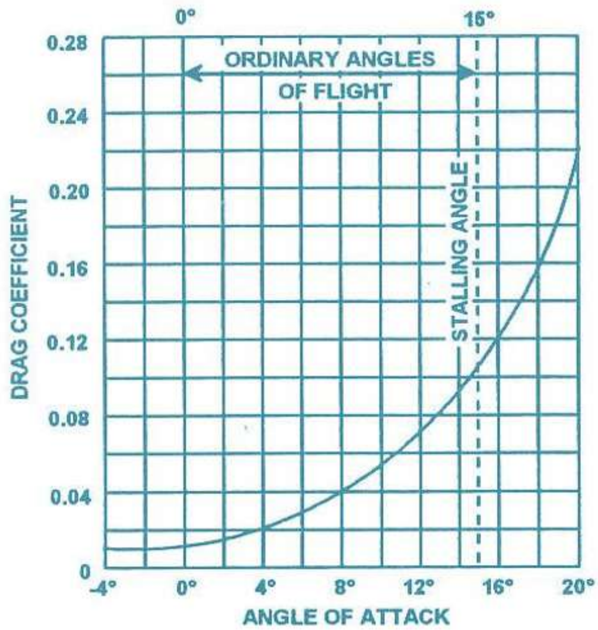
Again as with lift, the other factors are:

- AOA.
- Shape of wing and planform.
- Condition of wing surface.
- Reynolds' No.
- Speed of Sound (Mach No).

These therefore can be grouped together and represented by a single coefficient, known as the coefficient of drag (C_D).

2.71 Variation of C_D with angle of attack

In level flight at constant speed as dynamic pressure and wing area will remain the same, the increase in drag will occur due to changes in the angle of attack. It is therefore possible to establish a relationship between changes in the angle of attack and the drag coefficient (C_D). In plotting the angle of attack against the coefficient of drag (C_D) we produce what is known as the dragcurve.



2.72 Lift/Drag Ratio

Introduction

As already established for an aircraft in flight, drag will occur whenever an aircraft is producing lift. So, to determine an aircraft's efficiency in flight, it is necessary to consider the amount of lift produced compared to its drag.

2.73 Comparison of Lift to Drag

The actual values of lift and drag that an aircraft produces at any one point in flight can be calculated using the two formulas of the lift and drag.

Lift = $C_L \frac{1}{2} \rho V^2 S$ and Drag = $C_D \frac{1}{2} \rho V^2 S$

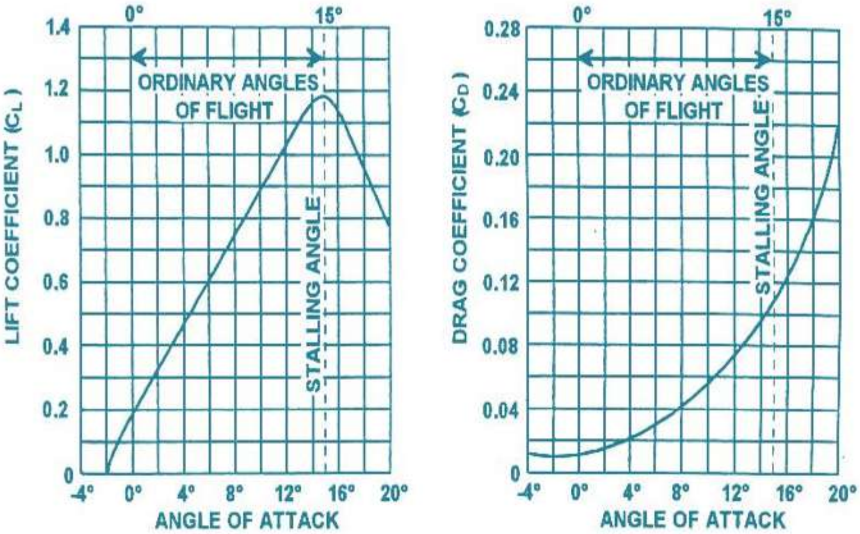
This means that the efficiency of the aircraft at that point could be found by dividing the lift force by the drag force.

Lift/Drag=C_L/C_D

This is known as the lift/drag ratio of an aircraft and can be simplified by cancelling out the factors $\frac{1}{2} \rho V^2 S$, since they are common to both.

2.74 Variation of Lift/Drag Ratio with Angle of Attack

As the lift/drag ratio, is the ratio between the coefficients of lift and drag. Variations of the lift/drag ratio will occur in flight whenever there is a change in the angle of attack, since both coefficients vary as the angle of attack changes.



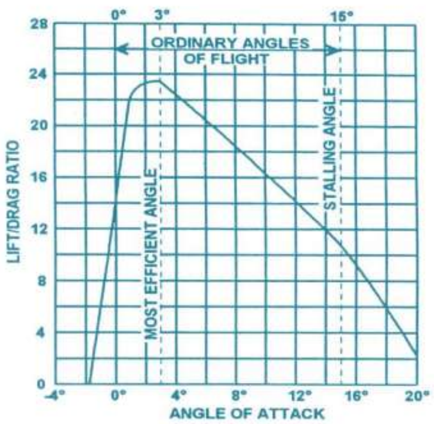
For maximum efficiency therefore, an aircraft should produce the greatest amount of lift when it is producing its least amount of drag ie its best lift/drag ratio.

Examination of the lift curve shows that maximum lift will occur about 15° angle of attack, where as the drag curve shows that the minimum drag will occur at an angle of attack of approximately-2°.

Calculating the amount actual lift to drag at either of these extremes however produces a low lift/drag ratio. As at the point of minimum drag (-2° AOA) not enough lift is being produced and at the point of highest lift figure (15° AOA) too much drag is beingproduced.

The highest lift/drag ratio and the most efficient angle of attack to fly the aircraft, is found by comparing the two curves of lift and drag together. This is known as the lift/drag ratio against angle of attack.

This graph shows that the lift/drag ratio increases rapidly up to about 3 or 4°angle of attack, at which



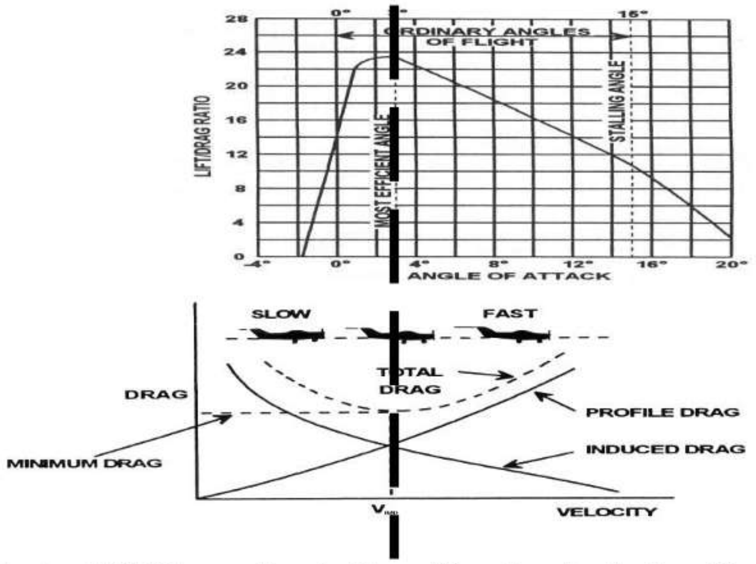
point the lift is nearly 24 times the drag. The exact figure being dependent on the type of aerofoil used, but for most asymmetrical wings it is about 4°. At larger angle of attack the lift/ drag ratio will steadily decreases, because even though the amount of lift being produced continues to increase, the drag at a higher angle of attack will be increasing at a greater rate.

2.75 Best All-Round Performance of an Aircraft

The best all round performance of an aircraft is found when an aircraft produces the greatest amount of lift to the lowest amount of drag ie its highest lift/drag ratio, which in most cases are about 3 or 4°angle of attack.

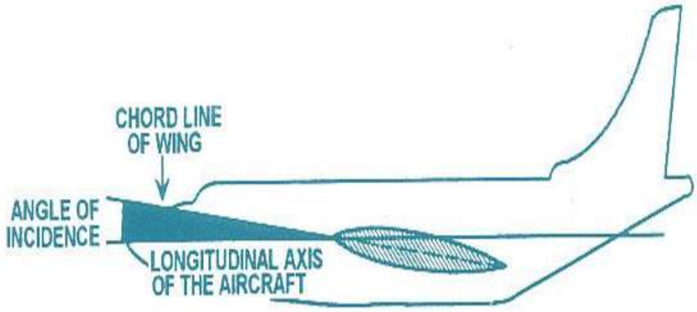
In establishing the minimum amount of drag an aircraft produces, in the previous drag chapter it was established that for a given amount of lift, minimum drag was achieved at the minimum drag speed (VIMD).

In level flight, the minimum drag speed can therefore be related to the angle of attack, as low angles of attack are associated with high airspeed and high angles of attack are associated with low



airspeeds. So, the best lift/drag ratio, ie 3 or 4°angle of attack will occur at the speed of minimum drag(VIMD).

Consequently, the angle of incidence on an aircraft is 3 or 4°. This is the angle at which the wing is fixed to the fuselage relative to the longitudinal axis.



So that in level flight for a given weight, aircraft are normally flown at the minimum drag speed (VIMD) to give the best all round performance.

2.76 Adverse Aileron Yaw:

Since the downward deflected aileron produces more lift, it also produces more drag. This added drag attempts to yaw the airplane's nose in the direction of the raised wing. This is called Adverse Yaw. Adverse Yaw is produced whenever the ailerons are deflected but the effect is usually reduced by incorporating one or more of the following design features:

a) Differential Aileron: In this design, for a given input of control, the up-going aileron is deflected through a larger angle than the down-going one thus reducing the difference in drag and the adverse yaw.

b) Frise Aileron: The Frise Aileron is so designed and installed, that the leading edge (nose) of the up-going aileron protrudes into the airstream below the wing to increase the drag on the down-going wing. Then the drag on both wings will be almost equal, thus reducing the onset of adverse yaw. This arrangement has the additional advantage that it assists the aerodynamic balancing (i.e., it relieves the pilot from excessive control loads).

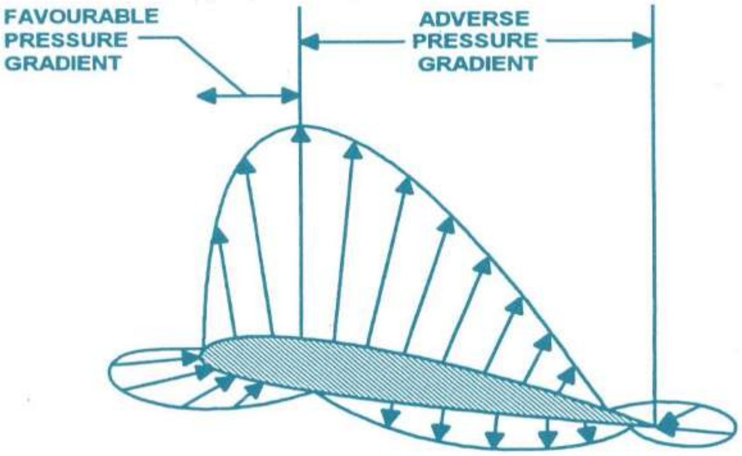
2.77 STALLING

Introduction:

As seen in earlier chapters, as air passes over an aerofoil section both its velocity and static pressure vary with distance from the leading edge. The pressure distribution this sets up over the upper surface greatly affects the flow characteristics of the boundary layer and will eventually cause it to breakaway or separate from the surface. Stall is a phenomenon of boundary layer separation and occurs at the critical angle of attack when the upper surface of the aerofoil is predominantly covered in separated airflow. At this point the aerofoil will no longer produce enough lift to support the weight of the aircraft and the separated airflow results in a dramatic rise in form drag overcoming the available thrust.

Boundary Layer Separation

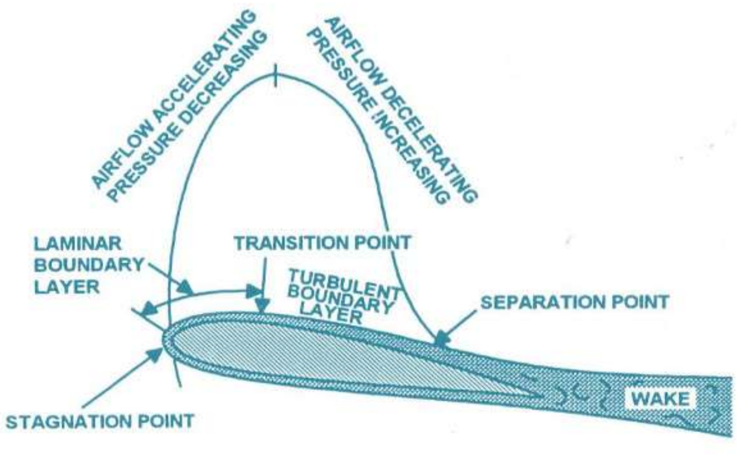
Boundary layer separation is produced as a result of the adverse pressure gradient, which develops over the aerofoil, which opposes the flow of the boundary layer. As air passes over an aerofoil it initially comes to rest at the stagnation point near the leading edge, where the static pressure will reach its maximum and the boundary layer starts to form. Air will then start to accelerate as it moves rearwards over the upper surface, reducing the static pressure producing a favourable pressure gradient for the generation of lift. After passing the point of minimum pressure however, the static



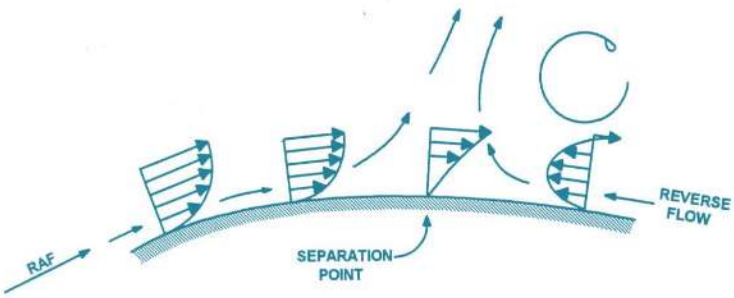
pressure will start to rise slowing down the airflow forming an adverse pressure gradient.

The adverse pressure gradient opposes the flow of the boundary layer and impedes its progress rearwards. Ideally this pressure gradient should extend from the point of minimum pressure to the rear of the aerofoil, where the rear stagnation point occurs.

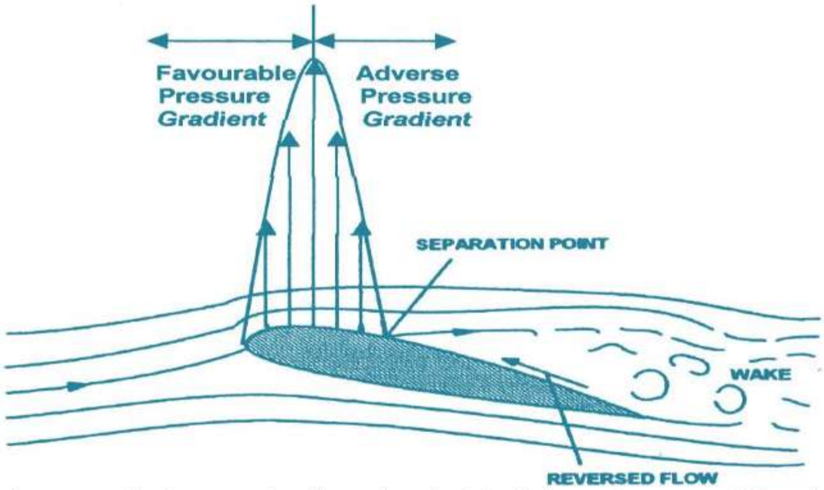
In the presence of a strong pressure gradient however, the energy of the boundary layer is insufficient to overcome the adverse pressure gradient and the boundary layer separates from the surface, as it can no longer move rearwards. The point where separation occurs is known as the separation point.



After air has separated from the aerofoil, the absence of the boundary layer after the separation point allows some of the turbulent flow behind the separation point to flow forward towards the leading edge. This is known as reverse flow and will help increase separation of the airflow passing over the wing.



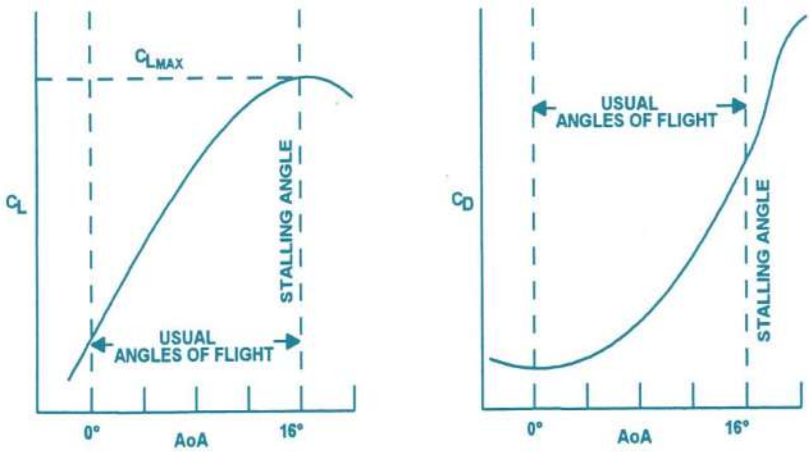
With increasing angle of attack the adverse pressure gradient increases in magnitude and the separation point moves forward as the pressure distribution curve narrows.



This results in a large turbulent wake forming behind the wing, resulting in an increase in drag and a decrease in lifting capabilities as the aerofoil reaches it critical angle or stalling angle of attack.

2.78 Stalling Angle of Attack

The stalling or critical angle of attack is the angle of attack at which an aerofoil surface will no longer produce enough lift to support the weight of the aircraft. This angle occurs at the point when the coefficient of lift is at it maximum, which for most aircraft is normally between 15 to18°AOA.
Beyond this angle, as the majority of the upper surface of the aerofoil is covered in separated airflow the lift coefficient decreases rapidly and the drag coefficient increases rapidly. Although not all lift is lost, as an aerofoil continues to give a certain amount of lift up to 90°.
In flight, an aircraft in a clean configuration will always stall at the same angle of attack regardless of airspeed or manoeuvre. If however the configuration is altered ie flap down, the aircraft will then always stall at a different angle which is the critical value for that configuration.



2.79 Stalling Speed

As an aircraft always stall at the same angle of attack, it is possible to establish a relationship between the stalling angle of attack and the speed that an aircrafts stalls at, using the lift formula. For an aircraft in level flight at a given height, the lift required is givenby:

Lift = C_L ½ ρ V^2 x S

This formula can be altered to represent angle of attack, since at the stalling angle of attack the coefficient of lift reaches a maximum value, so that at the stall the maximum lift is:

Drag = C_D½ ρ V^2 x S

Rearranging this formula for speed therefore gives a basic stalling speed in level fight:

In level flight as lift is equal to weight then the basic stalling speed can be written as

V_{STALL}=$[W/C_{LMAX}.\ \rho_{/2}.\ S]^{1/2}$

2.80 Methods adopted to increase stalling angle (Delay separation)

Stalling can be delayed mainly by any or combination of following methods:

SLOTS (Discussed under high lift devices 2.42)

Boundary Layer Suction and Blowing.

Vortex Generators.

BOUNDARY LAYER SUCTION

While blowing energizes the boundary layer in order to prevent separation, the principle of suction is the removal of the slowly moving air in the boundary layer, so that there in no layer to separate. Small holes, flush with the surface, are made in the surface of the aerofoil upstream of the separation point, and the air in the boundary layer is sucked into the wing through these holes. However, from this point onwards the boundary layer will re-form and thicken, and separation may still occur at some point downstream. To prevent this a series of suction holes must be made at various chord wise positions. The logical extension of this idea is the use of a porous wing surface, with suction applied every- where on the surface.

In addition to preventing separation, suction may also be used to prevent transition, and hence to keep drag low. Such a device would appear to be of particular interest in conjunction with the use of low drag wing sections. The principle behind the design of a low drag section is the maintenance of laminar flow. The disadvantage inherent in such designs is that separation occurs very readily when the incidence is increased by even a fairly small amount above the design value. Suction could be helpful both in maintaining laminar flow and in preventing separation.

BOUNDARY LAYER BLOWING

The principle of boundary layer blowing is similar to that of the leading edge slot. Highspeed air is blown into the boundary layer through a narrow slit in the upper surface of the aerofoil, where it re-energizes the boundary layer and prevents separation. Since the velocity of the air fed in this way is so much higher than the speed of the air passing through a leading edge slot, or a slotted flap, blowing will generally prove much more effective. The stall can be delayed almost indefinitely by this means. In addition, The jet of air has the effect almost indefinitely by this means. In addition, the jet of air had the effect of increasing the circulation round the wing, thus giving a direct lift increment at all incidence. The slot may be near the nose of the aerofoil, so that the blowing affect the whole of the upper surface. Alternatively, the slot maybe situated just upstream of the nose of a plain flap. In this position, the upstream of the slot will be affected to some extent by induction, but the main object is to prevent separation of the flow over the upper surface of the flap. Thus device is known as the blown flap.

The circulation effect is still present, though less important. There is some advantage in this device compared with that of slot placed further forward in that, in the latter case, the effect of blowing may be lessened by the time the flow reaches the rear of the aerofoil, where separation is most likely.

VORTEX GENERATORS

Many devices are used by the designer to control the separation or breakaway of the airflow from the surface of the wing - all these devices, in one way or another, over one part of the wing or another, have this in common, that they are intended to prevent or delay this breakaway. How? Well, that depends to some extent on the device, and we will consider vortex generators first .

The fundamental reason for the breakaway is that the boundary layer becomes sluggish over the rear part of the wing section, flowing as it is against the pressure gradient. The formation of a shock wave makes matters worse; the speed in the boundary layer is still subsonic which means that pressure can be transmitted up stream, causing the boundary layer to thicken and, if the pressure rise is too steep, to break away from the surface. Now vortex generators are small plates or wedges, projecting an inch or so from the top surface of the wing, i.e. three or four times the thickness of the boundary layer. Their purpose is to put new life into a sluggish boundary layer; this they do by shedding small lively vortices which act as scavengers, making the boundary layer turbulent and causing it to mix with and acquire extra energy from the surrounding faster air, thus helping it to go farther along the surface before being slowed up and separating from the surface. In this way the small drag which they create is far more than compensated by the considerable boundary layer drag which they save, and in fact they may also weaken the shock waves and so reduce shock drag also; and the vorticity which they generate can actually serve to prevent buffeting of the aircraft as a whole - a clever idea indeed .

2.81 Tip Stall

When an aircraft stalls it is important aerodynamically, that an aircraft stalls progressively from the root of the wing to the tip. The reasons for this are to:

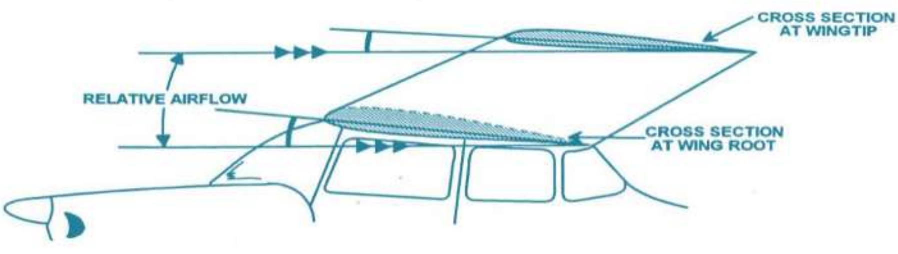
- Induce early buffet symptoms over the tail plane.
- Retain aileron effectiveness up to and beyond the critical angle.
- Avoid a large rolling moment that would occur if one wingtip stalled before the other causing wing drop.

To prevent tip stall therefore a number of features are designed into an aircraft, the most common being:

- Washout.
- Root spoilers.
- Change in section.

2.82 Washout

Washout is the geometrical twisting of the wing so that the wing tip is at a lower angle of attack than the wing root. As already mentioned, washout due to the changing angle of attack will reduce wing tip vortices. But more importantly it will ensure that wing root reaches the critical angle of attack before the wing tip, therefore ensuring that the wing will stall progressively from wing root to wingtip. [Wash in design ,on the other hand, where the wing is twisted permanently such that the incidence is more at the tip than at the root, is employed in rectangular wings to get the wing loading uniform throughout the span thereby reducing root stalling tendency].



2.83 Root Spoilers

Root spoilers are small wedge shape devices fitted at the leading edge of the wing near the root. This makes this part of the leading edge sharper so that it is more difficult for the airflow to follow the contour of the wing at a high angle of attack. This makes the air over the wing root separate before the contoured leading edge of the wing tip, inducing a stall at the root before the wing tip.

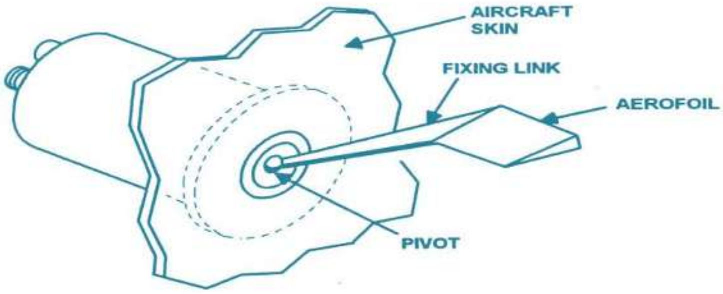
Change in section

Changes in the aerofoil section, by increasing the camber over certain parts of the aerofoil ensure that the wing has a gradual stalling characteristic from the root to tip. The change in camber of different sections alters the point of separation point over that section, so by designing the wing with more camber at the wing root it will ensure that the air separates over the root section first producing the stall.

2.84Aerodynamic symptoms of stall

The most consistent aerodynamic symptom of an impending stall arises from the separated flow behind the wing passing over the tail surfaces, which causes pre-stall buffet. This arises as the turbulent wake from the wings results in shaking or buffeting of the control surfaces, which is felt by the pilot through the control column and rudder pedals and occurs normally a few degrees before the critical angle is reached.

The amounts of pre-stall buffet an aircraft experiences, however, is dependent on the position of the tail surfaces in regards to the turbulent wake leaving the wings.

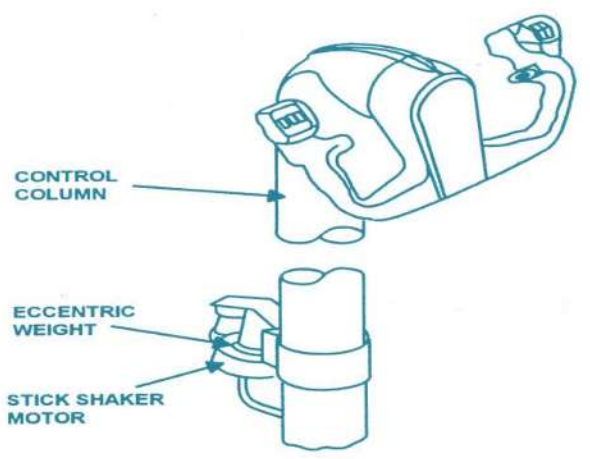


2.85 Stall Warning Devices

On most aircraft to ensure that the aircraft does not enter into a stall without warning, stall-warning devices are fitted to warn the pilot that the aircraft is approaching the critical angle. On some aircraft the device is a moving vane that is attached just under the leading edge of the wing that is activated by the movement of the stagnation point.

On other more sophisticated aircraft the stall warning is provided by an angle of attack sensor normally fitted either side of the aircraft near the nose. This device measures the angle of attack relative to the airflow, generating an electrical signal when near the stalling angle.

For aircraft that do not experience pre-stall buffet, an artificial pre- stall warning device called a stick shaker is often fitted. This device vibrates when it receives a signal from the stall warning computer, vibrating the control column when the aircraft approaches the stall.



On other aircraft that are difficult to recover from a stall, a stick pusher is employed that moves the control column forward to lower the angle of attack when the aircraft approaches the critical angle of attack.

2.86 AEROFOIL CONTAMINATION

It is assumed that Airfoils are free of any contamination,. But some of the most common forms of contamination are ice, snow and frost If any of these is accumulated on the aircraft, particularly on the wings, the capacity to develop lift will be reduced and drag will be increased.Ice commonly changes the shape of the aerofoil which disrupts airflow and make it less efficient. Further, ice, snow and frost changes the smooth even surface . The smooth even surface promotes laminar flow which is required to set up the pressure differential between the lower and upper surfaces that creates lift. Therefore the aircraft should be kept free from any such contamination.

If ice is allowed to accumulate on the aircraft during flight, the weight of the aircraft is increased while the ability to generate lift is decreased. Even 0.8 mm of ice on the upper wing surface increases the drag and reduces the aircraft lift by 25 percent.

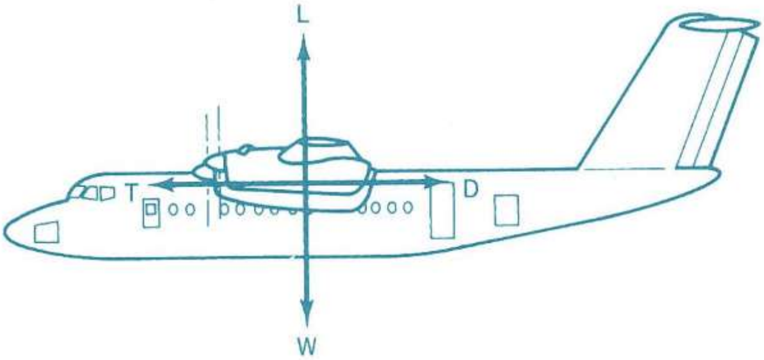
THEORY OF FLIGHT

SECTION 3.1: LEVEL FLIGHT

Introduction

During flight, an aircraft is said to be in steady level flight when the main forces that act upon the aircraft: Lift, weight, thrust and drag are in equilibrium ie there is no resultant force to accelerate or decelerate the aircraft.

In level flight, these forces normally act in the following directions:



and in order to maintain steady level flight, the opposing forces that must balance each other out, so that:

Lift = Weight and Drag = Thrust

When these forces are plotted against each other, like above it is often convenient to show them as acting through a single point, but in fact each of them have their own point of action:

- Lift acting through the Centre of Pressure(CP).
- Weight acting through the Centre of Gravity (C of G).
- Thrust and drag acting in opposite direction to each other and are parallel to the direction of flight, although the points, which they act through, will vary with aircraft attitude and design.

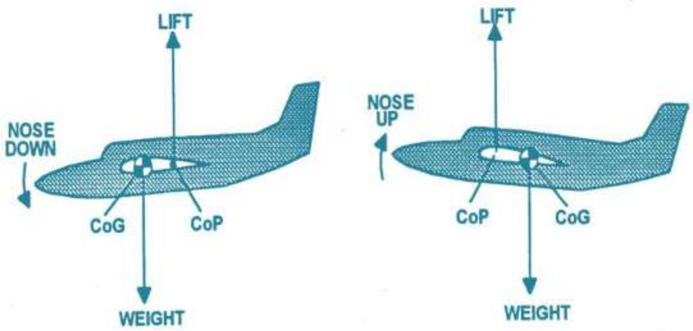
Pitching moments

In steady level flight, as the lift force opposes weight and the thrust produced opposes the drag, any movement or unbalancing of these two couples will set up a pitching moment, that will either pitch the aircraft nose-up or nose-down depending on how the arrangement of are:

- Lift/Weight couple.
- Thrust/Drag couple.

3.2 Lift/Weight Couple

During flight the positioning of the centre of pressure (CP) and the centre of gravity (C o G) are variable and under most conditions of flight are not coincidental. The centre of pressure moving with changes in angle of attack and the C of G moving with changes in weight due to the reduction in fuel. The outcome of this, is that the opposing forces of lift and weight set up a couple causing either a nose-up or nose-down pitching moment depending on whether the lift is in front or behind the C ofG.

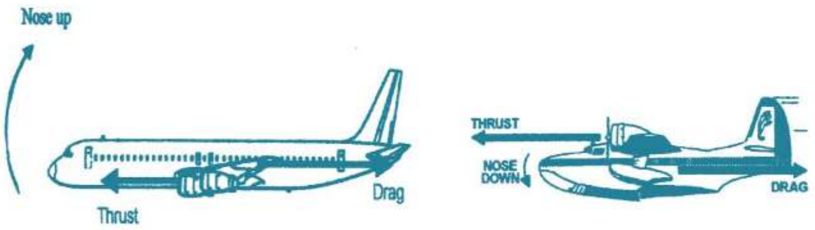


Lift acting behind weight causes a nose-down pitching moment and lift acting in front of weight causes a nose-up pitching moment

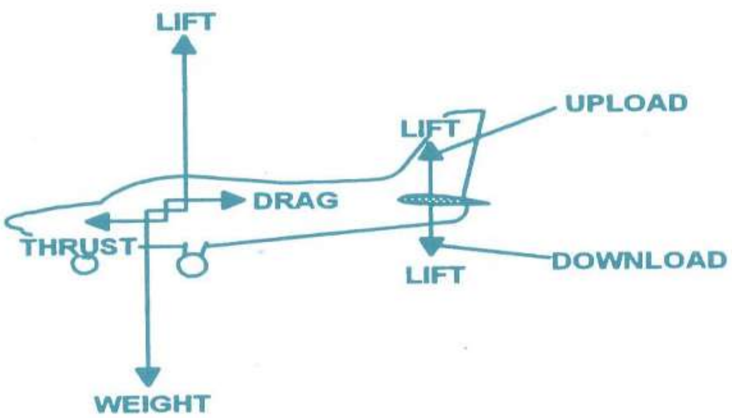
3.3 Thrust/Drag Couple

The same condition of pitching the aircraft either nose-up or nose-down also applies to the forces of thrust and drag. This occurs as the positioning of the lines of actions of thrust and

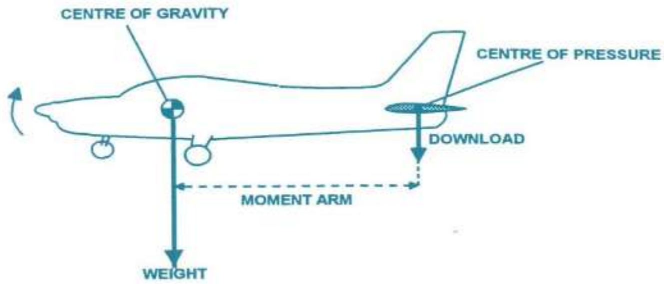
drag can also set up a couple that brings about a pitching moment.



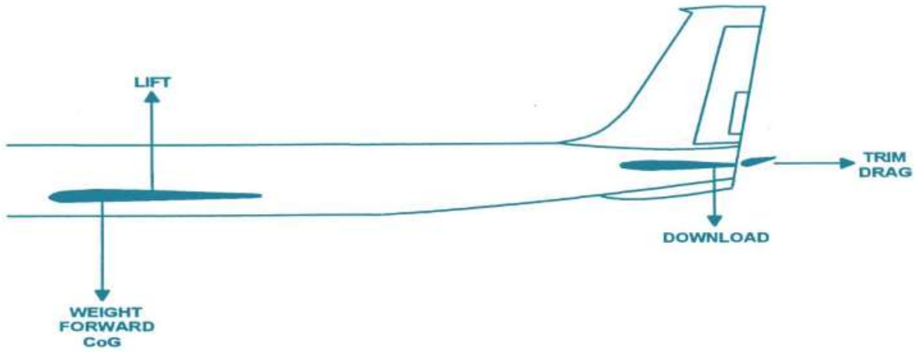
Thrust acting below drag causes a nose-up pitch and thrust acting above drag, a nose-downpitch.
Ideally the pitching moment arising from these two couples should neutralise each other so that in level flight there is no residual moment tending to rotate the aircraft.
This arrangement is not easy to attain, but in practise most aircraft have the forces arranged so that, if thrust is removed, ie in the event of engine failure, the remaining lift/weight couple will pitch the aircraft nose-down (without any action by the pilot) so that it assumes a gliding attitude.
The forces are therefore normally arranged for an aircraft where thrust acts below drag so that lift acts behind weight.
Additionally, since there is usually a considerable difference in magnitude between the couples, (lift/weight being the greatest) the distance or spacing between thrust/drag couple is normally greater in order to balance the pitching moments.
Balancing level flight forces
In an ideal world, as it has already been said, the pitching moments from the main two couples would balance each other out. In practice however, this is not always possible so a secondary method of balancing using the tailplane must be used.



In level flight therefore, if any of the two main couple produces either a nose-up or nose-down pitching moments, for instances a nose-down pitching moment, the tail plane can be trimmed to provide a downward force to correct the moment piching.



On some aircraft the actual tailplane position is adjustable to maintain level flight during different



phases of the flight, on other this is provided by control surface deflection of the aircraft trim system. In producing this force at any given airspeed the tailplane will produce an increase in drag. This extra drag is known as trim drag and will be covered in greater detail in the flight controls unit.

3.4 Effect of Speed on Level Flight

For an aircraft to maintain level flight, as lift must equal weight, it can be seen from the formula of lift (Lift = $C_L \frac{1}{2} \rho V^2 \times S$) that for an aircraft flying in a certain configuration and weight, if there is a variation in speed, then the CL (angle of attack) must be altered to maintain the lift required. For example if the speed of the aircraft is doubled, then the lift produced will quadruple, as it is velocity squared. So in order to maintain level flight the value of the lift coefficient must be reduced to a quarter. Halving the airspeed would therefore quarter the lift requiring the lift coefficient to bequadrupled.

The speed in level flight therefore, affects the attitude the aircraft is flown in. At a low forward airspeed the aircraft will require a high angle of attack so will be in a high nose-up condition, whereas at high speed the aircraft will require a low angle of attack. This difference in attitude of an aircraft being most noticeable on aircraft with wings of low aspect ratio (AR) as during the landing phase the aircraft is a very high angle of attack.

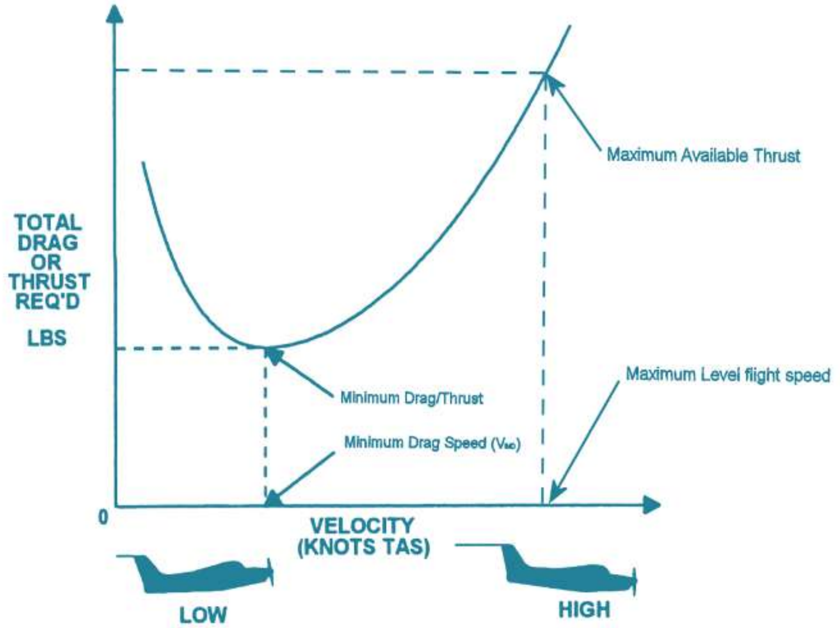
3.5 Effect of Weight on Level Flight

In level flight, since the weight of the aircraft is balanced by the lift, it follows that any weight change will require a corresponding change in lift.
For an aircraft flying level at a give angle of attack, for example the best L/D ratio (about 4°), at the VIMD airspeed, then if the weight is decreased by fuel usage the lift must be decreased to balance the new weight.
To maintain optimum condition therefore at about 4° AOA, the speed will need to be reduced to balance the new weight. It follows then that a heavier aircraft to maintain level flight at the same attitude and optimum angle of attack, at about 4°AOA, will require to be flown at a higher airspeed to maintain the lift/weight balance.

The best equivalent airspeed (EAS) for an aircraft in fact varies at the square root of the weight, as this is quite complicated to calculate, a simple method of estimating changes to the equivalent airspeed (EAS) for changes in weight is to half the percentage change. For example, a weight reduction of10% necessitates a drop in airspeed of 5% and an increase in weight of the same amount would entail a 5% increase in speed.
Changes to the aircraft weight will also affect the range of the aircraft, as any increase in aircraft weight will require a change in speed and higher thrust levels to overcome drag. As this will consume fuel at a faster rate the aircraft's maximum range will be reduced, provided that it is flown at a speed corresponding to the maximum TAS/drag ratio.

3.6 Aircraft Performance in Level Flight

As an aircraft is considered to be in steady and level flight when the four main forces acting upon the aircraft are in equilibrium. In practice however, it is the thrust available from the engines and the amount of airframe drag characteristics, which determine an aircraft's actual flight performance.
In level flight as these two forces must balance, the curves for thrust and drag are identical for a given weight, configuration and altitude. So maximum endurance in level flight occurs at the VIMD point when the thrust required will be at its lowest.



To maintain level flight therefore, the minimum level flight speed of an aircraft is usually governed by aerodynamics of the aircraft, ie the stalling angle of attack in a given configuration. The maximum level flight speed however is governed by the amount of thrust (power) available from the engines and will occur when thrust available equals thrust required.
Beyond these points it is no longer possible to maintain steady level flight as either the aircraft will stall or the engines will be unable to produce enough thrust to overcome the additional increase in drag.

3.6 MAXIMUM RANGE AND ENDURANCE

Maximum Range

Maximum Range in still air is achieved at the TAS which allows : maximum air distance for a given fuel burn-off; or conversely minimum fuel burn-off for a given air distance (i.e. the lowest fuel burn-off/air distance ratio).
By converting burn-off and air distance to rates, this ratio becomes fuel burn-off per unit time/air distance per unit time, i.e. fuel flow/TAS, and maximum range will be achieved at the TAS for which

this ratio is least. This occurs at the point on the Power vs TAS Curve where the tangent from the origin meets the curve. At all other points, the ratio power/TAS is greater.
Power is defined as force x velocity so:
Power Required = Thrust Required x TAS = Drag x TAS (since Thrust = Drag)
Therefore the Power/TAS ratio = (Drag x TAS) / TAS = Drag, and will of course have a minimum value when Drag is minimum, i.e. Maximum Range TAS is the TAS for minimum total Drag.
To sum up, the maximum range speed shows up on the Drag Curve at the Minimum drag point (which, as explained earlier, is also the point of maximum L/D ratio).

Maximum Endurance

Maximum endurance means either: the maximum time in flight for given amount of fuel; or
a given time in flight for the minimum amount of fuel.
It is appropriate to fly at maximum endurance speed when the speed over the ground is not significant, for instance,when:
holding overhead or near an aerodrome waiting to land; or carrying out a search in a specific area.Since fuel flow for an engine-propeller combination depends upon power set, minimum fuel flow (and therefore maximum endurance) will occur when minimum power to maintain steady straight and level flight is required.

3.7 Effect of Altitude on Level Flight

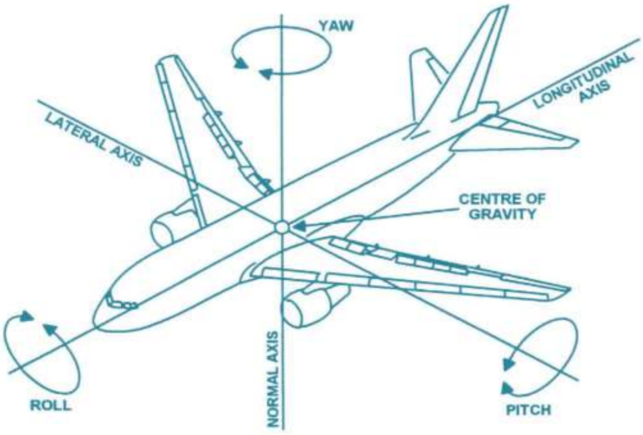
In flight, since not only the speed, but also the lift and drag vary with the ½ ρ V^2 factor, the relationship between equivalent airspeed and angle of attack is unchanged at altitude provided the weight remains constant. However, at higher speeds, compressibility effects tend to alter the relationship by reducing the C_L appropriate for a given angle of attack (compressibility above 0.4Mach).
For aircraft fitted with jet engines, flying at altitude does affect the endurance of the aircraft in level flight, as jet engines become more efficient at altitude using less fuel. For example, a jet engine aircraft flying at 40,000 ft the maximum range of the aircraft will be approximately 150% greater than that obtained from the same aircraft at sea level, provided that the aircraft is flown at both heights at its VIMD speed.

3.8 MANOEUVRES

Introduction

Manoeuvring an aircraft in flight away from straight and level flight can take place about any one or a combination of the aircraft's three major axes. These three axes being known as the:

- Lateral axis -Pitch.
- Longitudinal axis -Roll.
- Normal axis -Yaw.



3.9 Lateral Axis

The lateral axis of an aircraft is a straight line running through the centre of gravity that is parallel to a line joining the wing tips. Movement about this axis is termed pitching and the axis can also be known as the looping axis.

3.10 Longitudinal Axis

The longitudinal axis of an aircraft is a straight line through the centre of gravity from the nose to the tail of the aircraft. Movement about this axis is known as rolling and the axis is also known as the roll axis.

3.11 Normal axis

The normal axis of an aircraft is a straight line through the centre of gravity that is at right angles to both the longitudinal and
lateral axis. Movement about this axis is known as yawing and the axis is often referred to as the yawing axis.

As all three axes pass through the aircraft's centre of gravity and act at right angles to each other, the aircraft can move about all three axes simultaneously, but the axes are fixed relative to the aircraft, irrespective of its attitude.

In manoeuvring an aircraft about these its axes however, increased levels of stress are placed on the airframe and its components as the load factor changes. To prevent failure in flight therefore, the design authorities restrict the maximum loads permitted in a manoeuvre by imposing limits.

3.12 Effect on Load Factor

Any moving body that is in motion it is subject to Newton's three laws of motion. These laws state that when a body, such as an aircraft, move away from straight and level flight, ie a manoeuvre, it can only change direction if it is subjected to an external force that produces an acceleration, and that the degree of change will depend on the size of the external force.

This change in acceleration of the aircraft is often felt by a person flying in an aircraft as an apparent change in weight, which pulls you into your seat and is popularly referred to as g loading.

In a manoeuvre such as a turn or a pull-up therefore, the external force to move the aircraft is supplied by the wings producing additional lift to exceed the weight. This ratio of the lift produced by the wings to the weight of the aircraft is called the load factor (n).

3.13 Manoeuvring Envelope (or V-n Diagram or Flight Envelope)

The manoeuvring envelope is a graphical representation of the limitation imposed by speed (V) and load factor (n) while manoeuvring.

In level flight therefore, as lift equal weight, it is said to have a load factor equal to 1g, the term g is used as the weight of the aircraft is related to the gravity (W = mg).

In a manoeuvre away from level flight therefore, the load factor will always be greater than 1, as the load factor is multiples of static weight. For example a manoeuvre such as a turn which required the wings to produce a lift force 3 times its weight force, it would be said to be subject to3g.

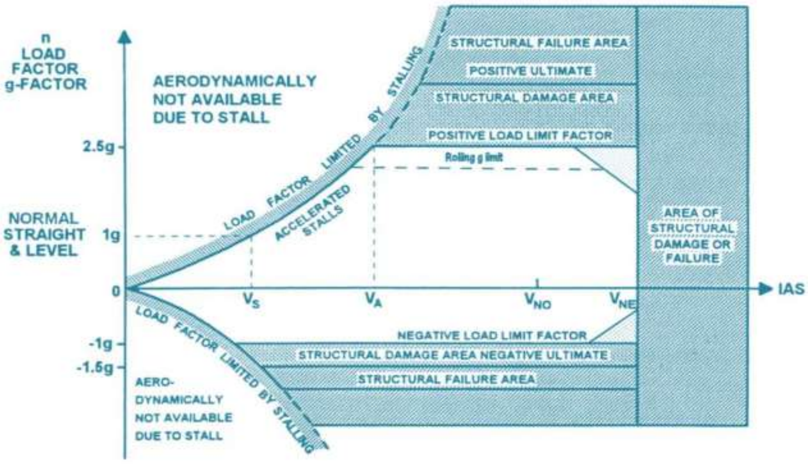
The harder or faster a manoeuvre is away from level flight, the greater will be the lift force required, so the higher will be the load factor and stress on the aircraft

3.14 Wing Loading

The wing loading of an aircraft is the proportion of its total weight that is carried per unit area of the wing. i.e., Wing Loading = W/S.
As the wing loading is the ratio of the weight of the aircraft to its wing area, it does not vary during a manoeuvre, even although the wings per unit area produce more lift. This is because in a manoeuvre the total weight and area remains the same. For a wing of a given area however, the greater the weight the greater will be the wing loading, so a greater amount of lift will be needed to manoeuvre it, which will affect the amount of load factor allowed in a manoeuvre.
operating limits of an aircraft and is used to:

- Lay down design requirements for a new aircraft.
- Illustrate the performance of their products by the manufacturers.
- Compare the capabilities of different types of aircraft.

In practice each type of aircraft has its own specific envelope, within which an aircraft can be safety operated in accordance with EASA requirements. The limits of the manoeuvring envelope being plotted between the velocity and load factor limits of an aircraft on a V-n diagram.

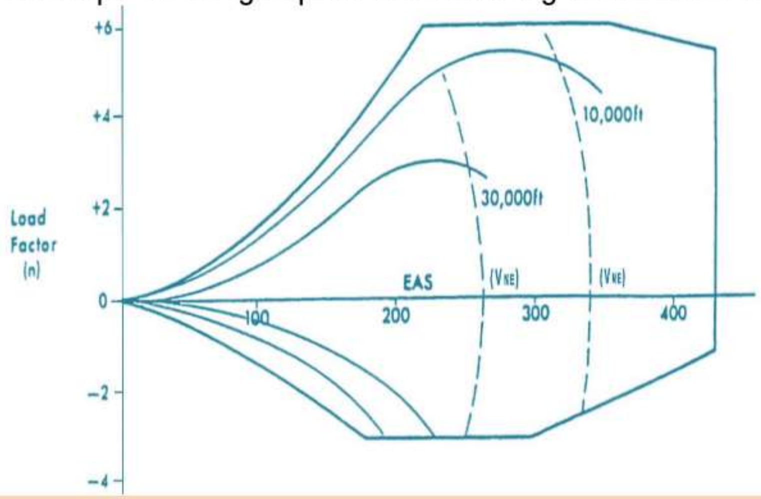


On the vertical axis of the graph is plotted the load factor, which gives the limit loads for the aircraft in different parts of flight. These limits will vary between different aircraft type, but for commercial transport aircraft, these are generally around + 2.5g and –1g.
To provide a safety margin against structural damage, all aircraft are built to withstand loads up to 1.5 times the limit load without occurring any structure failure. This is known as the ultimate load limit, and for a transport aircraft would be at around + 3.75g and– 1.5g.
In between the limit load and the ultimate load limit is the structural damage area. This area covers the built in safety margin, but as it is above limit load some damage will occur. This can range from pulled rivets just above the limit load to buckling and panel failure just below the ultimate load.
On the horizontal axis of the graph is plotted the speed limits. These limits are imposed as at high speed the force of the air acting on the on the aircraft, could lead to structural damage of surfaces, such as the tailplane or other flight controls that are placed into the oncoming airflow.

During normal level flight therefore, the aircraft is limited to a maximum normal operating speed (VNO), but in case of an over-speed, such as a dive it has a built in safety limit, which is usually between 5 to 10 % of the maximum normal operating speed known as the never exceed speed (VNE).
At the other end of the manoeuvring envelope, the aircraft is limited by the stalling speed of the aircraft. So the envelope shows the minimum speed required for straight and level flight (VS) for maximum take-off weight, and the stalling speeds in a manoeuvre up to the limit load (VA) for maximum take-off weight.

Further restrictions that are given in the envelope are the rolling g limit and the buffet corners. These limits lower than the normal g limitation as in a roll in addition to the normal g forces; the structure has to withstand the additional twisting forces caused by the roll control surface deflection. At high speed, buffet corner limits are imposed due to the additional forces caused by high air loads, such as turbulence when the aircraft is already highly loaded. The corners are normally built into the safety margin between the maximum normal operating speed (VNO) and the never exceed speed(VNE).

To complete the envelope for individual aircraft, the effects of altitude on airspeed and compressibility factors near supersonic flight have to be taken into account. These will lower manoeuvring envelope load limits and requires that the limits be drawn for various heights, an example of a complete envelope for a high-speed aircraft being shown below.



3.15 CLIMBING

Introduction

In a climb an aircraft gains potential energy by virtue of elevation by either one or two means:

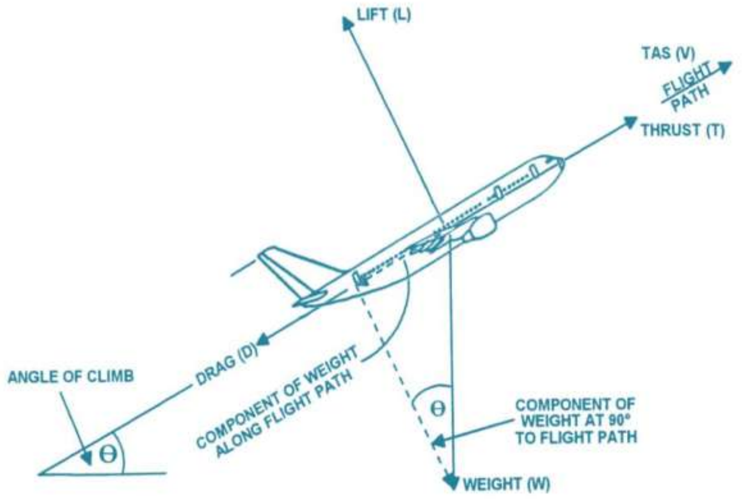
- The expenditure of propulsive energy in excess of that required for steady level flight, into potential energy.
- The expenditure of the aircrafts forward kinetic energy into potential energy(zooming).

Zooming for altitude is a transient process of exchanging the forward kinetic energy of the aircraft into potential energy. In this type of climb, the aircraft slows down as it climbs to a higher level, so the climb can only be maintained up to the stalling speed of the aircraft. Levelling off the aircraft before reaching its stalling speed would mean that at its new height, the aircraft would have less forward kinetic energy ie it willbe

travelling slower. The major portion of climbing however for most aircraft is a near steady process in which additional propulsive energy is converted into potential energy.

3.16 Forces in Climb:

When an aircraft climbs at a constant airspeed the forces acting on the aircraft are in equilibrium, and act in the following directions:



The size of the forces acting against each other however is dependent upon the angle of climb (θ), as the weight force is resolved into two components:

- One opposing the lift (W cosθ).
- The other acts in the direction of drag (W sinθ).

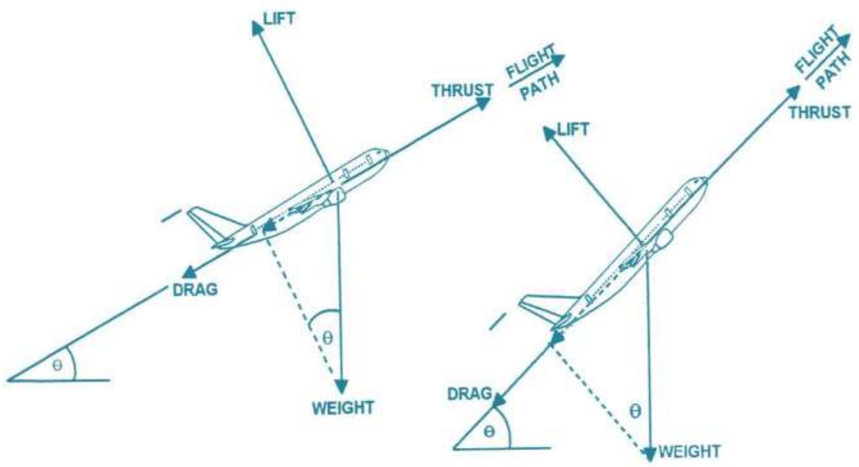
In a climb, therefore the following relationship exists:

- Lift = component of weight acting perpendicular to the flight path

$L = W \cos \theta$.

- Thrust = Drag + component of weight parallel to the flight

$T = D + W \sin \theta$.

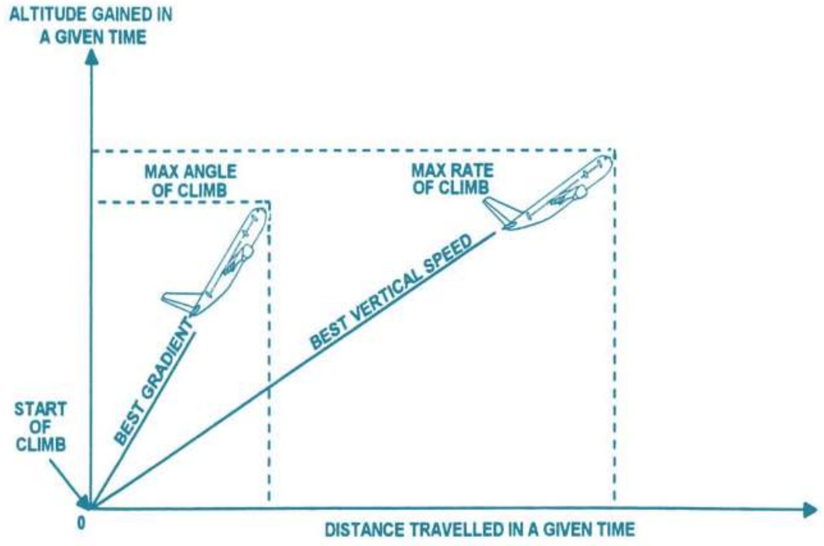


These changes of forces mean that in order to climb at a steady airspeed, as the angle of climb increases, the thrust requirements will steadily increase, whilst the lift requirements decrease. So it follows then that in a climb:

- Thrust is always greater than drag.
- Lift is always less than weight.

In a climb in order to climb at a steady speed, the additional thrust is required to climb is needed, firstly to overcome the drag, secondly to lift the weight at a vertical speed, known as its rate of climb and thirdly to accelerate the aircraft slowly as the true airspeed steadily increases with increasing altitude.

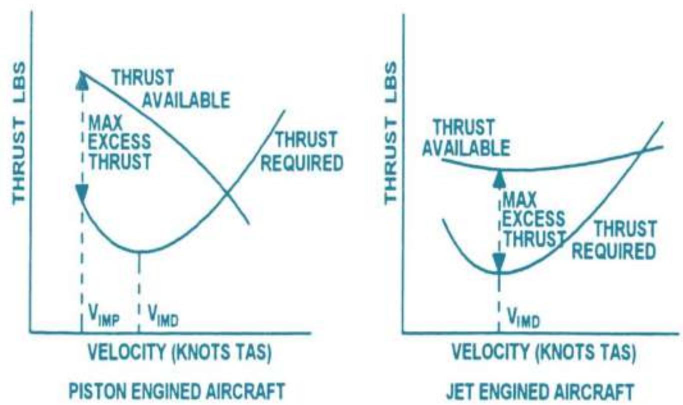
In practice however, an aircraft will climb either steeply at low airspeed, or will climb at a shallower angle at a higher airspeed ie a specific angle or a specific rate of climb. Both of which will depend on the on the power available from the engines.



3.17 Maximum Angle Of Climb

The maximum angle of climb is where the aircraft gains the most altitude in the shortest horizontal distance, ie the best gradient. This occurs when aircraft is flown at a relatively low airspeed and provides for good ground obstacle clearance.

To establish the maximum angle of climb, it was earlier established that in a climb:
$T = D + W \sin \theta$.
Rearranging, $\sin \theta = (T - D)/W$
For aircraft fitted with different types of engines, the maximum excess thrust is as follows:



The maximum angle of climb is therefore governed by the amount of excess thrust left after opposing drag for an aircraft of weight W.

Maximum Angle of climb therefore occurs when an aircraft is flown at a speed, which relates to the maximum excess thrust. For a jet- engined aircraft, as the available thrust remains virtually constant at a given altitude, the maximum excess thrust and maximum angle of climb occurs at the minimum drag speed (VIMD) for a given configuration.
On a typical piston or turboprop engine however, the maximum available power occurs at the indicated minimum power speed (VIMP), as thrust produced by a propeller reduces as speed increases. The maximum excess thrust occurring very near the stalling speed, so the safest and best

speed for maximum angle of climb on a piston or turboprop aircraft is approximately 10 knots above the configurations stalling speed.

3.18 Maximum Rate of Climb

The maximum rate of climb of an aircraft is where the aircraft climbs or gain the most altitude in the shortest time, ie the best vertical speed. To achieve this in addition to the forces that act on the aircraft in a steady climb, the aircraft must achieve a high vertical velocity.

This is known as the aircraft rate of climb and is normally expressed in feet per minute. The rate of climb of an aircraft being linked to its angle of climb since:
Rate of climb (V_C) = $V \sin \theta$.

3.19 ABSOLUTE CEILING & SERVICE CEILING

At the absolute ceiling, then, the maximum excess power is zero, and so is the maximum rate of climb. In fact, the absolute ceiling may be only a theoretical measure of the maximum altitude at which the aircraft can operate. There are two reasons for this. It is clearly undesirable, fro, the handling point of view, to fly at an altitude at which there is only one possible speed. Any disturbance in speed, occasioned perhaps by a gust, leads to a non-equilibrium condition. Control is lost, and may be difficult to recover. Again, the time taken to climb to the absolute ceiling using the steady state techniques we have been studying is generally infinite, as we shall see later. This may mean that in practice the aircraft cannot reach its absolute ceiling. However, all the foregoing analysis, on which this conclusion is based, is concerned with steady rates of climb, i.e., there are no accelerations or retardations involved. It is possible for some jet aircraft to zoom to a height which is even greater than their absolute ceiling, exchanging kinetic energy for potential energy and, of course, losing speed in the process. This is an extremely undesirable manoeuvre, since, at the end of it, the aircraft is in a condition in which it is out of the pilot's control.

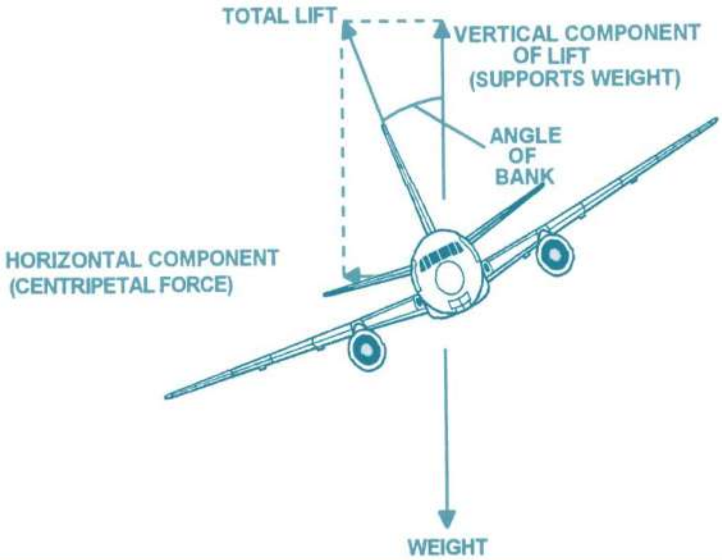
The absolute ceiling, then, is not necessarily the highest altitude which the aircraft can reach under its own power, but the highest altitude in which it can be flown steadily, straight and level. However, since it is generally unattainable, as we have seen, it is necessary to have some more practical measure of the greatest height at which the aircraft can normally be expected to operate. It is conventional to define for this purpose the altitude at which the maximum rate
of climb is some generally specified figure, greater than zero, small enough for the given altitude to be quite close to the absolute ceiling and so a reasonable measure of maximum operating height, but large enough for the given altitude to be attainable in a reasonable time. This altitude is known as the service ceiling of the aircraft. In the past, the figure for maximum rate of climb at the service ceiling has been specified as 100 ft/min for a piston-engined aircraft. In S.I. units, this is roughtly 0.5 m/s, so that we could define the service ceiling for a piston-engined aircraft as the altitude at which its maximum rate of climb is 0.5 m/s. The maximum rate of climb of a jet-engined aircraft is generally much higher than that of a piston-engined aircraft, and if the same definition were used in the case of a jet, the service ceiling would be still too close to the absolute ceiling. The service ceiling of a jet has often been defined as the altitude at which its maximum rate of climb is 500 ft/min, and we may now amend this to read the altitude at which maximum rate of climb is 2.5 m/s.

The service ceiling, then, can be reached in a reasonable time, and at this altitude there is a reasonable, though still narrow, range of speeds within which the aircraft can operate.
As we have seen, the greater the weight the smaller will be the maximum rate of climb at any altitude. Thus, the greater the weight, the lower will be both the service and absolute ceilings.
To determine the ceilings of the aircraft, the power required and power available curves are drawn at various altitudes, and from these the maximum rate of climb is determined at each height.

3.20 BANKED TURN

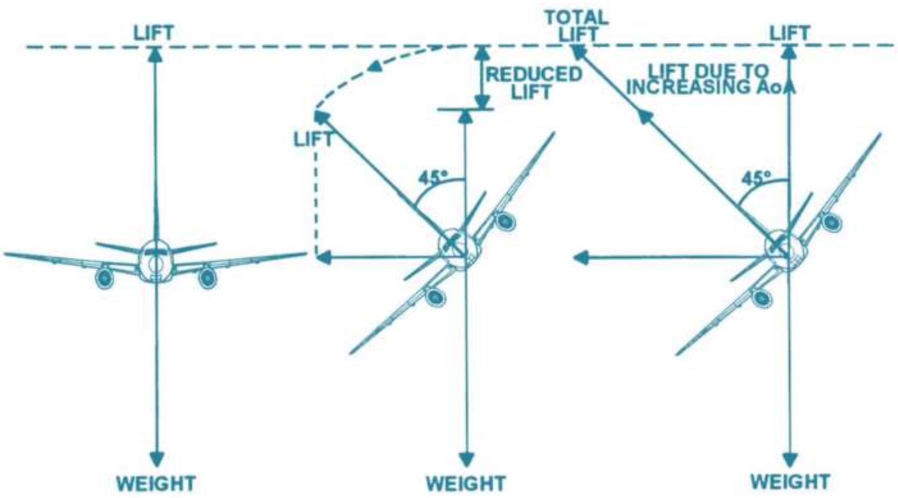
Introduction

For an aircraft to turn, a force is required to deflect the aircraft towards the centre of the turn. This is known as the centripetal force and arises when an aircraft is banked, as the total lift force is tilted, splitting the lift force into two components. The horizontal component of lift creates the centripetal force towards the centre of the turn, with the vertical component of lift supporting the weight of the aircraft.

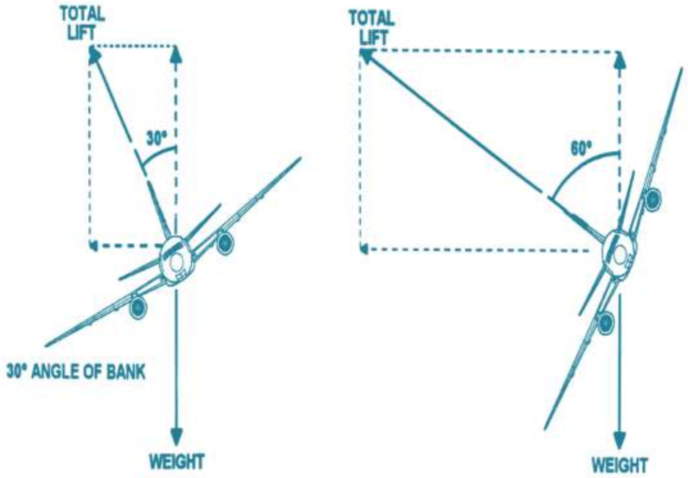


Turning an aircraft

To perform a turn, the ailerons are used to increase the lift over one wing and maintain the desired angle of bank. In this sort of manoeuvre as the aircraft banks, the vertical component of the lift force decreases, as the angle of bank increases, which leads to a loss in altitude and the aircraft sideslipping. In order to keep the aircraft level in the turn therefore, as the aircraft is banked the control column must be moved rearwards to increase the wings angle of attack and increase the total lift produced by the wings to recover the lost lift and balance the weight force.



In a turn therefore, the greater the angle of bank, the greater is the centripetal force and in order to maintain a level turn the greater will be the total lift requirement.



3.21 Effect of Weight in a Turn

In steady level turn, if thrust is ignored, then the lift produced by the wings will have to provide a force to balance the weight of the aircraft, and the additional centripetal force to turn the aircraft. To maintain an aircraft in a steady turn therefore as weight is increased, so must be the total lift on the aircraft in order to balance the new weight. This however will reduce the load factor permissible in the turn as it will increase the wing loading.
The factors that changes in weight affect in the turn are:
Load factor.
Minimum radius and rate of turn.

3.22 Load factor in the turn

As already discussed in the manoeuvring chapter, load factor is the ratio between the total lift produced by the wings and the weight of the aircraft and is known as g loading (g or n):

$$\text{Load Factor, } n = \frac{\text{Total Lift}}{\text{Aircraft Weight}} = L/W$$

In level flight, since the lift is equal to the weight and the load factor is 1g, in a turn as the lift is increased, the load factor will be greater than 1g. A relationship therefore exists between the angle of bank and load factor, as the greater the angle of bank, the greater the total lift required and the higher the load factor.
The relationship between load factor and angle of bank is given by the following formula:

$$\text{Load Factor} = \frac{\text{Total Lift}}{\text{Aircraft Weight}} = \frac{1}{\cos\theta}$$

Rearranging this formula for the total lift required in the turn gives:

$$\text{Total Lift} = \frac{\text{Aircraft Weight}}{\cos\theta}$$

For example in a 60° bank turn, the total lift required would be

$$\text{Total Lift} = \frac{\text{Aircraft Weight}}{\cos 60^{\circ}}$$

And as cos 60°= 0.5

$$\text{Total Lift} = \frac{\text{Aircraft Weight}}{0.5} = 2 \times \text{Aircraft Weight}$$

As this is more commonly known as g loading, during a 60° angle of bank the aircraft will experience a force of 2g.

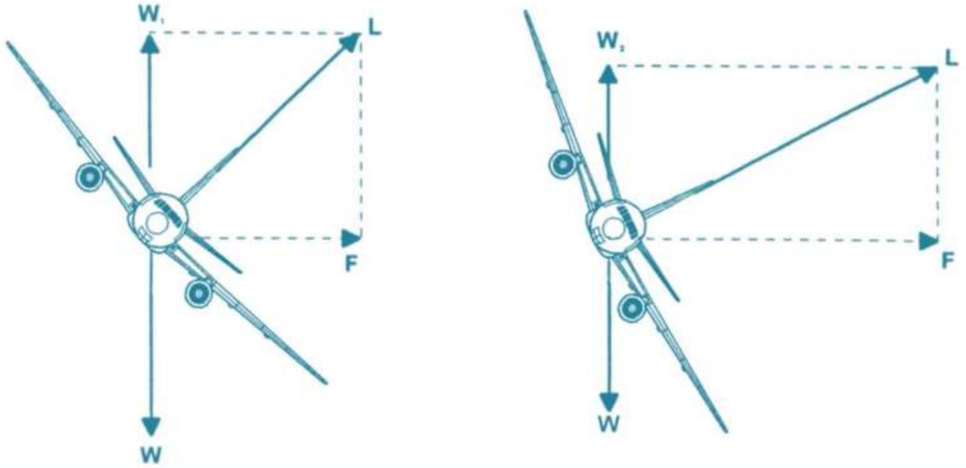
3.23 Minimum Radius of Turn

In flight, a minimum radius turn is achieved when the aircraft produces the greatest amount of centripetal force to pull the aircraft into the turn. As this will occur when the maximum total lift force is tilted inwards, a minimum radius turn is obtained at the maximum permissible angle of bank. In order to achieve this however, the following conditions must be satisfied:
Wing loading must be as low as possible.
The air must be dense as possible, ie at mean sea level.

The maximum values of the product of CL and angle of bank must be obtained.
In any sort of manoeuvre, one of the most important limits imposed on an aircraft is its limit load factor. As this is a ratio of lift to weight, the wing loading which is the ratio of weight to area must be at its lowest.

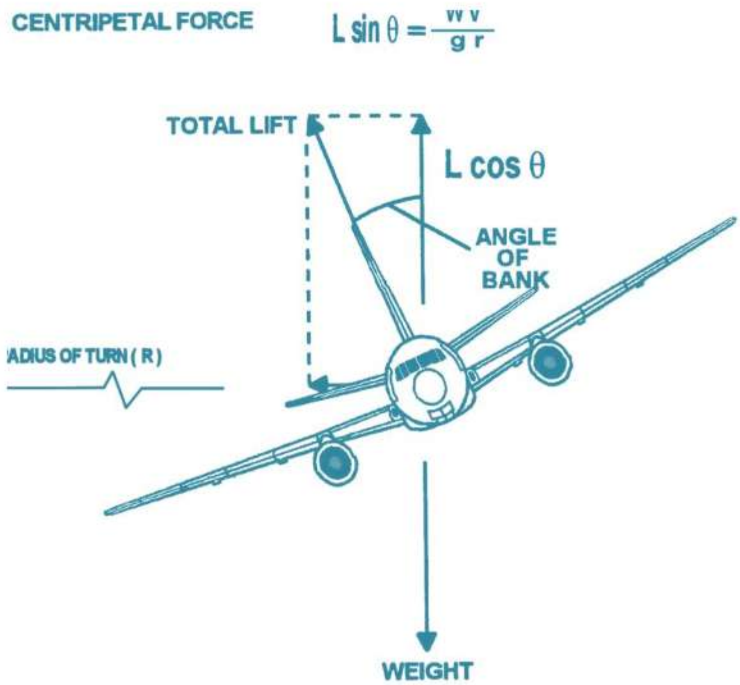
For example, if an aircraft that weighed 50,000 lbs had a wing area of 100 ft sq and structural limit of a 100,000 lbs. The wing loading would be 500 lbs/ ft sq and its maximum load factor in a manoeuvre would be 2g. If however the same aircraft's weight was reduced to 25,000 lbs its wing loading would be reduced to 250lbs/ ft sq and its maximum load factor in a manoeuvre would now be 4g.

In a turn therefore as load factor produced by the turn is dependent on angle of bank, a lighter aircraft of the same type as it will have a lower wing loading than the heavier one, will be able to achieve a greater angle of bank. This occurs as if two similar aircraft with the same wing area are turning, then the lighter aircraft will have a lower vertical lift requirement than the heavier aircraft, thereby providing a greater centripetal force towards the centre of the turn. Conversely, the higher the wing loading the greater will be the radius of turn.



3.24 Maximum Rate of Turning

To achieve the maximum rate of turn at a constant radius, the turn is carried out in the fastest possible speed. This can only be achieved if the centripetal force acting inwards is at it maximum, which again will depend on the permissible angle of bank.



To find maximum speed in a turn at a constant radius and permissible angle of bank, the horizontal and vertical forces in the turn need to be examined.

The horizontal force in the turn (centripetal force) is:

$$L\sin\theta = \frac{W V^2}{g r}$$

And the vertical force opposing weight is:

$$L\cos\theta = W$$

Combining these two forces as:

$$\tan\theta = \frac{\sin\theta}{\cos\theta}$$

So that:

$$\tan\theta = \frac{WV^2}{g r} \times \frac{1}{W} = \frac{V^2}{g r}$$

Rearranging this formula for the radius gives:

$$r = \frac{V^2}{g\tan\theta}$$

It can be seen therefore that the radius of a turn is totally independent of weight and is determined solely by its airspeed, and it's the angle of bank.

Thus, for a given radius if the speed is increased then the angle of bank must be increased. This increases the size of the centripetal force required to hold the aircraft at a constant radius, but as this also increases the load factor on the wing, so it requires that the wing loading is as low as possible.

So as with the minimum radius of turn, a maximum rate of turn can only be obtained when the:

The maximum values of the product of CL, speed and angle of bank must be obtained.

Wing loading must be as low as possible.

The air must be dense as possible, ie at mean sea level.

NOTE: As altitude increases the rate of turn and minimum turn radius decreases.

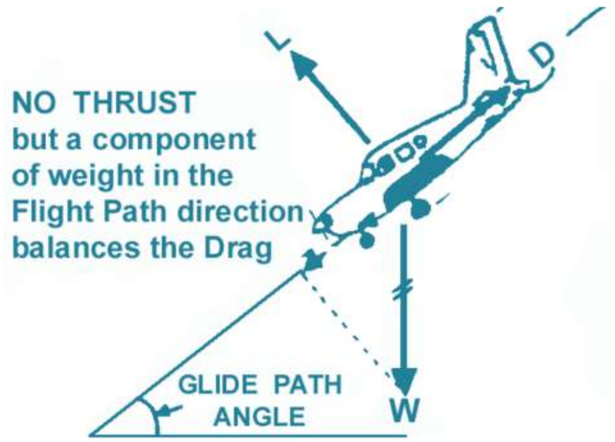
Effect of flaps in a turn

The lowering of flaps in a manoeuvre will produce more lift and can be advantageous, particularly when maneuvering an aircraft at low speed as it will produce a smaller radius turn. This is provided so that when flaps are lowered the flap limiting speed is not a critical factor and there is sufficient thrust to overcome the extra drag.

3.25 GLIDING

If the aeroplane is descending, with no thrust being produced by the engine/propeller, only three of the four main forces will be acting on the aeroplane-Weight, Lift and Drag-and in a steady glide these forces will be equilibrium as the resultant force acting on the aeroplane is zero.

Suppose that the aeroplane is in steady straight and level flight and the Thrust is reduced to zero. The Drag force is now unbalanced and will act to decelerate the aeroplane-unless a descent is commenced where the



Component of the Weight force acting in the direction of the flight path is sufficient to balance the Drag. This effect allows the aeroplane to maintain airspeed by descending and converting potential energy due to its altitude into kinetic energy (motion).

Resolving the forces in the flight path direction shows that a component of the Weight force acts along the flight path in a descent, balancing Drag and contributing to the aeroplane's speed.

Resolving the forces vertically, the Weight is now balanced by the total Reaction (i.e. the resultant of the Lift and Drag).

Notice that the greater the Drag force, the steeper is the glide. The shallowest glide is obtained when, for the required Lift Drag is least, i.e. at the best Lift/Drag ratio.

If the L/D is high, the angle of descent is shallow, i.e. a flat angle and the aeroplane will glide a long way.

If the L/D is poor (low), with a lot of Drag being produced for the required Lift, then the aeroplane will have a large angle of descent, i.e. a steep glide angle and will therefore not glide very far.

Two points can be made here :

1. An aerodynamically efficient aeroplane is one which can be flown at a high Lift/Drag ratio. It has the capability of gliding further for the same loss of height than an aeroplane that is flown with a lower L/D ratio.
2. The same aeroplane will glide furthest through still air when it is flown at the angle of attack (and airspeed)

that gives its best L/D ratio. This angle of attack is usually about 4 degrees.

The Wrong Airspeed (too fast or too slow) Steepens the Glide:

If the aeroplane is flown at a smaller angle of attack (and therefore faster), the L/D ratio will be less and the aeroplane will not glide as far-it will 'dive' towards the ground faster and at a steeper angle.

If the aeroplane is flown at a greater angle of attack (lower airspeed) than that for the best L/D ratio the L/D ratio will be less and therefore the optimum glide angle will not be achieved. This may be deceptive for the Pilot-the nose attitude may be quite high, yet aeroplane is descending steeply.

To Glide the Furthest in Still Air, fly at the Recommended Airspeed (and therefore Angle Attack) that

gives the
Best Lift/Drag Ratio.
If you are gliding at the recommended airspeed and it looks like you will not reach the desired point, do not raise the nose to increase the glide distance. It will not work. The higher nose attitude may give the appearance of stretching the glide, but in fact it will decrease your gliding distance.

Flaps Steepen the Glide (i.e. increase the Glide Angle):

Any flap settings will increase the Drag more than the Lift and consequently the L/D ratio is lower. This gives a steeper glide.
The Smaller Flap settings increases Lift significantly, with only a small increase in Drag-hence the name Lift Flaps sometimes given to low flap settings.
The Larger Flap Settings give large increase in Drag with only a small increase in the Lift-hence the name Drag Flaps for the larger flap settings. Large flap settings will give a much steeper glide. (The lower nose attitude required with flap extended give the Pilot much better visibility.)

Reduced Weight does not change the Glide Angle, but reduces the best Gliding Speed:

If the Weight is less, the aircraft will have a lower airspeed at any particular angle of attack compared to when is heavy. At the angle of attack for the best L/D ratio (and therefore for the best glide), the airspeed will be lower but the glide angle the same. This also means that the rate of descent for the aeroplane when it is lighter will be less.

3.26 POLAR CURVE:

A polar curve is a graph which establishes the relation between rate of sink of a glider with its forward speed. It mainly illustrates performance characteristics of a glider. The two main parameters of a glider's performance are its minimum sink rate and its best glide ratio, also known as the best glide angle. These occur at different speeds. Knowing these speeds is important for cross country flying. In still air, the polar curve shows that flying at the minimum sink speed enables the pilot to stay airborne for as long as possible. But at this speed, the range will not be that far as if it flew at the speed for the best glide.
By measuring the rate of sink at various air-speeds, the same can be plotted on a graph. The points can be connected by a curve known as Polar Curve. The origin for a polar curve is where the air-speed is zero and the sink rate is zero. A whole series of lines could be drawn from the origin to each of the points, each line showing the glide angle for that speed. However, the best glide angle is the line with the least slope. We can see that the best glide ratio is shallower than the glide ratio for minimum sink.

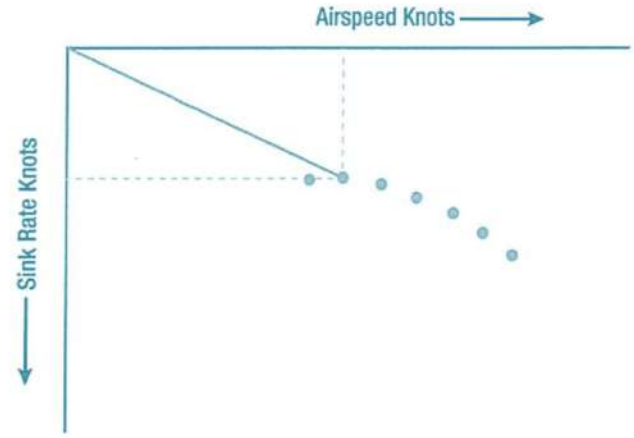


Figure 3-3. Polar curve showing glide angle for minimum sink.

3.27 TRANSONIC FLIGHT

[SUBSONIC, SONIC AND SUPERSONIC FLOW PATTERNS]

We have already discussed about flight at subsonic, sonic, and supersonic speeds, and it should now be clear that the problems of flight are quite different in these three regions, but the dividing lines between the regions are of necessity somewhat vague. The subsonic region hitherto is being considred to be below a Mach Number of 0.8, the transonic region from M 0.8 to M 1.2, and the supersonic region above M 1.2. There are arguments in favour of considering the transonic region as starting earlier, say at a Mach Number of about 0.75 or near the point marked in the figure as the critical Mach Number, and extending up to say a Mach Number of 1.6 or even 2.0. In terms of sea-level speeds this would mean defining subsonic speed as being below 450 knots, transonic speeds as 450 up to 1000 or even 1200 knots, and supersonic speeds above that.

Perhaps the best definition of the three regions is to say that the subsonic region is that in which all the airflow over all parts of the aeroplane is subsonic, the transonic region is that in which some of the airflow is subsonic and some supersonic, and the supersonic region is that in which all the airflow is supersonic. Once again we are in trouble if we take our definition too literally.Even at very high speeds we may have local pockets of subsonic flow - just in front of a blunt nose for example. So the space shuttle would only be transonic even at the fastest point of reentry!Also with this definition we are none the wiser as to the speeds or Mach Numbers at which each regions begins or ends; the beginnings and endings will of course be quite different for different aeroplanes.
In this chapter our main concern is with speeds in the transonic range, and particularly in the narrow range between Mach Numbers of 0.8 and 1.2. This range, as is probably already evident, presents us with some of the most baffling but fascinating problems of flight; it is the range in which most of the change takes place, the change from apparent incompressibility to actual compressibility, the gradual substitution of supersonic flow for subsonic flow; it is the range about which we are even now most ignorant.

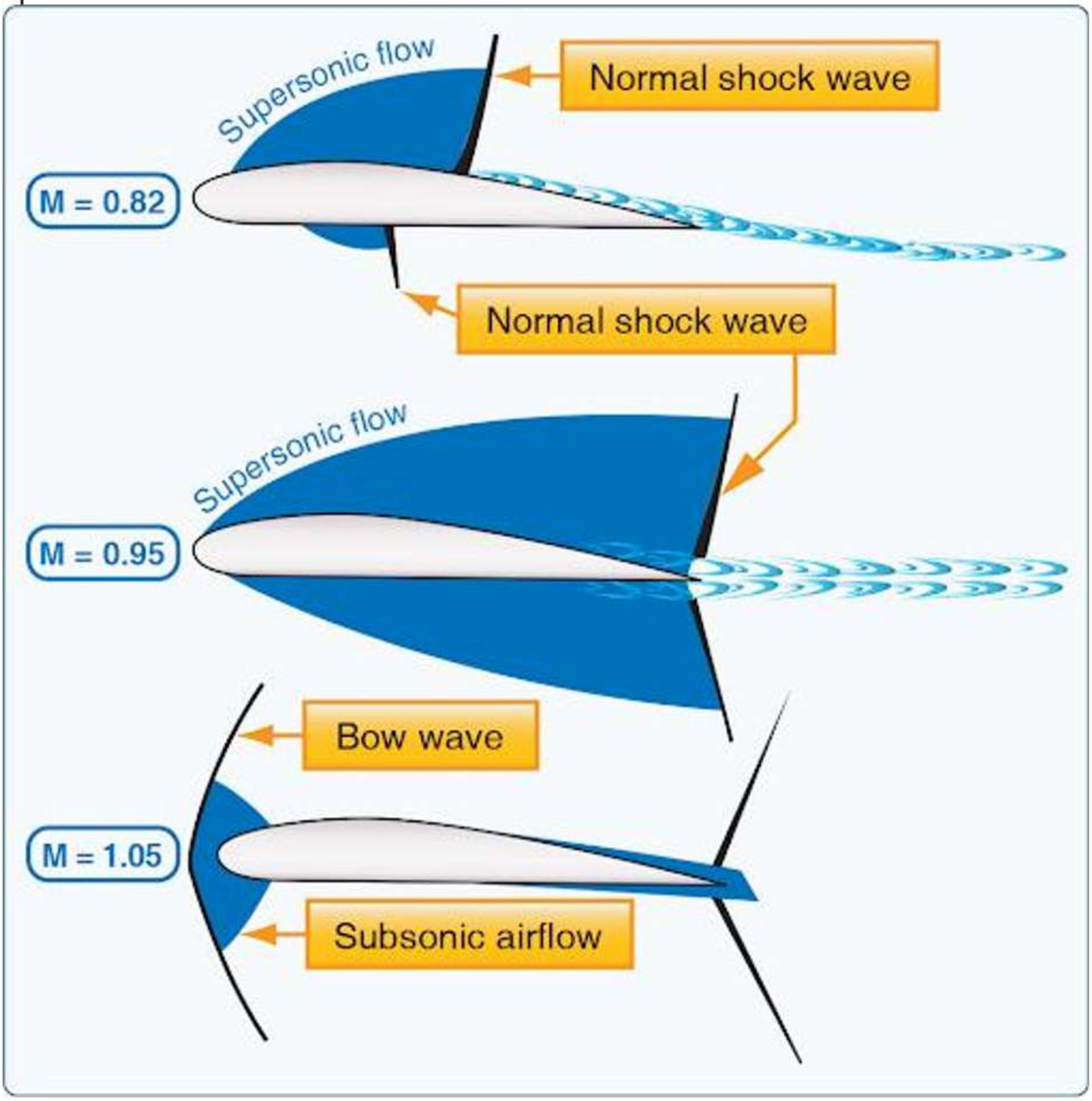
3.28 FORMATION OF SHOCK WAVES

In an earlier paragraph we described how a shock wave is formed at a speed of about three-quarters of the speed of sound, i.e. at about M = 0.75. On a symmetrical wing at zero angle of attack the incipient shock wave appears on both top and bottom surfaces simultaneously, approximately at right angles to the surfaces, and, as one would expect, at about the point of maximum camber. On a wing at a small angle of attack, even if the aerofoil section is symmetrical, the incipient shock wave appears first on the top surface only - again as one would expect, because it is on the top surface that the speed of the airflow first approaches the speed of sound.

The following figure shows how the shock-wave pattern changes (on a symmetrically shaped sharp-nosed aerofoil at zero angle of attack) as the speed of airflow is increased from subsonic, through the transonic range to fully supersonic flow.

Between the formation of the incipient wave (at a Mach Number of about 0.75 or 0.8) and the time when the wing as a whole is moving through the air at a speed of sound (M = 1.0), the shock wave tends to move backwards, but in doing so becomes stronger and extends farther out from the surface, while there is even more violent turbulence behind it. At a speed just above that of sound another wave appears, in the form of a bow wave, some distance ahead of the leading edge; and the original wave, which is now at the trailing edge, tends to become curved, and shaped rather like a fish tail . As the speed is further increased the bow wave attaches itself to the leading edge, and the angles formed between both waves and the surfaces become more acute .Still further increases of speed have little effect on the general shock-wave pattern .

At each wave there is a sudden increase of pressure, density and temperature, a decrease in velocity, and a slight change in direction of the airflow. The thickness of a shock wave, through which these changes take place, is only of the order of 2 to 3 thousandths of a millimetre - they look thicker on photographs because it



is not possible to get a perfectly plane shock wave in the experiment. The changes at the shock wave are irreversible, which is another way of saying that the high pressure behind the wave cannot be communicated to the lower pressure in front - messages can only go down stream. It is interesting to note, however, that the incipient waves only extend a short distance from the surface, and leaks are possible round the ends of the waves; as speed increases the waves extend and there is less and less possibility of such leaks. It is interesting to note, too, that the decrease in velocity, which occurs behind the shock wave, means that when an aircraft is moving through the air, and a shock wave is formed, the air behind the shock wave begins to move in the direction in which the aircraft is travelling.

In addition to showing the shock-wave patterns, the above fig. also indicates the areas in which the flow is subsonic orsupersonic. In (a) at M = 0.6 it is all subsonic (clearly we are still in the subsonic region); at M = 0.8 the flow immediately in front of the shock wave is supersonic, but all the remainder is subsonic (we are now in the transonic region with both types of flow); at M = 1 the area of supersonic flow has increased but the flow behind the shock wave is still subsonic
(as we shall learn later it is always subsonic behind a shock wave that is at right angles to the flow, it can only be supersonic behind an inclined or oblique shock wave); at M = 1.1 nearly all the flow is supersonic, but there are still small regions of subsonic flow, immediately in front of the leading edge at what is called the stagnation point where the flow is brought to rest, and immediately behind the trailing edge (we are still in the transonic region, but not for much longer); at M = 2 the flow is all supersonic - we are through the barrier (though to be strictly correct, unless the bow
wave is actually attached to the leading edge, which will only happen if the edge is very sharp, there will still be a small area of subsonic flow at the stagnation point between the bow wave and the leading edge; and of course in the boundary layer itself the air immediately next to the surface is at rest relative to the surface, and most of the remainder of the airflow in the boundary layer is subsonic).

The figure also shows how the extent of the separated region, or thickened boundary layer tends to decrease with increasing Mach Number, and this suggests that as wave drag becomes relatively less so. This may also give a clueto the decrease in drag coefficient as we pass through the barrier .
When supersonic flow is clearly established, all changes in velocity, pressure, density, flow direction, etc., take place quite suddenly and in relatively confined areas. The areas of flow change are generally distinct and the phenomena are referred to as "wave" formations. All compression waves occur suddenly and are wasteful of energy. Hence, the compression waves are distinguished by the sudden "shock" type of behaviour. All expansion waves are not so sudden in their occurrence and are not wasteful of energy like the compression shock waves. Various types of waves can occur
in supersonic flow and the nature of the wave formed depends upon the airstream and the shape of the object causing the flow change. Essentially, there are three fundamental types of waves formed in supersonic flow: 1. the oblique shock
wave (compression), 2. the normal shock wave (compression), 3. the expansion wave (no shock).

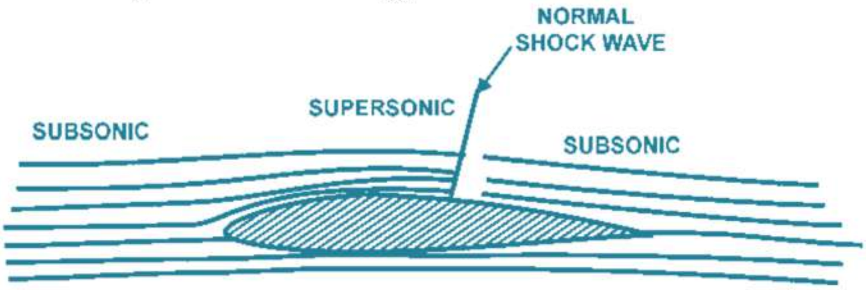
i. Normal Shock Wave

If a blunt nosed object is placed in a supersonic airstream the shock wave which is formed will be detached from the leading edge. This detached wave also occurs when a wedge or cone angle exceeds some critical value. Whenever the shock wave forms perpendicular to the upstream flow, the shock wave is termed a "normal" shock wave and the now immediately behind the wave is subsonic. Any relatively blunt object in a supersonic airstream will form a normal shock wave immediately ahead of the leading edge slowing the airstream to subsonic so the airstream may feel the presence of the blunt

nose and flow around it. Once past the blunt nose the airstream may remain subsonic or accelerate back to supersonic depending on the shape of the nose and the Mach number of the free stream. In addition to the formation of normal shock waves described above, this same type of wave may be formed in an entirely different manner when there is no object in the supersonic airstream. It is particular that whenever a supersonic airstream is slowed to subsonic without a change in direction a normal shock wave will form as a boundary between the supersonic
and subsonic regions. This is an important fact since aircraft usually encounter some "compressibility effects" before the flight speed is sonic. As the local supersonic flow moves aft, a normal shock wave forms slowing the flow to subsonic. The transition of flow from subsonic to supersonic is smooth and is not accompanied by shock waves if the transition is made gradually with a smooth surface. The transition of flow from supersonic to subsonic without direction change always forms a normal shock wave.

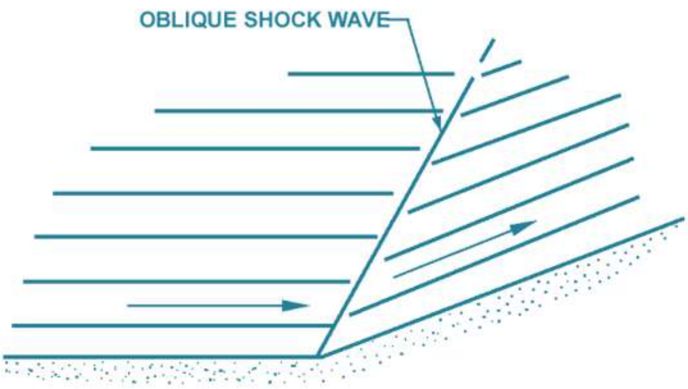
A supersonic airstream passing through a normal shock wave will experience these changes:

1. The airstream is slowed to subsonic; the local Mach number behind the wave is approximately equal to the reciprocal of the Mach number ahead of the wave-e.g., if Mach number ahead of the wave is 1.25 the Mach number of the flow behind wave is approximately 0.80.
2. The airflow direction immediately behind the wave is changed.
3. The static pressure of the airstream behind the wave is increased greatly.
4. The density of the airstream behind the wave is increased greatly.
5. The energy of the airstream (indicated by total pressure-dynamic plus static) is greatly reduced. The normal shockwave is very wasteful of energy.



ii. Oblique Shock Wave

Consider the case where a supersonic airstream is turned into the preceding airflow. Such would be the case of a supersonic flow "into a corner" as shown in Fig. A supersonic airstream passing through the Oblique shock wave will experience these changes:



SUPERSONIC FLOW INTO A CORNER

1. The airstream is slowed down; the velocity and Mach number behind the wave are reduced but the flow is still supersonic.
2. The flow direction is changed to flow along the surface.
3. The static pressure of the airstream behind the wave is increased.

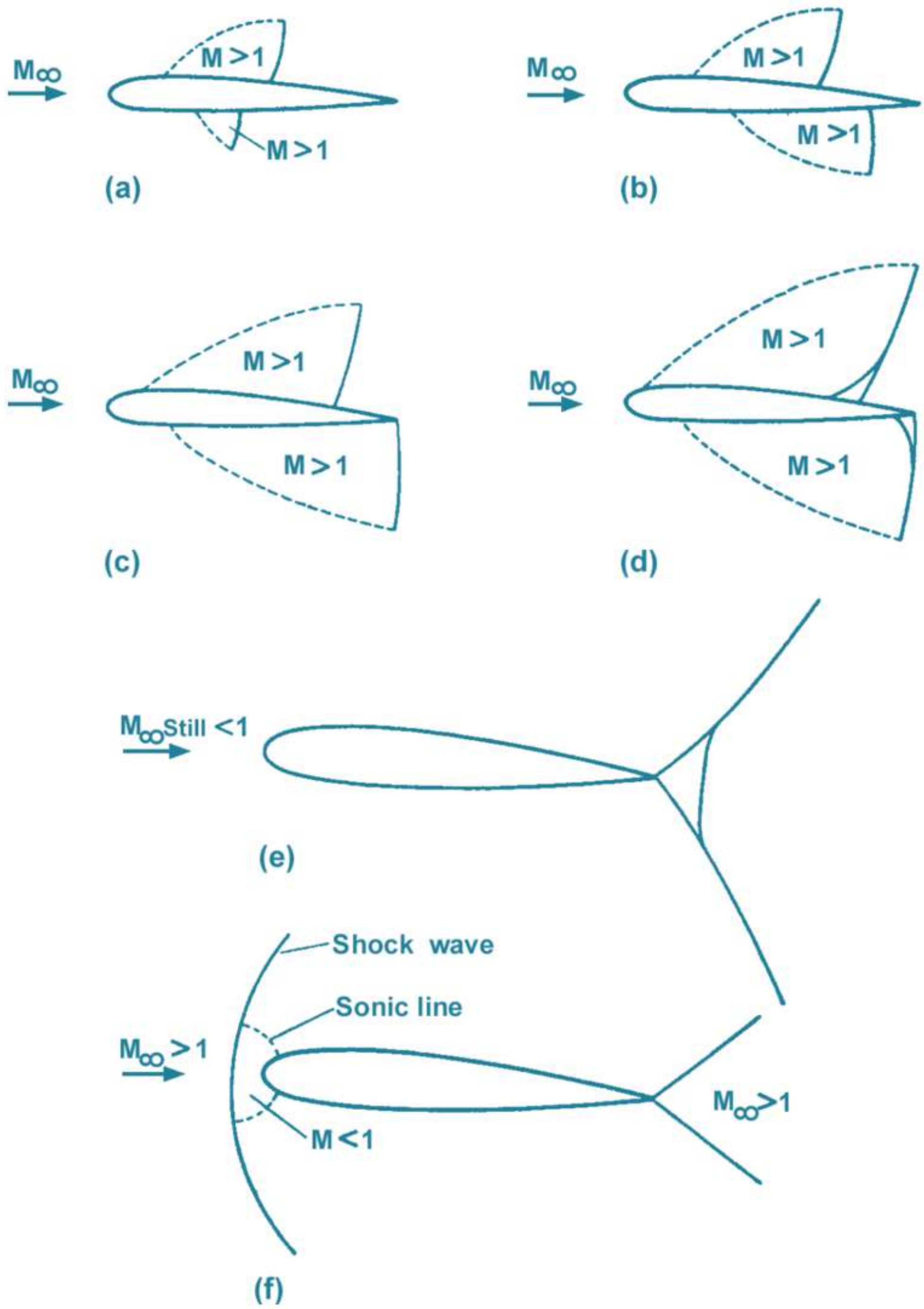
4. The density of the airstream behind the wave is increased.

5. Some of the available energy of the airstream (indicated by the sum of dynamic and atmospheric pressure) is dissipated and turned into unavailable heat energy. Hence, the shock wave is wasteful of energy.

A typical case of oblique shock wave formation is that of a wedge pointed into a supersonic airstream. The oblique shock wave will form on each surface of the wedge and the inclination of the shock wave will be a function of the free stream Mach number and the wedge angle. As the free stream Mach number increases, the shock wave angle decreases; as the wedge angle increases the shock wave angle increases, and, if the wedge angle is increased to some critical amount, the shock wave will detach from the leading edge of the wedge. It is important to note that detachment of the shock wave will produce subsonic flow-immediately after the central portion of the shock wave.

iii. Bow Wave

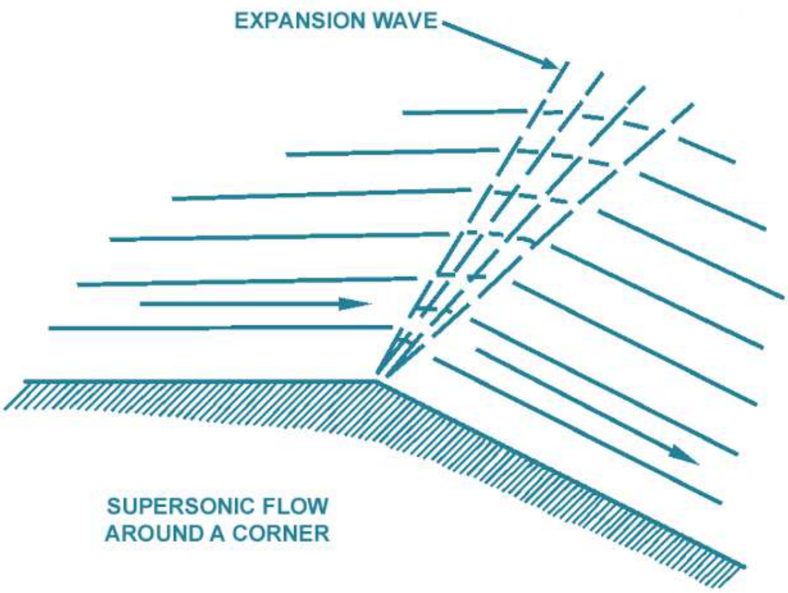
Consider then a supersonic stream approaching the leading edge of a subsonic, i.e., round-nosed, aerofoil. In order to flow round the nose, the air has to turn through a right angle. At supersonic speeds, this impossible, and therefore a normal shock is created ahead of the nose. Behind this shock, the flow is subsonic, and can therefore flow round the nose. Within a short distance, however, the flow again accelerates to supersonic speeds. The flow pattern is then as indicated in the following Fig.. This shock ahead of the leading edge, called a detached bow shock.

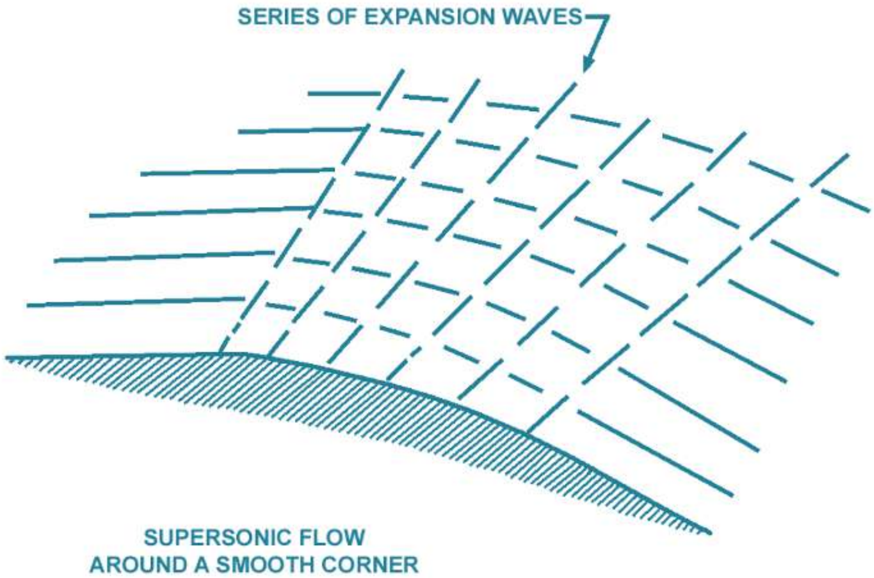


iv. Expansion Wave

If a supersonic airstream were turned away from the preceding flow an expansion wave would form. The flow "around the corner" shown in following Fig. will not cause sharp, sudden changes in the airflow except at the corner itself and thus is not actually a "shock" wave. A supersonic airstream passing through an expansion wave will experience these changes:

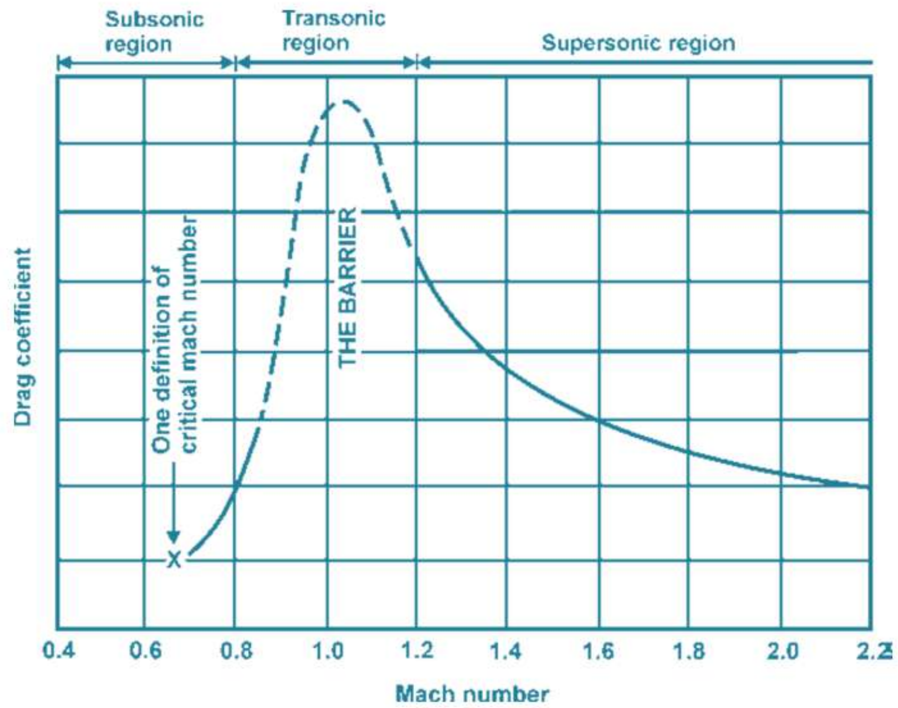
1. The airstream is accelerated; the velocity and Mach number behind the wave are greater.
2. The flow direction is changed to flow along the surface-provided separation does not occur.
3. The static pressure of the airstream behind the wave is decreased.
4. The density of the airstream behind the wave is decreased.
5. Since the flow changes in a rather gradual manner there is no "shock" and no loss of energy in the airstream. The expansion wave does not dissipate airstream energy.





3.29 CRITICAL MACH NUMBER

When an aerofoil at low incidence is immersed in a flow at high subsonic speeds, the flow round the aerofoil is accelerated locally so that the Mach number at some points is higher than the value in the free stream. This is especially so on the upper surface, where velocities are generally higher than on the lower surface. If the free stream Mach number is increased sufficiently, there will come a stage when the local Mach number reaches unity at some point on the upper surface, though the free stream is still subsonic. The free stream Mach number at which this first occurs is called the Critical Mach number, is denoted by Mcrit,and is the lower limit of the transonic flow regime. For values of M just greater than Mcrit, there will then be a small region of supersonic flow on the upper surface, terminated by a normal shock,

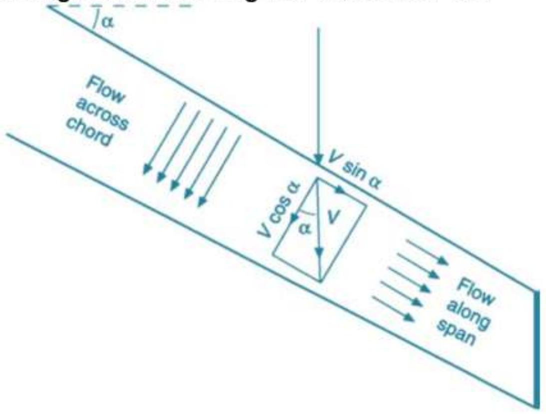


3.30 TO INCREASE CRITICAL MACH NUMBER : SWEEP BACK

The second main way of raising the critical Mach Number (and this applies only to the wings, tail, fin, and control surfaces) is sweepback - not just the few degrees of sweepback that was sometimes used, rather apologetically andfor various and sometimes rather doubtful reasons, on subsonic aircraft, but 40^0, 50^0, 70^0 or more.

Sweepback of this magnitude not only delays the shock stall, but reduces its severity when it does occur. The theory behind this is that it is only the component of the velocity across the chord of the wing (V cos α which is responsible for the pressure distribution and so for causing the shock wave ,the component V sin α along the span of the wing causes only frictional drag. This theory is borne out by the fact that when it does appear the shock wave lies parallel to the span of the wing, and only that part of the velocity perpendicular to the shock wave, i.e. across the chord, is reduced by the shock wave to subsonic speeds. As the figure clearly shows, the greater the sweepback the smaller will be the component of the velocity which is affected, and so the higher will be the critical Mach Number, and the less will be the drag at all transonic speeds of a wing of the same t/c ratio and at the same angle of attack.

Experiment confirms the theoretical advantages of sweepback, though the improvement is not quite so great as the theory suggests. The dotted line in the following diagram shows how a wing swept back at 45^0 has a higher Critical Mach Number than a straight wing at all values of t/c ratio, the advantage being greater for the wings with the higher values of t/c.



When α increases, V cos α (which is responsible for local Mach number) decreases and hence Critical Mach number increases. Sweepback not only increases the critical Mach Number, but it reduces the rate at which the drag coefficient rises (the slope of the curve), and it lowers the peak of the drag coefficient - and 45^0 of sweepback does all this better than 30^0. Incidentally this figure also shows that, above about M2, sweepback has very little advantage - but that is another story and, in any case, aeroplanes cannot fly at M2 without first going through the transonic range.

Of course, as always, there are snags, and the heavily swept-back wing is no exception. There is tip stalling - an old problem, but a very important one; in the crescent-shaped wing an attempt has been made - with some success - to alleviate this by gradually reducing the sweepback from root to tip. CL max is low, and therefore the stalling speed is high, and CL max is obtained at too large an angle to be suitable for landing - another old problem, and one that can generally be overcome by special slots, flaps or suction devices. There are also control problems of various kinds, and the designer doesn't like the extra bending and twisting stresses that are inherent in the heavily swept-back wing design.

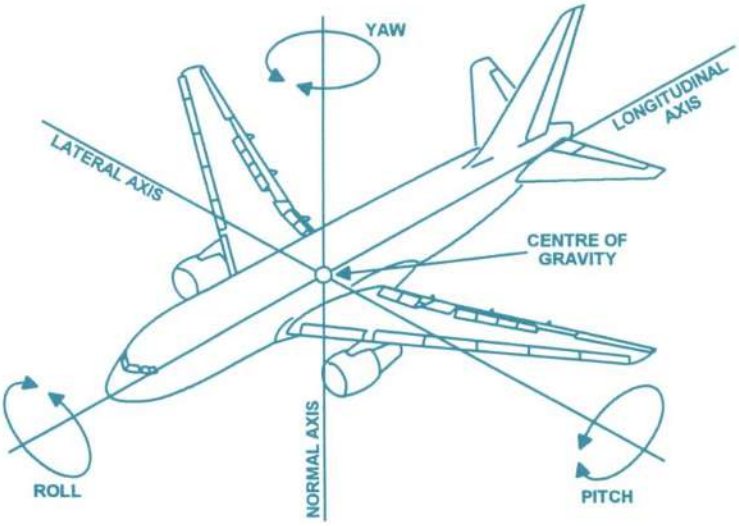
But whatever the problems sweepback seems to have come to stay - at least for aircraft which are designed to fly for any length of time at transonic or low supersonic speeds.

STABILITY

4.1 Introduction

In level flight, whenever an aircraft is disturbed the reaction of the aircraft to the disturbance, will depend on the level of stability that an aircraft possesses. The stability of an aircraft therefore, is the natural tendency of an aircraft to return to its level flight position following a disturbance without any assistance or inputs from the pilots.

Stability therefore occurs whenever an aircraft is rotated about any one or a combination of its three axes



In flight the different types of motion and the stability it affects, is shown in the table below.

Stability	Axes	Motion about the axis
Longitudinal	Lateral	Pitch
Lateral	Longitudinal	Roll
Directional	Normal	Yaw

Stability of an aircraft about these axes however is not entirely independent of each other, as depending on the design, lateral and directional stability tend to act together in certain circumstances to produce certain undesirable motion.

This occurs as the axes of an aircraft act at right angles to each other, and all pass through the aircraft's centre of gravity. This allows an aircraft to move freely about any one of its three axes simultaneously, so that an aircraft can be unstable about two axes, but stable about a third and visa versa.

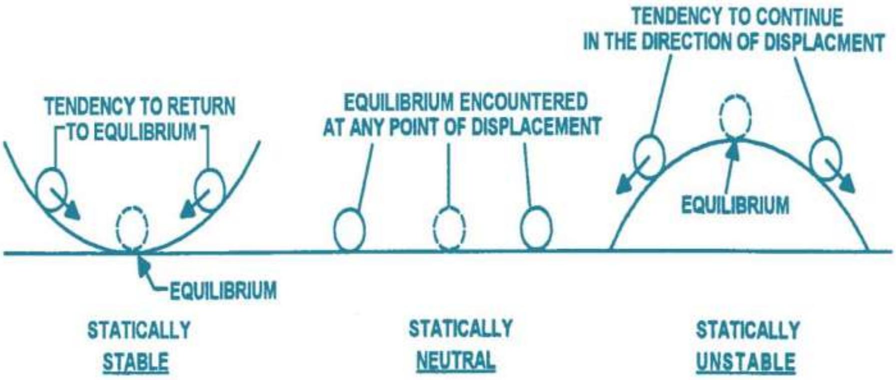
Since stability occurs without any inputs from the pilots, the actual stability characteristics of an aircraft are governed by its design. In designing stability into an aircraft however, designers and engineers must take into account the workload requirements of the pilot, as the higher the stability, the harder it is for the pilot to alter the position or attitude of the aircraft by using its flying control surfaces.

A close relationship therefore exists between stability and controllability, so that the actual levels of stability achieved are a compromise between the complete stability and the desired handling characteristics of the aircraft. For example, the stability requirements for example of large commercial aircraft will be vastly different than that of a smaller lighter aircraft or a military fighter. The compromise however means that no aircraft is ever completely 100% stable, as the upper limits of stability are determined by the lower limits of controllability.
In designing stability into an aircraft, the stability of an aircraft is considered as both static and dynamic in nature. The static stability being the immediate reaction of the aircraft to a disturbance, and the dynamic stability the aircraft's reaction to the disturbance over a period of time.

4.2 Static Stability

Static Stability of an Aircraft

The static stability of an aircraft is considered to be either positive, negative or neutral and is the initial tendency an aircraft displays after it has been disturbed from its given equilibrium position.
If an aircraft moves back towards its original position after a disturbance, it is said to be statically stable or have positive stability. If however it continues to move in the direction of the displacement it is said to be statically unstable or have negative stability and if it tends to remain in the disturbed position, neither moving back towards its original position or away from it, it is said to be statically neutral or have neutral static stability.
The type of static stability of an aircraft can experience, being easily demonstrated by using a ball and a curved container.



If a ball is moved from its rest point to the top of the bowl and then released, it would initially move back towards the centre and oscillates about the middle before finally coming to a rest back where it started. This describes positive stability, as the ball initially moved back towards its original position, so the object is said to be statically stable.

If however the container was turned upside down and the ball moved, the ball would move away from its rest point and continue to move in the direction of any applied force. This motion describes negative stability, as the ball when disturbed initially moved away from it rest point so the object is said to be statically unstable.

Finally if the container was removed and the ball disturbed, the ball will move to a new position where it would remain. This describes an object with the neutral stability, as the ball neither moves towards or away from its rest point, so the object is said to be statically neutral.

4.3 Dynamic Stability

Dynamic stability of an aircraft is the movement of an aircraft after a disturbance in response to its static stability with respect to time. For example, an aircraft that is statically stable will after a disturbance, try to return to its original position but more than likely will overshoot. The inbuilt stability of the aircraft will then attempt to correct this overshoot and an oscillatory motion known as

a phugoid will occur.
In any disturbance it is rare to find that an aircraft after it has been disturbed, react without some kind of oscillation, or part of one. The exact behaviour however, will depend mainly on its design features, but the five most common behaviour patterns are:

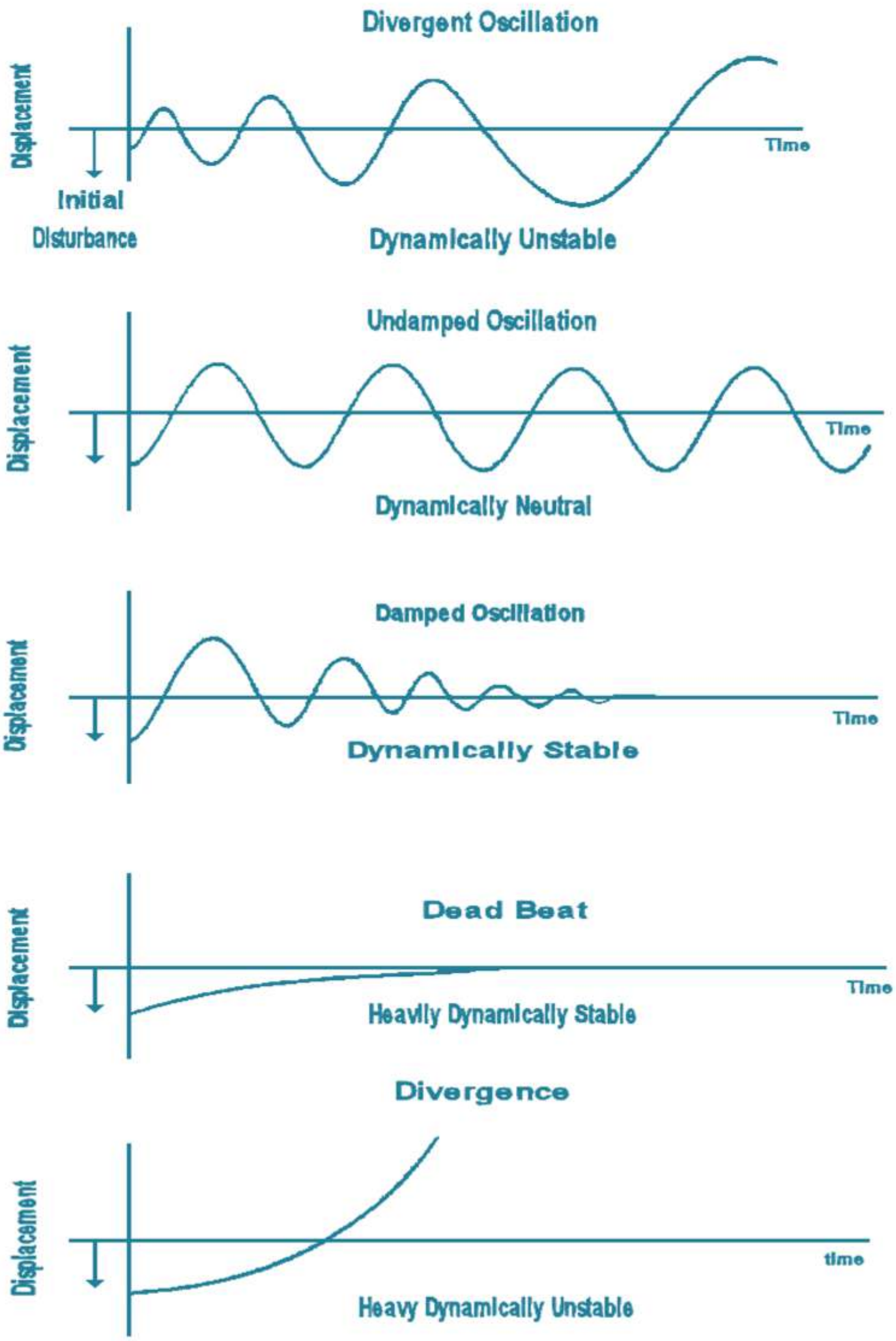
- Dynamically Unstable – the oscillations are divergent with the amplitude of the oscillations increasing over time.

- Dynamically Neutral – the oscillations are undamped, so the amplitude of the oscillations stays constant with time.

- Dynamically Stable - the oscillations are damped, so the amplitude of the oscillations decreases with time.

- Heavy Dynamically Stable – heavily damped so oscillation stop rapidly with no overshoot, known as Dead-beat stability.

- Heavy Dynamically Unstable – the oscillation is completely divergent.



As any one of these behaviour patterns can occur over any of the different axes in flight, the overall stability of an aircraft after a disturbance can be quite complicated, especially if the aircraft is moving about all three axes simultaneously. So in order to study the stability of an aircraft, it is common to initially consider the stability about each axis independently and then look at how the different types of stability interact.

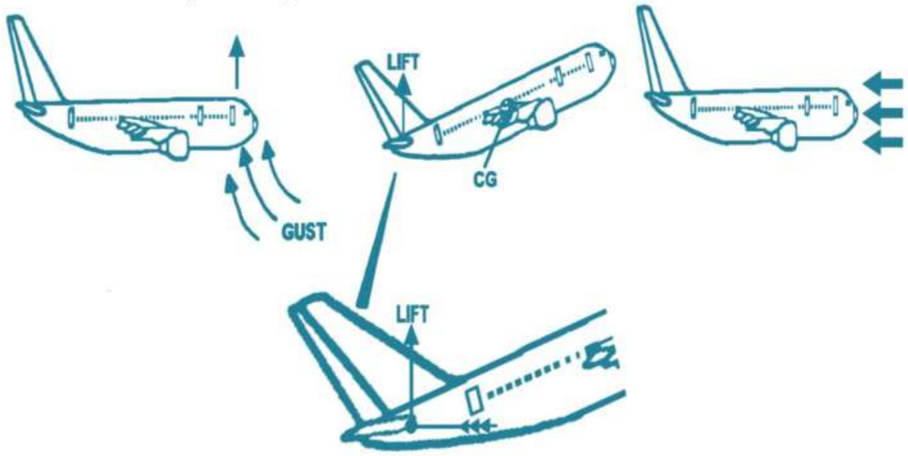
4.4 Longitudinal Stability

The longitudinal stability of an aircraft is the stability concerning the pitching movement of the aircraft about its lateral (or transverse) axis. The movement about the lateral axis is known as the longitudinal stability as in this type of disturbance it is the longitudinal axis of the aircraft that moves up or down as the aircraft's pitches either nose up or nose down.

In a disturbance in pitch, to return the aircraft to level flight, the tailplane, or horizontal stabiliser, as it is now commonly known, needs to produce either an upload or download that will overcome the disturbance and pitch the aircraft back level.

For example if an aircraft is disturbed by a sudden gust of wind that pitches the aircraft nose-up, the tailplane will produce an opposite force to pitch the aircraft back nose down. This occurs because even although the aircraft is now in a nose up condition, it will initially due to its momentum continue in the direction of its original level flight path for a small period of time.

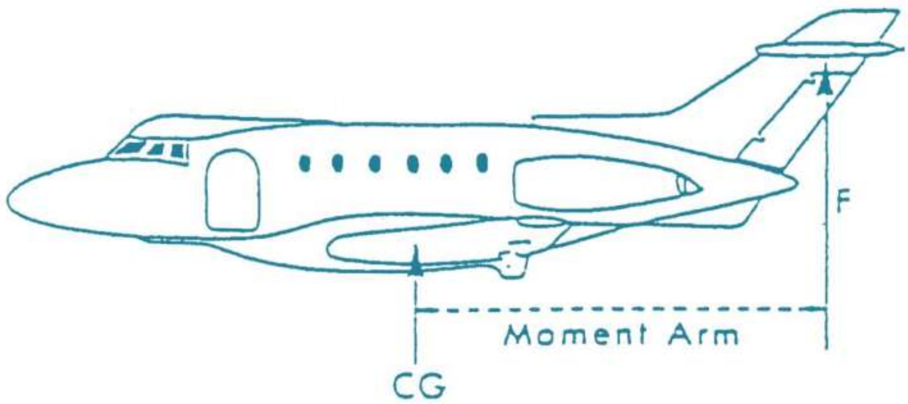
In this nose up attitude, the angle of attack on both the mainplane and the tailplane is increased, which will produce lift on both surfaces. The effect of the increase in lift on the mainplane being to try and increase the aircraft's nose up attitude, as its centre of pressure moves forward. At the same time however, the increase in angle of attack on the tailplane will create lift on the upper surface of the tailplane producing an upload that overcomes both the disturbance and the additional lift of the wings, to produce overall a nose-down pitching moment that will restore the aircraft to its original attitude.



The degree of longitudinal stability of an aircraft therefore, is depends upon the size of the restoring moment provided by the tailplane, which is determined mainly by:
The length of the longitudinal moment arm.
Size and shape of the tailplane or horizontal stabiliser.

4.5 Length of the Longitudinal Moment Arm

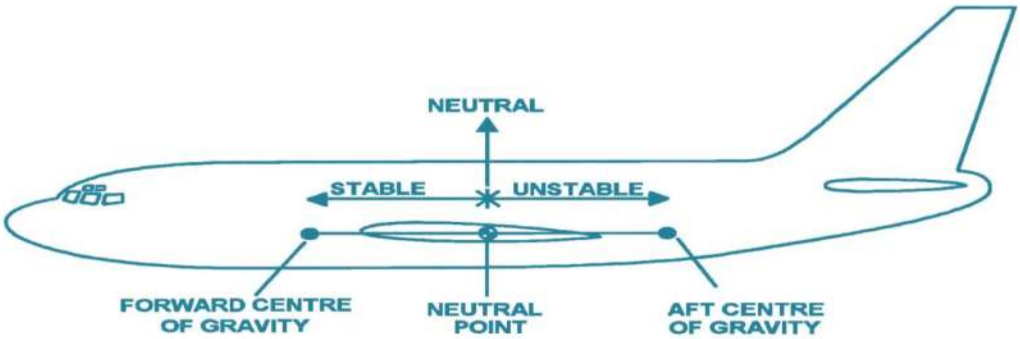
The longitudinal moment arm of an aircraft is the distance measured from the aircraft's centre of gravity to the centre of pressure of the tailplane (Cp tail). This affects the longitudinal stability of an aircraft, as the aircraft pitches about the centre of gravity, so the moment arm will multiply any lift produced by the tailplane to produce a large pitching moment.



Any movement of the centre of gravity will either increase or decrease the length of the moment arm, which will affect the longitudinal stability of an aircraft, as it will alter the size of the restoring moment.

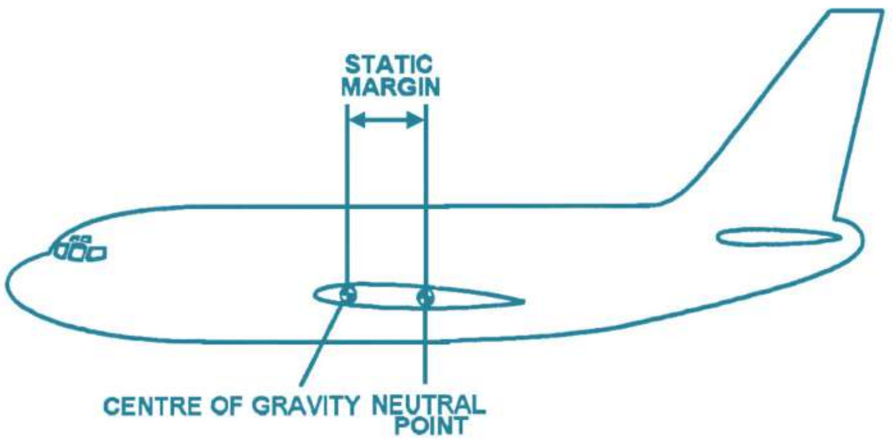
Generally, the further forward the centre of gravity is, the greater will be the aircraft stability, but since a high level of stability results in poor controllability. The further forward is the centre of gravity is, the greater will be the stick force necessary to manoeuvre the aircraft. An aircraft therefore reaches a point where the stick force becomes excessively large and the aircraft becomes difficult to manoeuvre, especially at low speeds where it would become uncontrollably nose heavy.
To prevent this happening, a forward limit is set which give the aircraft its maximum stability but minimum handling characteristics. By comparison, if the centre of gravity is moved progressively rearward, the degree of stability steadily decreases, as does the stick force required, and the aircraft becomes more maneuverable but will return less rapidly to the trimmed position.

Eventually as the centre of gravity is moved rearwards, a point is reached where the aircraft will no longer return to a trimmed position but remain in its disturbed position. This is the aircraft's neutral point and the centre of gravity position that gives an aircraft neutral static stability. Any further movement therefore of the centre of gravity past this point will make the aircraft longitudinal statically unstable requiring an input from elevator control system to return the aircraft back to level flight.



The final position of the centre of gravity is the rear or aft position. This is the furthest rearward position of the centre of gravity that the controls surfaces can return the aircraft back to level flight, so any movement of the centre of gravity beyond this point would mean that if disturbed an aircraft would not be able to return to level flight and would continue to diverge.

As most aircraft however are designed to be longitudinally statically stable, the range of movement of the centre of gravity is confined to between the forward centre of gravity and a point just ahead of the neutral point, this is known as the static margin or C of G margin of an aircraft, and ensures that an aircraft after a disturbance can return to level flight without pilot assistance.



The size of the static margin for an aircraft is given in the aircraft manual and will vary greatly between different types of aircraft. For example, on some military aircraft the CG margin is as low as a few centimetres but on large passenger aircraft it can be greater than a metre.

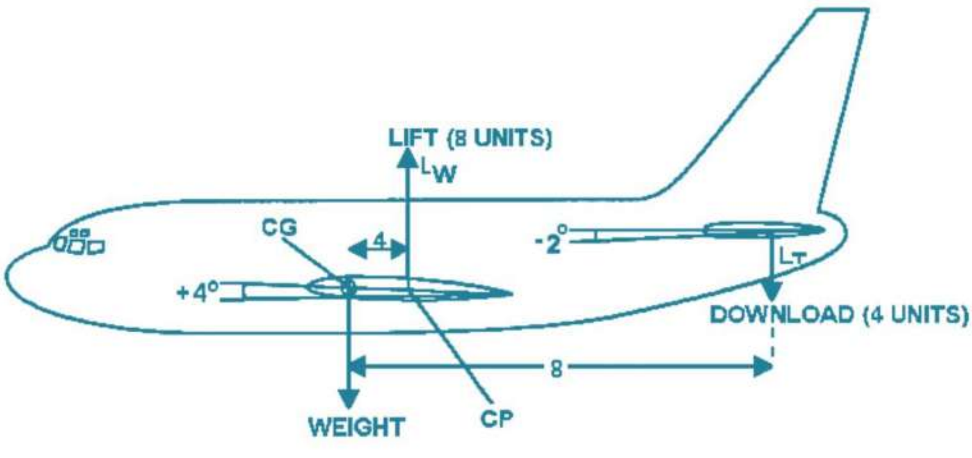
4.6 Size and Shape of the Tailplane or Horizontal Stabiliser

Like all aerofoils, the planform size and shape of the tailplane or horizontal stabiliser will affect the amount of lift the tailplane produces at a given angle of attack. In designing the tailplane therefore, designers and engineers need to take account that although the size of the planform area is directly proportional to the lift produced by the tailplane, its aspect ratio, taper and angle of sweepback, will all have an effect on the tailplane's coefficient of lift (C_L tail), which will affect the overall lift produced.

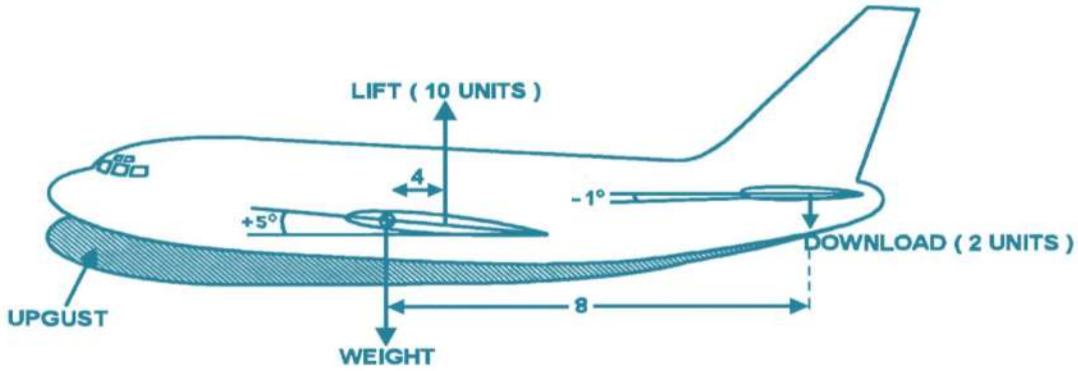
In designing the tailplane, as the length of the moment arm will multiply any force, the overall size of the tailplane is relatively small compared to that of the mainplane. The size of the moment arm multiplied by the tailplane area is known as the tail volume and is one of the main parameters that designer's use in determining the size of tailplane required. This is because when the tail volume is compared to the wing volume, wing area times its moment arm, the size of the clockwise or anticlockwise moments required to balance out the aircraft can be worked out.

For example in level flight, one of the functions of the tailplane is to balance out any discrepancies of the main two couples, so if an aircraft is flying with an optimal angle of attack of 4° on the mainplane, and let it produces a lift force (L_W) of 8 units through the wings centre of pressure that is 4 units away from the centre of gravity. Then in order to maintain level flight, the tailplane, which is 8 units away from the centre of gravity, must produce a force so that the sum of the clockwise moments produced by the tailplane equals the anti-clockwise moments produced by the lift on the mainplane. To balance out the aircraft therefore, the download (L_T) at the tailplane centre of pressure must be 4 units, which would require the tailplane to have a negative angle.

$L_T \times 8 = L_W \times 4$
$4 \times 8 = 8 \times 4$
$32 = 32$



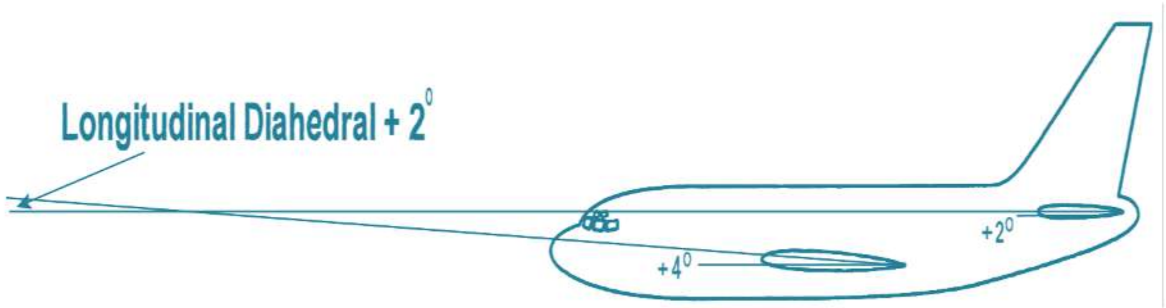
If however, the aircraft is suddenly disturbed by an up gust of wind that pushes the nose upwards. The aircraft due to its momentum will momentarily continue in its original flight path so that the angle of attack on the both mainplane and tailplane increases. If this, for example brings about an increase in the amount of lift generated by the wings to 10 units, and a reduction in the download acting on the tailplane to 2 units. The sum of the clockwise moments compared to the anticlockwise moments is no longer in balance, so a pitching moment will occur.



In this condition as the anticlockwise moments of the wing volume are now greater than the clockwise moments of the tail volume:

$L_W \times 4 = 10 \times 4 = 40$ units
$L_T \times 8 = 2 \times 8 = 16$ units

The aircraft will pitch in the anti-clockwise direction (nose down) to return the aircraft to its former trimmed position. For a larger disturbance, the angle of attack on the tailplane would now become positive, creating an upload that will increase the anticlockwise pitching moments in order to return the aircraft back to its trimmed position.
In level flight, as the arrangement of main couples normally require the tailplane to produce an upload or a download, the angle of incidence of the wings and the tailplane are normally set different. This is known as the longitudinal dihedral angle of the aircraft, and is measured between the chord line of the tailplane and chord line of the mainplane.



Note: In the above examples it has been assumed that the lines of action has not moved significantly with respect to the centre of gravity, and therefore the length of the moment arm remains unaltered, although in practice they would.

4.7 Other Factors affecting Longitudinal Stability

In a disturbance, other factors that affect the longitudinal stability of an aircraft are:
Size and shape of the keel surface rear of the centre of gravity.
Position of the tail plane.
Stick free surfaces.

4.8 Size and Shape of the Keel Surface Rear of the Centre of Gravity

The size and shape of the aircraft keel surface rear of the centre of gravity can affect the longitudinal stability of an aircraft, as when an aircraft is disturbed, the rear of the aircraft is brought directly into line with the relative airflow causing interference. This creates a pressure differential between the upper and lower surfaces of the fuselage that produces lift over the rear of the fuselage to help restore the pitching moment about the centre of gravity.

4.9 Position of the Tail Plane

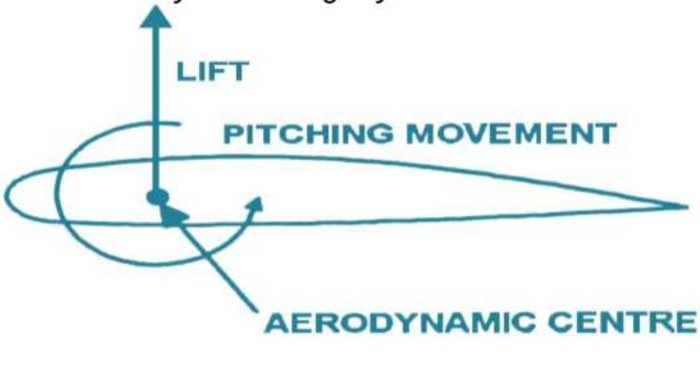
The positioning of the tailplane on an aircraft can affect longitudinal stability, as if the tailplane is placed in line with the mainplane, the downwash from the wing could interfere with the air passing over the tailplane so reducing its effective angle of attack.
For tailplane's positioned in line with the mainplane, this occurs in a nose up disturbance, as the disturbance increases the mainplane's angle of attack, which produces an increase in lift and increase the size of the downwash leaving the wing.
The effect of an increase in downwash of the air leaving the wing is to push down the relative airflow altering the angle at which it hits the tailplane. This reduces the tailplane's effective angle of attack reducing its lift and reducing the size of any restoring moment.

4.10 Stick-Free Surfaces

On some aircraft to help with controllability, part of the elevator is allowed to trail freely in line with the relative airflow. This is known as a stick free surface and affects an aircraft's longitudinal stability, as the part of the control surface that is allowed to trail free does not produce any lift as it is at a zero angle of attack to the relative airflow. As the area at an angle of attack is now reduced, the size of the lift force and hence any restoring moment is also reduced.
Under stick free conditions therefore, to maintain an aircraft in a stable condition, the moment arm must be increased by moving neutral point further forward and the size of the C of G margin reduced. It follows then that the size of the C of G margin is also a measure of longitudinal stability, and that allowing part of a control surface to float free will reduce the longitudinal stability of the aircraft.

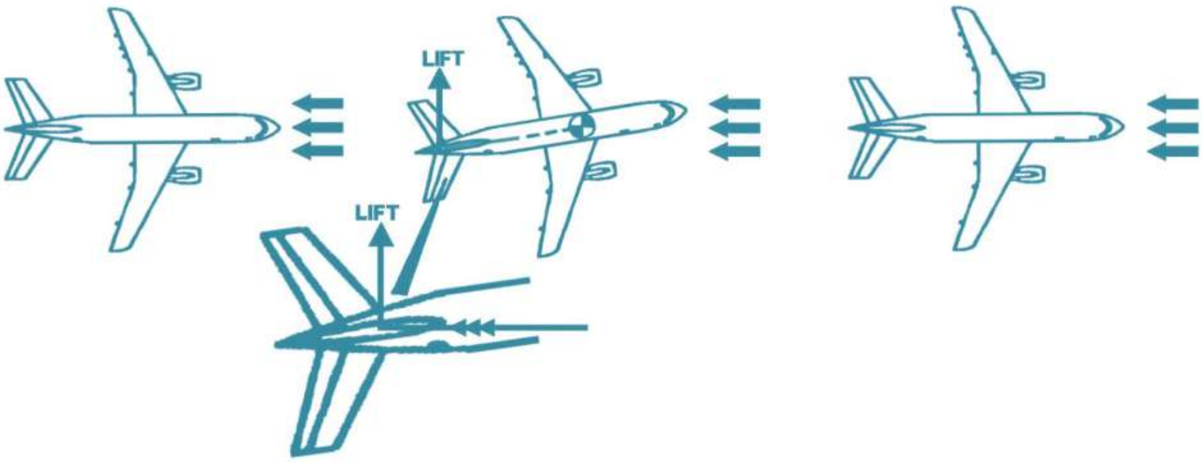
4.11 Aerodynamic Centre

In many textbooks on stability, aerodynamicist will write of the aerodynamic centre (AC) rather than the centre of pressure. For aircraft with an asymmetrical aerofoil it has been established that as the angle of attack increases the centre of pressure moves along the chord line towards the leading edge and vice versa. On most aircraft since a nose-down pitching is always present, due to the aircraft's line of action, increasing the angle of attack will increase the intensity of the pitching moment.
At a constant airflow however, there is a point on the aerofoil chord line about which the pitching moments remains constant, regardless of any changes in the angle of attack. This point is called the aerodynamic centre (AC) and is usually found slightly in front of the centre of pressure in level flight.



4.12 Directional Stability

The directional stability of an aircraft is its natural, or inbuilt tendency to recover from a disturbance in YAW. In this type of disturbance, the directional stability of the aircraft is provided mainly the fin or vertical stabiliser. For example, if an aircraft in level flight is disturbed by a gust of wind, which causes it to yaw to the left. The aircraft, due to its momentum will continue initially in its original flight path even although the nose of the aircraft has moved sideways and the aircraft will begin to sideslip. This action places the fin at an angle of attack to the relative airflow, which will produce a small aerodynamic lift force about the fin, which when multiplied by the directional moment arm produces a strong enough restoring moment to yaw the aircraft back to its original position.



The degree of direction stability, therefore, depends upon the size of the restoring moment that is provided by the fin, the size of the restoring moment being determined mainly by:
The length of the directional moment arm.
Design of the fin or vertical stabiliser.

4.13 Length of the Directional Moment Arm

The length of the directional moment arm is the distance from the centre of gravity to the centre of pressure of the fin (CP FIN). Like longitudinal stability, as the length of the moment arm multiplies any aerodynamic force produced at the fin. Any increase in the length of the moment arm length, by moving the centre of gravity forward, increases the size of the restoring moment and increases the directional stability of the aircraft. Conversely any rearward movement of the centre of gravity decreases the length of the moment arm and decreases directional stability.

4.14 Design of the Fin or Vertical Stabiliser

The design of the fin or vertical stabiliser on most aircraft is a symmetrical aerofoil fitted above the centre line. In this position it will provide an aerodynamic force whenever the aircraft is disturbed in yaw, as one side of the fin is placed at a positive angle of attack to the relative airflow.
In designing the type of fin required to provide the restoring moment designers will in addition to the size for producing a restoring force, take into account the speed of the aircraft. This is because at high speed when an aircraft is subject to a large yawing motion it is possible to stall the fin, which could produce motion over the other two axes.
To prevent this from happening, as the value of the lift coefficient of the fin (CLFIN) varies with changes in the aspect ratio and sweepback of the surface, designers can increase the stalling angle by increasing the sweepback, decreasing the aspect ratio or by fitting multiple fins of low aspect ratio. These changes however since the lift coefficient is reduced, reduce the size of any restoring moment.
NOTE: Directional stability is also referred to in some textbooks as **'weather-cock stability'** and can affect the lateral stability of an aircraft, as will be explained in the next section.

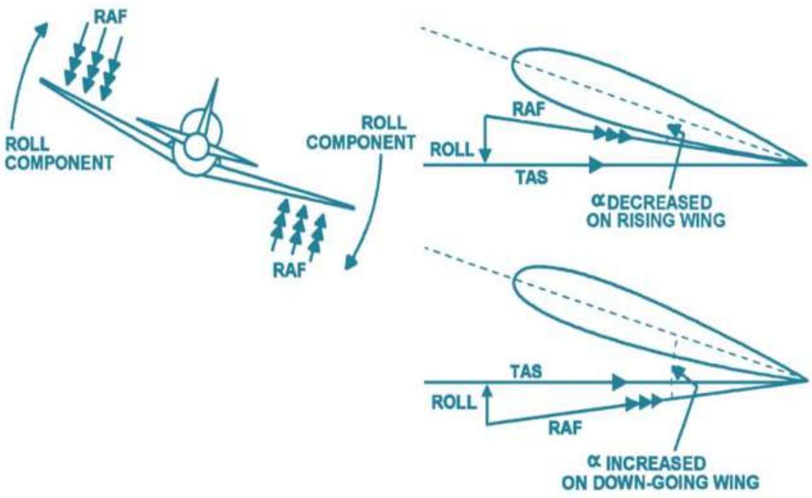
4.15 Lateral Stability

The lateral stability of an aircraft is the natural or inbuilt tendency of an aircraft to recover from a disturbance about it longitudinal axis. In this type of disturbance however, the aircraft's ability to recover depend upon a number of factors including the aircrafts yawing characteristics. This makes the lateral stability of the aircraft quite complicated, so in order to understand it, lateral stability is broken down into the following components:

- Rolling stability.
- Spiral stability.
- Dutch roll stability.

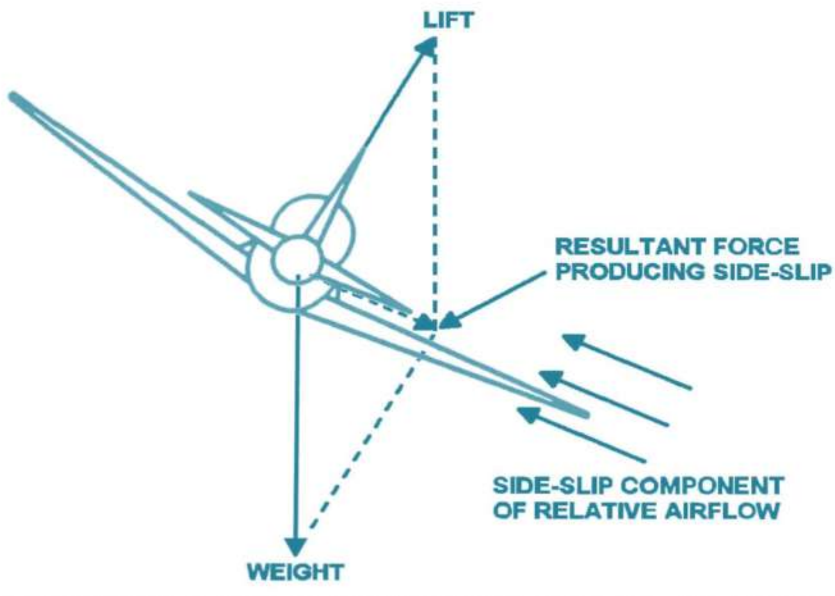
Rolling stability

The rolling stability of an aircraft is the ability of the aircraft to return to a wing level position after a disturbance. In a roll, as long as the aircraft is not near the stall, the degree of disturbance will be damped out naturally by the wings, as the angle of attack on the down-going wing will increase, whilst the angle of attack on the up going wing decreases.



The extra lift produced by the down-going wing however will not bring the aircraft back to a wing-level position, as the damping effect is proportional to the rate of roll and will decrease as the aircraft nears level flight conditions. Thus in the absence of any other forces, an aircraft disturbed in a roll will assume and remain in a banked attitude.

In this condition however, the aircraft due to its inertia will continue initially to move in a forward direction. This tilts the lift force sideways so it no longer directly opposes weight and results in the aircraft sideslipping in the direction of the dropped wing, which brings about a sideways component of relative airflow.

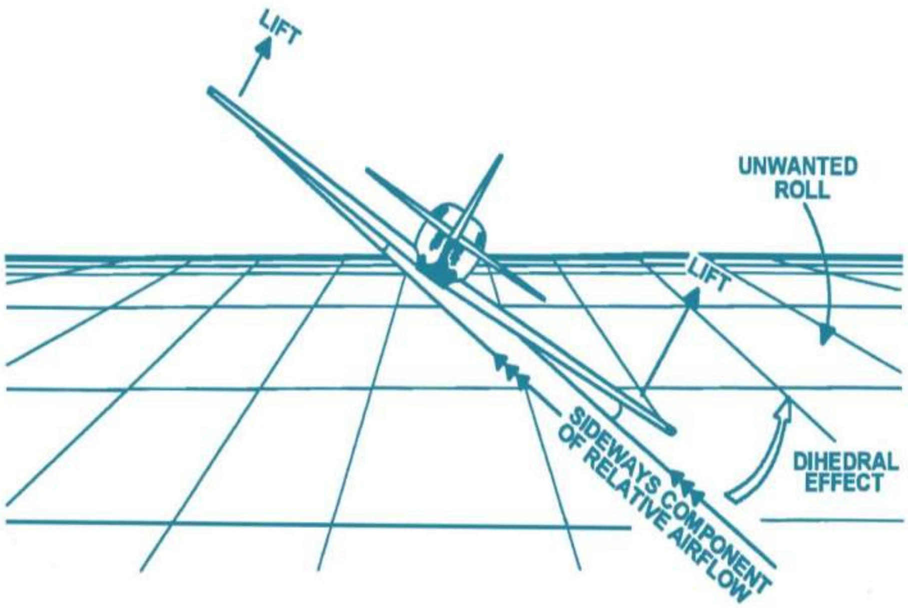


The result of the aircraft sideslipping is that an additional lift force may be generated on the down-going wing to restore the aircraft back to its original wings-level attitude, only if the aircraft has a combination of one or more of the following design features:

- Wing Dihedral.
- Sweepback.
- Wing Position.
- Keel and Tailplane position.

4.16 Wing Dihedral

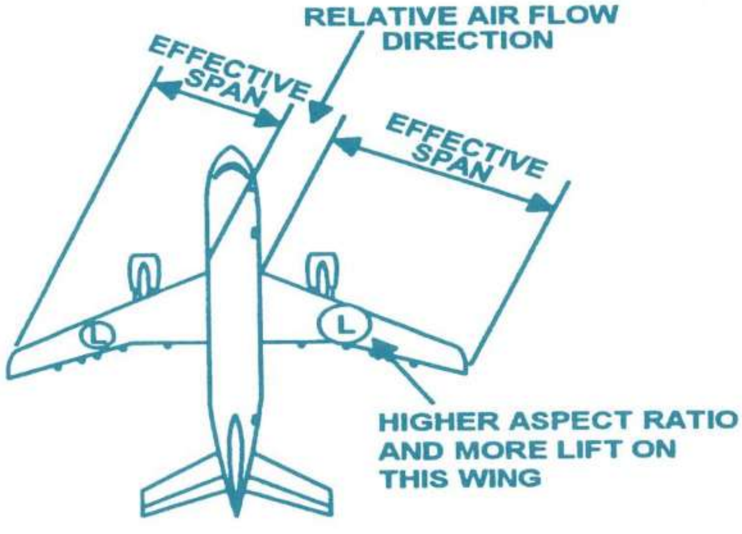
Lateral stability of an aircraft is often referred to as the 'dihedral affect', as when an aircraft sideslips, an aircraft with a dihedral wing will quickly recover to a wing level position. This occurs because as an aircraft sideslips, the lower wing due to the dihedral will have a higher angle of attack to the sideslip relative airflow, than the upper wing, so will produce lift in addition to the inbuilt damping affect, which will restore the aircraft back to a wing level condition.
The larger the amount of wing dihedral therefore, the higher will be the lateral rolling stability. Conversely if an aircraft is designed with the wings at an anhedral angle, the opposite effect occurs and the aircraft becomes less stable in a lateral disturbance.



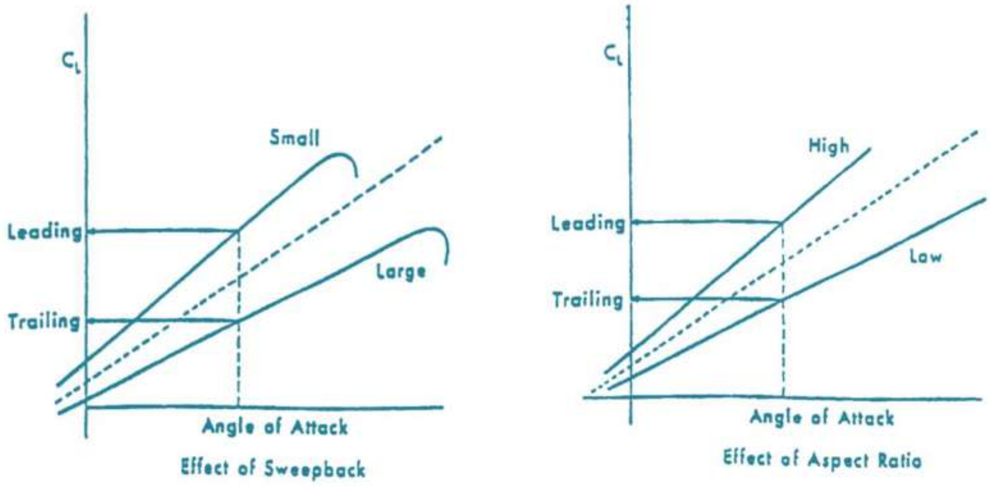
4.17 Sweepback

Sweepback of an aircraft wings affects the lateral stability of an aircraft, as when an aircraft sideslips, the lower wing because of its angle of sweep will now present more of its span to the relative airflow than the upper wing.

This produces a change in aspect ratio (AR) of the upper and lower wings, as the effective chord of the lower wing is decreased whilst that of the upper wing is increased. As this will increase the aspect ratio (AR) of the lower wing and decreases the aspect ratio of the upper wing, the lower wing will produce a greater amount of lift than the upper wing and restore the aircraft back to a wings level position.



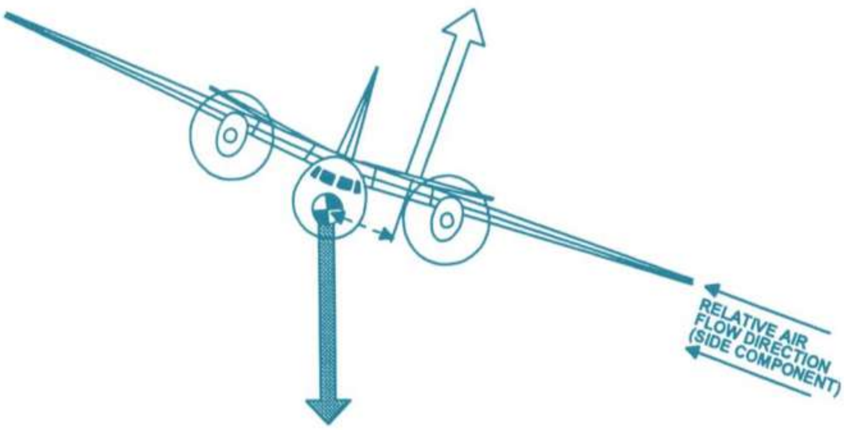
As sweepback has the same effect as dihedral, aircraft incorporating both, may become to stable especially at low airspeeds, as sweepback and changes in aspect ratio result in variations of the lift forces of the leading and trailing wings at a high angle of attack.



To prevent the aircraft becoming too stable and increase the handling characteristics at high angles of attack, it may be necessary to incorporate some negative dihedral (anhedral) on aircraft that are fitted with large swept backed wings.

4.18 Wing Position

The position of the wings in relation to the centre of gravity of an aircraft affects its lateral stability, as the higher the wing position above the centre of gravity, the more stable an aircraft becomes. This is because in a sideslip, a high wing acts in a similar manner to the dihedral wing, with the lower wing producing more lift than the upper wing.



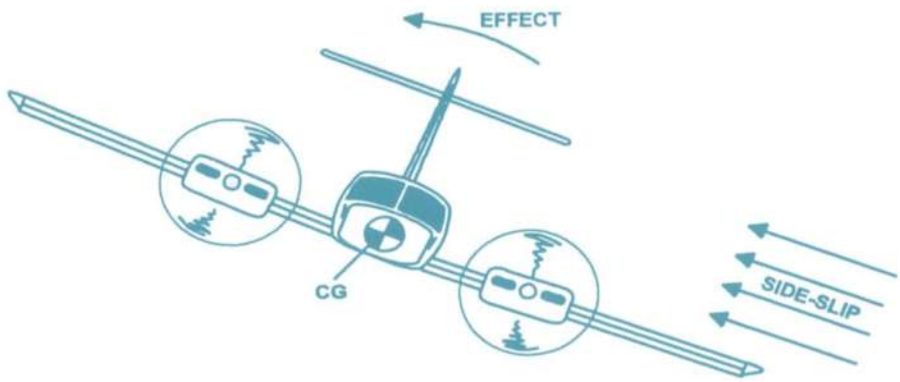
The effect of a high wing position on aircraft stability has been demonstrated to be equivalent to approximately of dihedral. So on some aircraft, this additional stability makes the aircraft so stable that in order to give the aircraft a certain level of controllability, the aircraft may be required to be fitted with either very low dihedral or even anhedral wings to destabilise the aircraft.

High wing stability is also known as the pendulous effect, since the centre of gravity is below the position of the wings, it makes the aircraft acts like a pendulum, moving around its rest point before coming back to rest where it started. Conversely if an aircraft is fitted with low wings, the centre of gravity is now above the wing position and the opposite effect occurs. So that in a disturbance the aircraft will become unstable, the affect of a low wing position being equivalent to about 1°- 3° anhedral.

From these two facts, it can be seen that there is zero effect on lateral stability when the wings are mounted centrally on the fuselage in line with the centre of gravity.

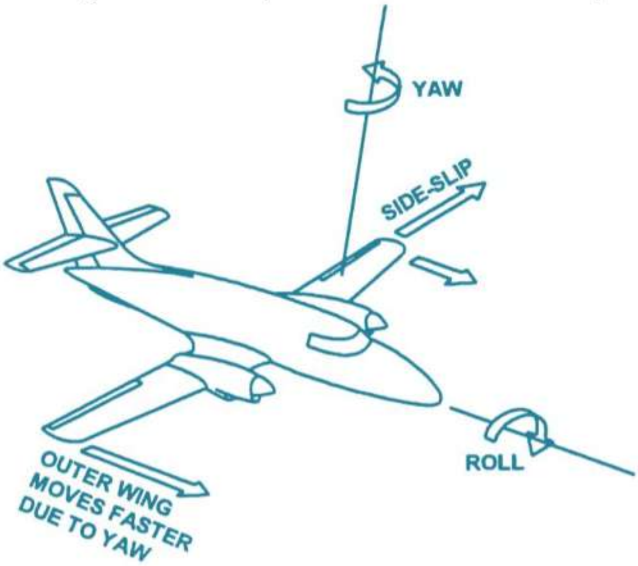
4.19 Keel and Tailplane position

As an aircraft sideslips, its side surfaces; the fuselage and fin, will assume a position perpendicular to the sideslip relative airflow. It follows then that those surfaces, which are above the aircraft centre of gravity will produce a restoring moment. The tailplane of a T-Tail configuration aircraft will act like a high wing, as it is above the centre of gravity and increase the stability of an aircraft.
T- Tail aircraft may therefore become too laterally stable, requiring the wings to be positioned at either a low point on the fuselage or at an anhedral angle to reduce lateral stability and increase handling characteristics.

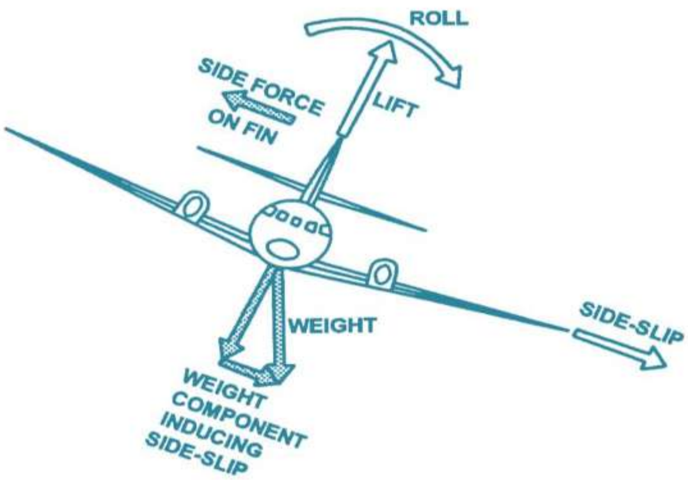


4.20 Spiral Stability

The spiral stability of an aircraft is the resistance of the aircraft to a downward spiralling motion brought about by the aircraft yawing after it has been disturbed laterally.
When an aircraft rolls and sideslips, the sideslip relative airflow will also act on the keel surface, including the fin, which will produce a lift force about the fin that tries to yaw the aircraft in the direction of the down-going wing.
During sideslip, if the rolling stability is low; the aircraft will take a long time to recover, the directional stability will try to straighten itself up in line with the sideslip component.



This is known as weathercocking, in a banked attitude this will cause the aircraft's rate of roll to increase. This form of instability occurs, as the aircraft yaws, the outer wing of the aircraft will accelerate producing more lift than the down-going wing; so the aircraft will roll further in the direction of the down-going wing. The increase in roll will increase the angle of bank, resulting in further sideslip, weathercocking and roll, which if left unchecked will lead to a steep spiral dive.



To prevent spiral instability, the directional stability of the aircraft must be reduced below that of the roll stability. So that when an aircraft is disturbed and sideslips, the dihedral effect will make the wing roll level before the aircraft yaws and increases the roll. This can be achieved by reducing the area of the fin, or by increasing wing dihedral to increase the lateral stability.

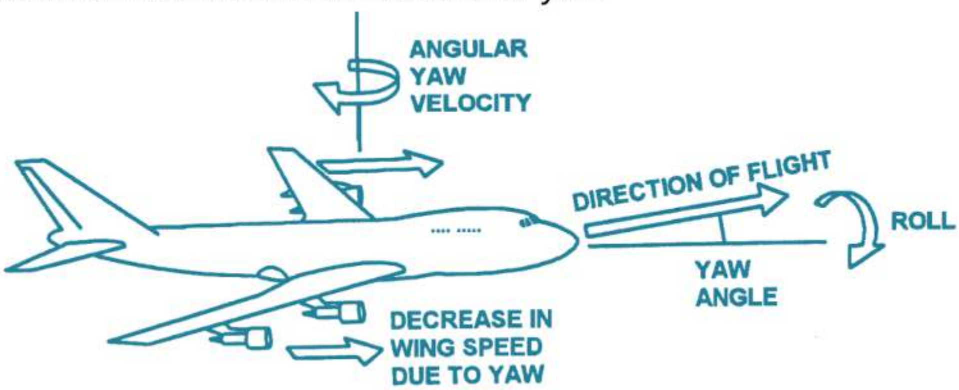
4.21 Dutch Roll Stability

Dutch roll is a form of oscillatory instability, and is characterised by a combined rolling, yawing and sideslip movement or **'wallowing'** motion, where the aircraft continually yaws and rolls from side to side until corrective action is taken or natural damping takes place.

This type of instability is considered more serious than spiral instability. It is commonly found on aircraft with a combination of high wing loading and sweepback, particularly at low indicated airspeed and high altitude.

As most modern commercial aircraft fall into this category, Dutch roll is one of the most common forms of instability that must be catered for today. The instability arises when the directional stability is less than the lateral stability of a sweptback aircraft that is disturbed in yaw.

For example if an aircraft is disturbed in yaw to the right, the left wing will advance and as a result will increase speed and lift, whilst the right wing slows down and produces less lift. The lift generated by the left wing is further increased as the wing becomes less swept as it advances and offers a greater span to the relative airflow, whereas the right wing becomes more swept and decreases the span to the relative airflow, an effect which is similar to that of dihedral. The result of this imbalance is to bring about a roll in the aircraft in the direction of yaw.



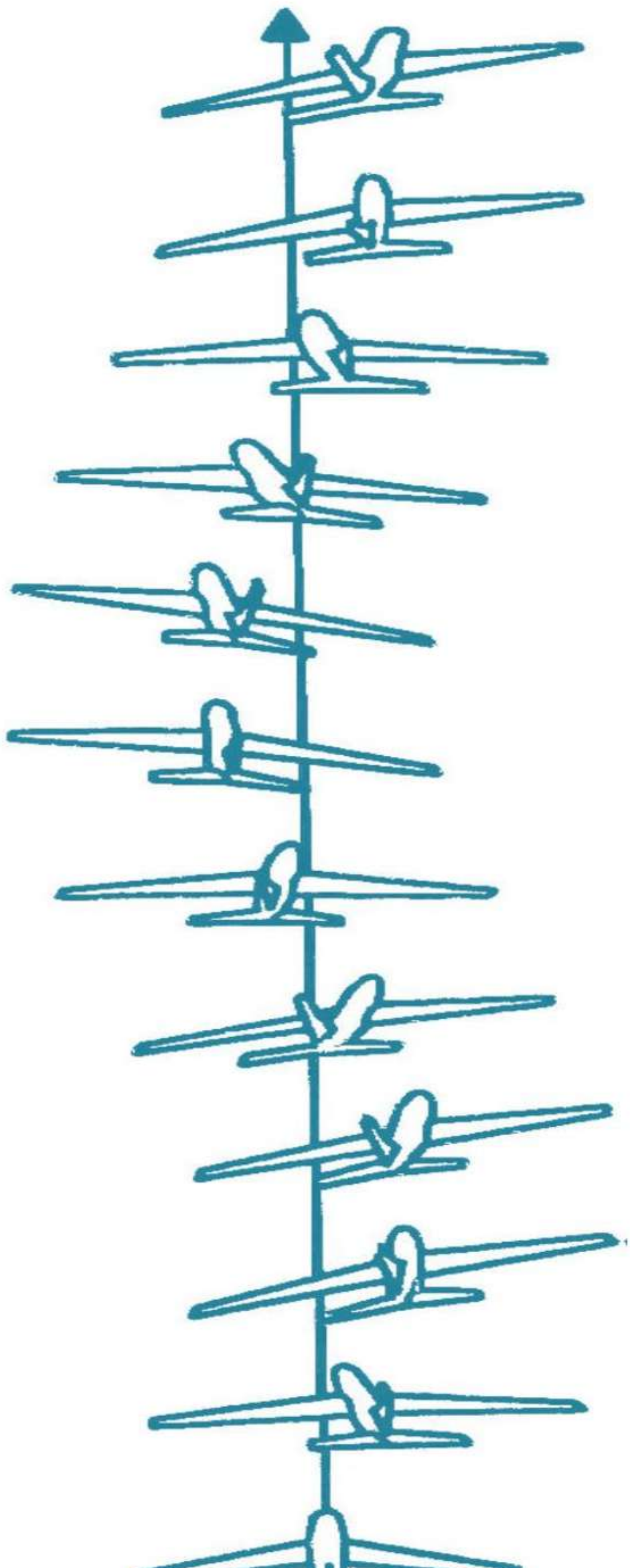
As the aircraft rolls, the advancing wing will reach a point where it will now produce more drag due to its larger exposed area, so it will start to slow down and the right wing will advance so the aircraft yaws to the left. This advances the right wing, which produces an increase in lift and the aircraft now rolls to aircraft the left.

This unstable motion is primary due to excessive lateral stability of an aircraft, as when an aircraft rolls, the dihedral of the down-going wing will start bring the wings back level before the aircraft can recover itself due to the disturbance in yaw. So the final result is an undulating or corkscrew motion where the rolling and yawing oscillations have the same frequency, but are out of phase with each other. One method therefore to prevent Dutch roll occurring is to reduce the amount of lateral stability an aircraft has compared to its directional stability. This can be achieved by either reducing the dihedral of the wing, or even making it slightly anhedral, as it would give the aircraft more time to recover from the yaw disturbance, before the dihedral effect took place.

Another method could be to increase the directional stability of the aircraft by increasing the size of the fin this however may adversely affect the aircraft's handling characteristics, as it will increase its weathercocking tendency, which may lead to spiral instability problems.

Dutch roll stability is therefore a trade off with spiral instability, as too much weathercocking will lead to spiral instability, but too much dihedral will lead to Dutch roll instability.

A more common method used to eliminate Dutch roll is to fit the aircraft with a yaw damping system to prevent the aircraft yawing excessively in a disturbance so preventing the roll. These devices will also prevent any pilot induced oscillations (PIO's), as the magnitude of the oscillatory motion will start comparatively small and therefore will be extremely difficult for a pilot to be able to co-ordinate their reaction in phase with the stability characteristics of the aircraft. So that any manual input to correct the oscillation will only result in an overcorrection, which will intensify the resulting oscillatory motion.



4.22 COUPLED EFFECTS:

Yaw causes Roll

When an aircraft is yawed, the outer wing will travel through a greater distance than that of the inner wing. This makes the inner wing to travel at greater speed, thereby increasing the lift on that wing. This will lead to a roll. Thus yaw causes roll.

Roll causes Yaw

When an aircraft is rolled not as part of coordinated banked turn, side slipping will occur. This side slip will produce a relative airflow towards its lateral surface. Since the keel area behind the C.G being more than just ahead of it, due to the presence of vertical stabilizer, there develops a yawing moment. The leverage (i.e., the distance between the C.G and fin) is a major contributory factor here. Thus roll causes yaw.

4.23 ASYMMETRIC STABILITY FEATURES :

The asymmetrical lateral motion is made up of three factors viz. Sideslip, yaw and roll. A complicated series of motions take place simultaneously, though each may be treated independently to a reasonable degree of accuracy. The cross coupling exists between the directional static stability and lateral static stability and gives rise to three important dynamic motions observed: Directional divergence, Spiral Divergence and Dutch roll.

a) Directional divergence:

Directional divergence is a result of an directionally unstable aircraft. When the aircraft yaws or rolls into a sideslip so that side forces on the aircraft are generated, the yawing moments that arise continue to increase the sideslip. Thus if an aircraft flying straight and level experiences a small displacement in yaw to starboard, which will cause the displacement to increase. In the resulting yaw attitude, the aircraft will be subjected to a side force to starboard, which will cause it to deviate from its original flight path. The side force will increase with the yaw angle, so that the flight path will continue to curve away from the original direction. Directional divergence can be avoided in design simply by building in sufficient positive directional static stability.

b) Spiral Divergence:

Spiral Divergence is characterised by an aircraft that is very stable directionally but not very stable laterally. This is a fairly complicated motion, involving a mixture of side force and moments in both rolling and yawing sense. In this case when the aircraft is in a bank and side slipping, the side force tends to turn it into the relative wind. The outer wing travel faster thereby generating more lift and the aircraft will roll to still a higher bank angle. This phenomenon is known as Spiral Divergence. No lateral stability is present to negate this roll. The bank angle increases and the aircraft continue to turn in to the sideslip in ever tightening spiral.

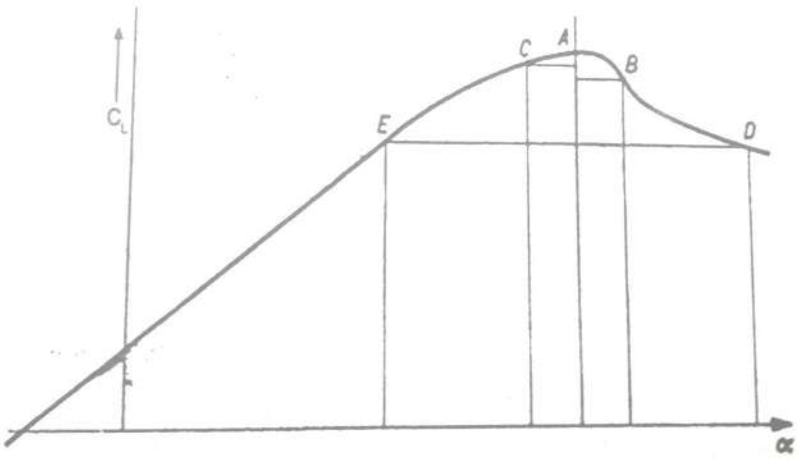
c) Dutch Roll:

Dutch roll is a motion exhibiting characteristics of both Directional divergence and Spiral Divergence. Dutch roll occurs when the aircraft has relatively strong static lateral stability and somewhat (relatively) weak directional stability. If a sideslip disturbance occurs, as the aircraft yaws in one direction, the aircraft rolls away in a countermotion. The aircraft wags its tail from side to side. The Dutch roll is a coupled roll and yaw motion (lateral- directional oscillation) and aircraft often require yaw dampers to suppress this motion.

The aircraft is designed to have enough lateral stability so that there is no tendency towards spiral divergence. Enough directional stability is then built-in to ensure damping towards directional divergence. The relationship between the directional and static stability is such that Dutch roll is adequately damped.

4.24 AUTOROTATION

Consider an aircraft which is flying straight and level at an angle of attack very close to the stalling angle. Suppose that its condition corresponds to the point A on the lift curve as shown below.



Suppose now that the aircraft is subjected to a disturbance in roll, causing one wing to drop. This wing will now have a downward velocity, the airflow over it will have a relative upwash velocity, and the effective incidence will be increased. This may result in the wing become stalled, with a consequent sharp reduction in lift on this downgoing wing. The upgoing wing will, by the same token, experience a reduction in effective incidence by the same amount as the increase on the other side, and this will cause its lift to be reduced also. Since the lift curve is likely to be flatter for incidences just above it, the loss of lift may be less on the upgoing wing than on the down going one. This is illustrated in the above figure, where the points B and C on the lift curve represent respectively the conditions of the downgoing and the upgoing wings. Therefore, there will be a rolling moment resulting from the difference between the lift of the two wings, and this will be in the same sense as the original roll, and so will constitute negative dumping in roll. The aircraft will therefore not only continue to roll, but will actually accelerate in roll. This phenomenon is known as autorotation.

As the rate of roll reaches a certain value, the corresponding change in incidence of the two wings is such that the lift coefficient is again the same on both sides, as depicted by points D and E on the lift curve. Then the aircraft will continue to autorotate at a steady rate.

In any case, the ailerons become ineffective once autorotation has begun, so that the motion cannot in general be corrected by use of ailerons. The remedy for the condition is quite simply to reduce the incidence. Neither wing will then be stalled, and the autorotation is eliminated either as a result of positive damping in roll, or through the deliberate use of the ailerons, which regain their effectiveness once the wing is no longer stalled.

4.25 THE SPIN

The phenomenon of autorotation will not occur in isolation with an aircraft in flight, since lateral disturbance which initiates the autorotation also instigates a directional disturbance (since roll causes yaw).The resulting motion is known as spinning. The directional motion is created as a result of the difference in drag between the two wings. The down-going wing is stalled, so that the drag on that side is much greater than on the other side. There is an interaction between yawing moment due to roll and rolling moment due to sideslip and ultimately a steady condition is reached which is a steady spin. In the process, the aircraft descends along a helical path. The rate of spin and the steepness of the descent for a given aeroplane are functions of its initial incidence and of its lateral and directional stability characteristics. High incidence, especially incidence well beyond stall, leads to a so-called flat spin in which the rate of rotation is high, but the descent not very steep. If the spin occurs at a rather lower incidence, then the resulting spin tends to be slower but steeper and is called as a steep spin.

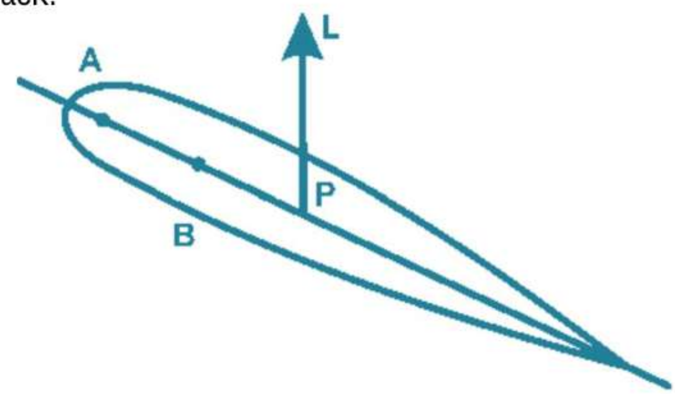
The correct recovery procedure from spin consists in applying full opposite rudder first, in order to reduce the sideslip, and then deflecting the elevator downwards to reduce the incidence.

4.26 AERODYNAMIC BALANCING

The forces which are necessary to move the various controls, i.e., the elevator, ailerons or rudder, may in some cases be very large, especially in the case of large aircraft, with large control surface, and/or at high speeds. This implies that the control surface hinge moments are too large to be acceptable from the pilot's point of view. By careful design it is possible to make use of aerodynamic forces to help to deflect the control surface thus reducing the restoring hinge moment and the corresponding stick force. An aerodynamic device which performs this function is known as an aerodynamic balance. There is several different types of aerodynamic balance, of which the most common are listed and described in the following paragraphs.

i. Set back the Hinge

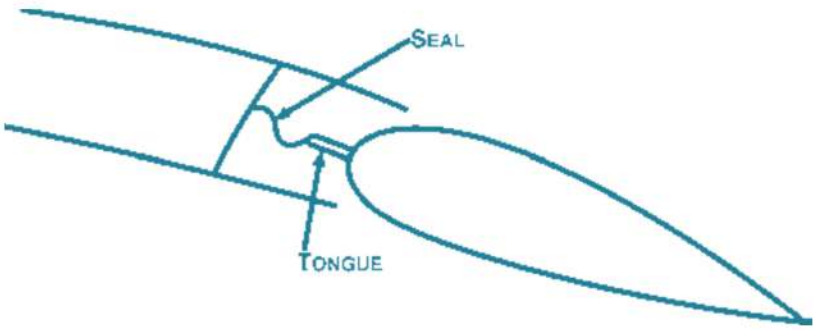
Downward deflection of an elevator, say, will normally produce a lift force, L, acting on the elevator through its centre of pressure P, as depicted in section in Fig. If the elevator hinges is at A, this lift force produces a nose-down hinge moment, which is the restoring moment which the pilot has to counterbalance in order to keep the elevator down. If the hinge is set further back at B, say, then for the same elevator deflection and elevator lift increment, the hinge moment will be much less. Thus aerodynamic balance is provided by the simple process of setting back the hinge. It would appear that the hinge could be set as near to as one would wish to P, and so provide any required amount of aerodynamic balancing. However, P is not necessarily a fixed point, and in general moves forward with increasing elevator deflection. If the hinge is set too far back, there is a danger that under some conditions P might be forward of the hinge, so that the resulting hinge moment would be nose-up. This would represent an unstable condition, in which the hinge moment co-efficient b2 is positive. Such a condition known as overbalance, and must be avoided. There is thus a limit to the amount of balance one can achieve by setting back the hinge, and there are also structural reasons why the hinge should not be set too far back.



ii. Sealed Nose Balance

With this type of balance, sketched in Fig. given below . A plate projects forward from the nose of the control surface. This plate, or tongue, is joined to the main part of the wing, tailplane or fin by a

loose fold of impermeable fabric, which constitutes a seal between the regions above and below the control, or on the two sides of the control surface, in the case of a rudder. The space above the tongue in the case of an elevator, say, is open to the air above to the tailplane and similarly the space below the tongue is open to the air below the tail. When the elevator is deflected downwards
lift is increased on the elevator. This is the result of generally reduced pressure on the upper surface, increased pressure on the lower surface. In particular, the pressure just above the tongue is low, and just below it is high, so that there is an upware force on the tongue which provides a nose-up hinge moment, which is the required balancing moment.



iii. Geared tabs (Also discussed under secondary control surfaces 2.53)
In this case, the control surface is fitted with a tab in such a way that when the main control moves downwards, say, the tab is automatically deflected upwards. This tab (Balance-tab)deflection produces a downward force on the tab, and hence a nose-up control hinge moment, which helps to keep the control down. The tab is geared to the main control, so that its deflection is always proportional to the control deflection, in accordance with a particular gear ratio. Thus the balancing effect increases with control deflection, but there is little danger of overbalancing.

Another related device is the so-called servo-tab, which is designed to provide all the hinge moment required to deflect the control. The principle is that when the pilot moves the control column this controls the tab directly. The deflected tab then creates a hinge moment which deflects the control. This is not strictly an aerodynamic balance, although the stick force necessary to deflect the tab is much less than that which would be required to deflect the main control directly,
so that the effect is the same. There are also various kinds of spring tabs which , in effect , distribute the stick force between the tab and the main control in varying rations. Thus, the servo-tab is at one extreme and the geared balance tab is at the other. The ratio in which the load is distributed between tab and main control is simply determined by the mechanical linkages in the control circuit. The correct design of these linkages yields the required value for the hinge moment coefficient , i.e., the correct amount of aerodynamic balancing.

iv. Frise Aileron (Also discussed under Adverse Yaw-2.76)
The Frise type of balance consists in designing the shape of the control surface in such a manner that when it is deflected upwards the nose projects below the level of the main surface of the wing, say. The consequence is a pressure on the nose which provides a nose-down hinge moment, and so reduces the restoring nose-up moment. Such a design has already been described before in connection with its use to offset adverse aileron yaw.

The danger with this type of balance is that if large control deflections are used over balance is almost certain to result. For this reason, it is only used on ailerons, where two geared controls, the port aileron and the starboard aileron, move in opposite directions. The design is such that when the control moves downwards the nose does not project above the main wing surface, so that the down going aileron is not balanced at all. Thus, even if the upgoing aileron is overbalanced for large deflections, the combination of the two ailerons will generally remain stable. As we have seen, the extra drag on the side where the lift is reduced by upward aileron deflection also performs a useful function in offsetting adverse aileron yaw.

v. Horn Balance

A horn balance consists simply in part of the control surface projecting far forward of the hinge line, so that it can be regarded as effectively as a heavily set-back hinge over part of the span of the control surface. When an elevator, say, is deflected downwards, there is a lift force on the horn which, being forward of the hinge line, provides a nose-up hinge to partly offset the nose-down moment on the rest of the elevator. The horn may be shielded or unshielded.

4.27 AEROELASTIC EFFECTS

We have hitherto made the assumption that the aircraft structure is perfectly rigid, i.e., that it cannot be deformed, no matter what loads are applied to it. This is, of course, an idealization which is not realized in practice. In fact, the airframe is subjected to aerodynamic loads which depend on its external shape. The consequence of these loads is to strain the airframe, so that its shape is slightly modified in some respects, and this change in shape leads to a modification of the aerodynamic loads. This interaction between the aerodynamic loads and the elastic strain of the airframe is known as aeroelasticity. At relatively low speeds, the aerodynamic forces are relatively small, and the resulting, strain of the airframe produces only negligible effects. At higher speeds, the aerodynamic loads and the consequent strain are correspondingly greater and aeroelastic effects may be important, though it must be emphasized that they do not necessarily become important at the same speeds as those at which compressibility effects first arise. We shall not present a general discussion of aeroelasticity but we shall give an account of three important phenomena which could arise as a result of aeroelastic effects.

i) Wing Torsional Divergence

Consider a wing at incidence. The pressure distribution, with the main loads located near the nose, is such as to cause the wing to twist in the nose-up sense. Because the structure is not perfectly rigid, it does in fact twist, and its shape becomes distorted relative to the wing root section. It twists about an axis known as the torsional axis of the wing, which is usually aft of the line of aerodynamic centres. This twist, by increasing the effective incidence, creates a lift increment which then acts forward of the torsional axis, so that the effect is unstable, in the sense that the more it twists the bigger is the twisting moment tending to cause it to twist still further. However, the tendency to twist is, of course, resisted by elastic forces due to the stiffness of the structure.

This resistance to twist increases rapidly with the amount of twist, or strain, until it balances the aerodynamic twisting couple and equilibrium, is reached. However, as the speed increases, the aerodynamic forces increase rapidly, in proportion to V^2, and therefore so also does the twisting moment. The elastic stiffness is not affected by speed, and so the amount of twist increases with speed. Eventually, a speed is reached at which the elastic resistance to twist is only just sufficient to counteract the twisting moment, and equilibrium is only achieved with the wing at breaking point. This speed is a critical speed called the wing torsional divergence speed, and any increase in speed above this value will result in structural failure-the wing will break off.
There is no real remedy for this situation. It is therefore essential to be able to predict this critical divergence speed, and to make the airframe strong and stiff enough to ensure that it is higher, by a substantial safety margin, than any speed which will ever be achieved in any condition in flight.
Similar considerations apply to wing bending, and there is a critical wing flexural divergence speed which, similarly, must be made so high that it will not be reached in flight.

ii) Control Surface Flutter and Mass Balancing.
Consider now an elevator which is hinged along a line which is well forward of the centre of gravity of the elevator. Suppose the aircraft is in a steady condition when a sudden disturbance causes the tail, and with it the elevator, to be displaced upwards. Because of its inertia, the elevator will tend to rotate about its hinge line in such a way that downward deflection results. This will produce more lift on the tail, and thus the fuselage, which is an elastic structure, will bend, the tail moving further upwards. This will cause the elevator to deflect still further downwards, and so the process continues. Resistance to this motion is, of course, provided by the elastic stiffness of the control circuit, which, if the stick is fixed, opposes the motion of the elevator. Similarly, the stiffness of the fuselage provides resistance to the tendency to bend. However, an oscillation may develop which, in certain circumstances is undamped, depending on the interaction of the inertia, aerodynamic and elastic effects described above. This oscillation is known as elevator flutter, and, if not checked, will ultimately cause structural failure.

There is generally a simple remedy. Suppose that the distribution of the mass of the elevator could be altered, so that its centre of gravity lies almost near the hinge line. Then the initial disturbance of the hinge line will not create any elevator deflection, and flutter will not occur. Further, if the centre of gravity of the elevator is forward of the hinge line, then upward movement of the hinge will cause the elevator to be deflected upwards, creating a downward increment in tail lift which, so far from creating the kind of instability which gives rise to flutter, acts as a damping factor and helps to eliminate the effects of the disturbance.

The careful arrangement of the mass distribution of the elevator, in order to eliminate the inertia-aeroelastic coupling which produces flutter, is called mass-balancing. It is not to be confused with aerodynamic balancing, to which it is totally unrelated. In the case of the simple kind of flutter just described, the object can be achieved by simply attaching a tongue to the nose of the control and placing a mass on the end of it. This has the desired effect of moving the elevator centre of gravity forward. To eliminate the possibility of flutter even after a much more general kind of disturbance, more complete mass-balancing, involving the moments and products of inertia about the relevant axes, may be necessary. The aileron may be caused to flutter in just the same way as the elevator, with the bending wing playing the role corresponding to that of the bending fuselage. An example of a more complicated motion which might occur would be a combination of wing torsional and flexural oscillations due to aileron inertia. Again, the remedy lies in mass balancing of the aileron.

Mass balancing
Control surfaces are often balanced in quite a different sense. A mass is fitted in front of the hinge. This is partly to provide a mechanical balancing of the mass of the control surface behind the hinge but may also be partly to help prevent an effect known as 'flutter' which is liable to occur at high speeds). This flutter is a vibration which is caused by the combined effects of the changes in pressure distribution over the surface as the angle of attack is altered, and the elastic forces set up by the distortion of the structure itself. All structures are distorted when loads are applied. If the structure is elastic, as all good structures must be, it will tend to spring back as soon as the load is removed or changes its point of application. In short, a distorted structure is like a spring that has been wound up and is ready to spring back. An aeroplane wing or fuselage can be distorted in two ways, by bending and by twisting, and each distortion can result in an independent vibration. Like all vibrations, this flutter is liable to become dangerous if the two effects add up. The flutter may affect the control surfaces such as an aileron, or the main planes, or both. The whole problem is very complicated, but we do know of two features which help to prevent it - a rigid structure and mass balance of the control surfaces. When the old types of aerodynamic balance were used, e.g. the inset hinge or horn balance, the mass could be concealed inside the forward portion of the control surface and thus two

birds were killed with one stone; but when the tap type of balance is used alone the mass must be placed on a special arm sticking out in front of the control surface. In general, however, the problems of flutter are best tackled by increasing the rigidity of the structure
and control-system components.

Large aircraft and military types now invariably have powered controls, and these are much less sensitive to problems of flutter as the actuating system is very rigid. Perhaps it should be emphasised that the mass is not simply a weight for the purpose of balancing the control surface
statically, e.g. to keep the aileron floating when the control mechanism is not connected; it may have this effect, but it also serves to alter the moments of inertia of the surface, and thus alter the period of vibration and the liability of flutter. It may help to make this clear if we realise that mass balance is just as effective on a rudder, where the weight is not involved, as on an elevator or aileron.

On old military biplane aircraft, the exact distribution of mass on the control surfaces was so important that strict orders had to be introduced concerning the application of paint and dope to these surfaces. It is for this reason that the red, white and blue stripes which used to be painted on the rudders of Royal Air Force machines were removed (they were later restored, but only on the fixed fin), and why the circles on the wings were not allowed to overlap the ailerons. Rumour has it that when has it that when this order was first promulgated, some units in their eagerness to comply with the order, but ignorant as to its purpose, painted over the circles and stripes with further coats of dope!

iii) Control reversal

Consider a wing fitted with an aileron. The aileron is designed to produce positive increments inwing lift when it is deflected downwards. But downward deflection modifies the pressure distribution over wing and aileron in such a way that this increment in lift act well aft of the wing torsional axis, so that as a result the wing is twisted in the nose-down sense. This causes a reduction in effective incidence, and so a reduction in lift. However, the elastic stiffness of the wing creates a resistance to the wing twist, so that in the equilibrium condition the reduction in lift due to twist is generally
less than the increase due directly to aileron deflection. Thus downward aileron deflection gives increase in lift overall, as expected, although the aileron effectiveness is reduced as a result of the twisting of the wing.

However, with increase in speed, the twisting moment, which arises from the aerodynamic loads, increase rapidly, while the elastic resistance is not changed, so that the wing twist more and more, for the same aileron deflection. There is a critical speed at which the loss in lift due to twist at a given aileron deflection is only just equal to the increase in lift due to that deflection and the aileron is then totally ineffective. Above this speed, aileron deflection downwards will actually results in reduced lift overall and deflection, of the ailerons will result in a roll in the opposite sense to that which results from the same deflection at lower speeds. This phenomenon is known as aileron reversal and the speed at which it occurs is called the aileron reversal speed. This control result which can also occur in relation to the elevator and rudder, must be avoided, so that it is a design requirement that control reversal speeds must be higher than any physical speed to be achieved in flight.