SIMMER DREAM

PRINCIPLES OF FLIGHT

This book is to support learning from "Principle of Flight" course available at www.simmerdream.com.

Copying and sending this book outside the website www.simmerdream.com is strictly prohibited.

Created by Dario Castelluccio for Simmer Dream

www.simmerdream.com

INDEX

1. BASIC AERODINAMIC THEORY

PRINCIPLE OF CONTINUITY

ENERGY and MASS can neither be created nor destroyed, only a change from one form to another is allowed.

To demonstrate the effect the Principle of Continuity has on aerodynamic theory, it is instructive to consider a streamline flow of air through a tube which has a reduced cross-sectional area in the middle.

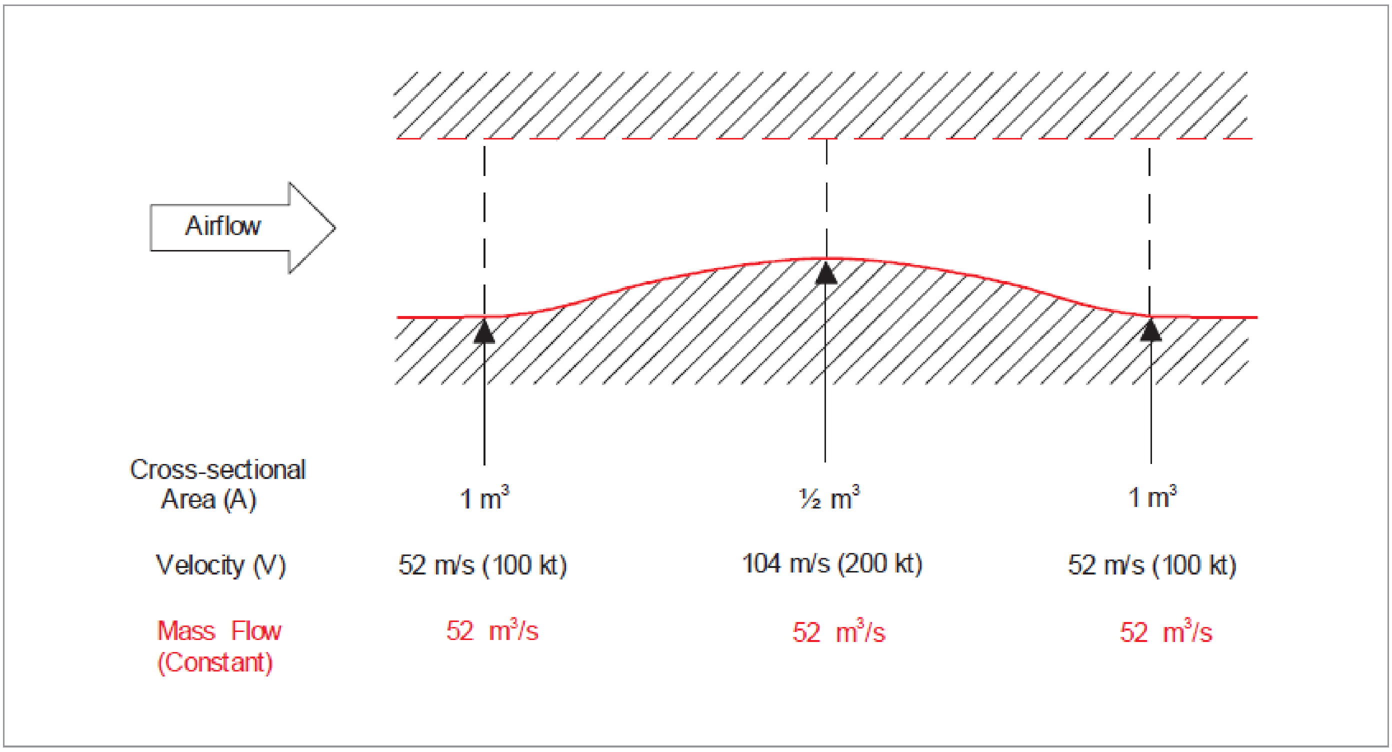
The air mass flow, or mass per unit time, through the tube will be the product of the cross sectional area (A), the airflow velocity (V) and the air density (ρ). Mass flow will remain a constant value at all points along the tube.

The Equation of Continuity is: $A \times V \times \rho = \text{Constant}$

Because air is a compressible fluid, any pressure change in the flow will affect the air density. However, at low subsonic speeds (< M 0.4) density changes will be insignificant and can be disregarded.

The equation of continuity can now be simplified to: A × V = constant, or:

$$\text{Velocity (V)} = \frac{\text{Constant}}{\text{Area (A)}}$$



BERNOULLI'S THEOREM

"In the steady flow of an ideal fluid the sum of the pressure energy and the kinetic energy remains constant".

An ideal fluid is both incompressible and has no viscosity.

Pressure + Kinetic energy = constant

or

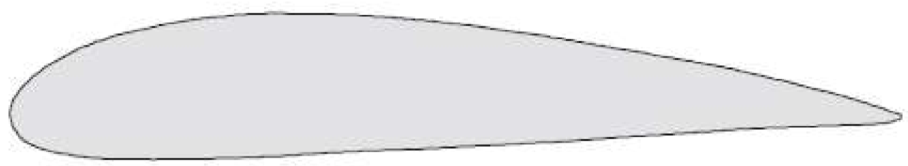
$$p + 1/2\ p\ V^2 = \text{constant}$$

Static pressure + Dynamic pressure = constant

The constant can be called TOTAL PRESSURE or PITOT PRESSURE

AEROFOIL

An airfoil is a specially shaped body capable of generating an aerodynamic force.

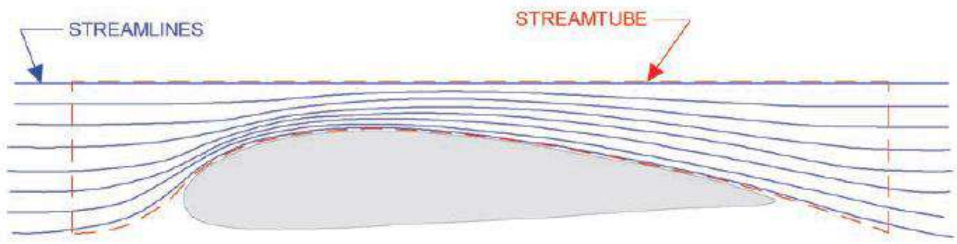


Typical aerofoil section

STREAMLINES AND STREAMTUBES

A streamline is the path traced by a particle of air in a steady airflow, and streamlines cannot cross. When streamlines are shown close together it illustrates increased velocity, and vice versa. Diverging streamlines illustrate a decelerating airflow and resultant increasing pressure, and converging streamlines illustrate an accelerating airflow, with resultant decreasing pressure.

A streamtube is an imaginary tube made of streamlines. There is no flow into or out of the streamtube through the "walls", only a flow along the tube.



Streamlines and a streamtube

SUMMARY

At flow speeds of less than about M 0.4, pressure changes will not affect air density.

Continuity:

• Air accelerates when the cross-sectional area of a streamline flow is reduced.
• Air decelerates when the cross-sectional area increases again.

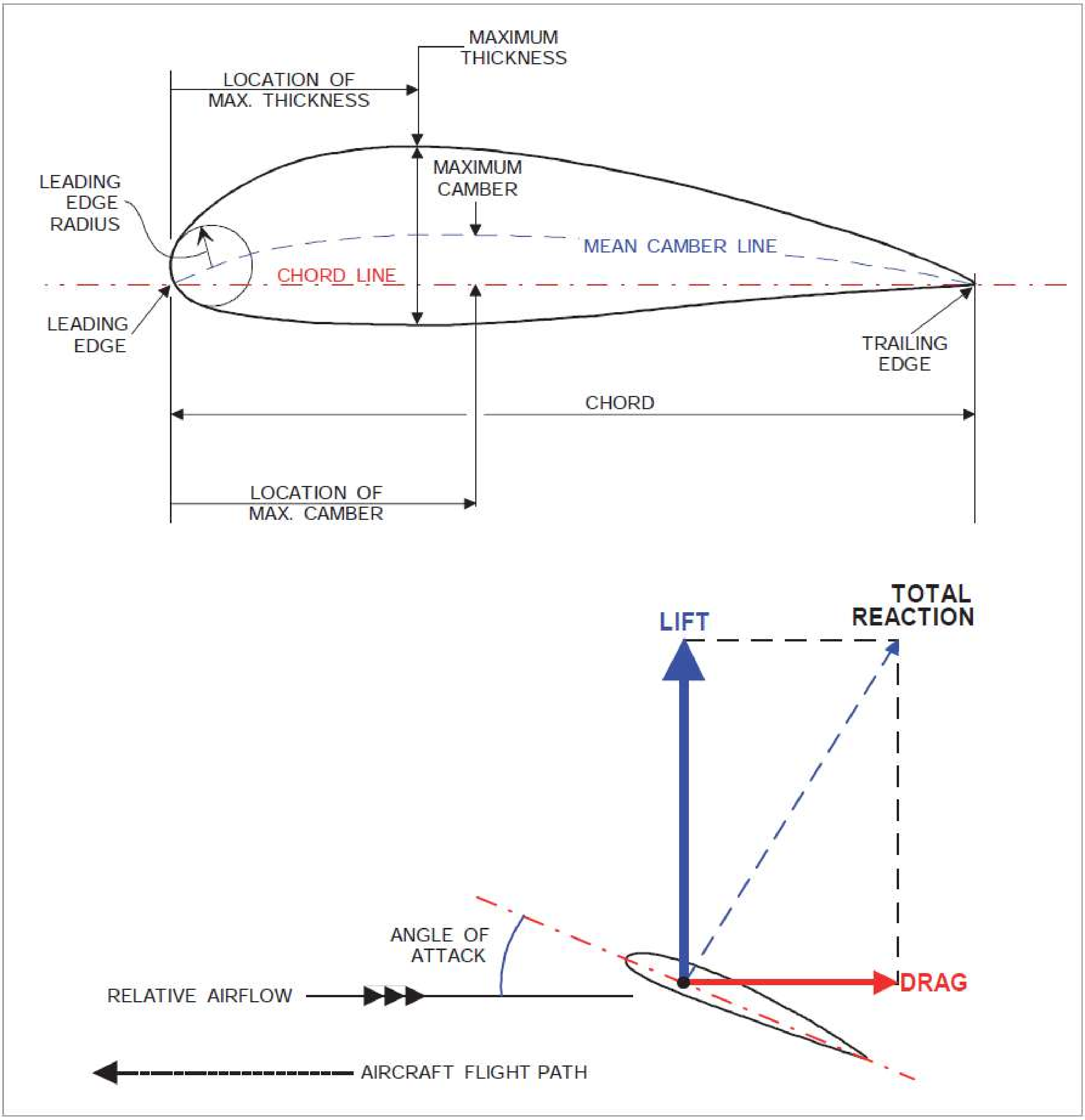
Bernoulli:

• If a streamline flow of air accelerates, its kinetic energy will increase and its static pressure will decrease.
• When air decelerates, the kinetic energy will decrease and the static pressure will increase again.

By harnessing the principle of continuity and Bernoulli's theorem an aerodynamic force can be generated.

2. SUBSONIC AIRFLOW

AEROFOIL TERMINOLOGY



Aerofoil: a shape capable of producing lift with relatively high efficiency.

Chord line: a straight line joining the centres of curvature of the leading and trailing edges of an airfoil.

Chord: the distance between the leading and trailing edges measured along the chord line.

Angle of incidence: the angle between the wing root chord line and the longitudinal axis of the aircraft.

Mean Line or Camber Line: A line joining the leading and trailing edges of an airfoil, equidistant from the upper and lower surfaces.

Maximum camber: the maximum distance of the mean line from the chord line.
If the camber line is above the chord line, the airfoil has a positive camber, while if the camber line is below the chord line, the airfoil has a negative camber. A symmetrical airfoil has no camber because the camber line and the chord line are coincidental.

Thickness / Chord Ratio: the maximum thickness or depth of an airfoil section.

Leading edge radius: the radius of curvature of the leading edge.

Relative airflow / Relative wind: air that flows parallel to and in the opposite direction to the flight path of the aircraft. It's unaffected by the passage of the aircraft through it.

Total reaction: the resultant of all the aerodynamic forces acting on the airfoil section.

Lift: the aerodynamic force which acts at 90° to the Relative Airflow.

Drag: The aerodynamic force which acts parallel to and in the same direction as the Relative Airflow (or opposite to the aircraft flight path).

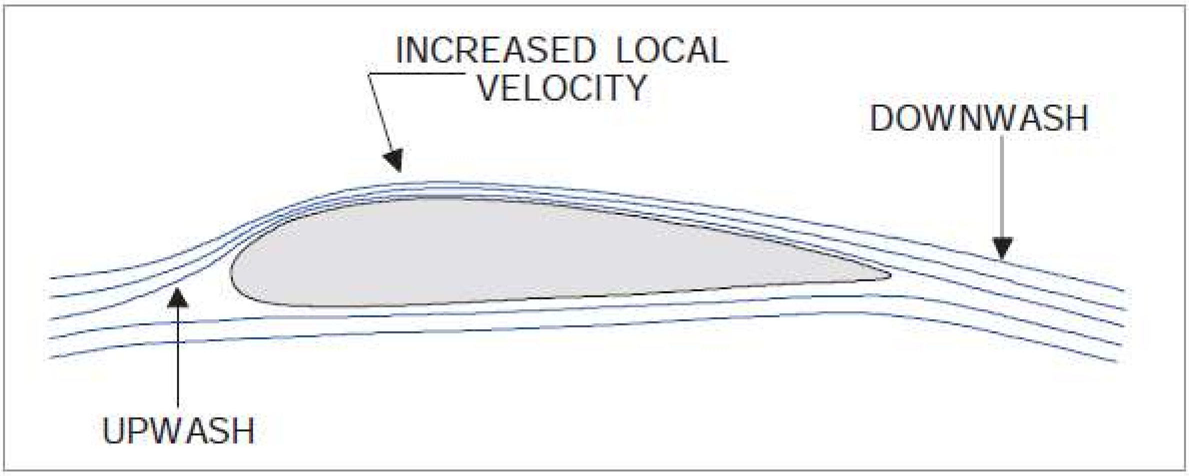
Angle of Attack: The angle between the chord line and the Relative Airflow.

BASICS ABOUT AIRFLOW

When considering airflow velocity, it makes no difference to the pressure pattern if the aircraft is moving through the air or the air is flowing over the aircraft: it is the relative velocity which is the important factor.

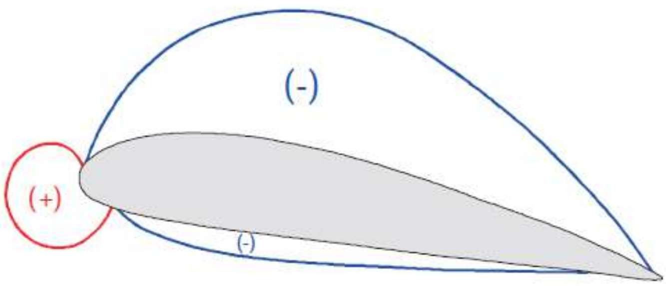
Two dimensional airflow: assumes a wing with the same airfoil section along the entire span with no spanwise pressure differential or flow.
Three dimensional airflow: three dimensional flow is the true airflow over an aircraft and consists of a hypothetical two dimensional flow modified by various pressure differentials.

TWO DIMENSIONAL AIRFLOW
An airflows towards an airfoil it will be turned towards the lower pressure at the upper surface; this is termed **upwash**. After passing over the airfoil, the airflow returns to its original position and state; this is termed **downwash**.

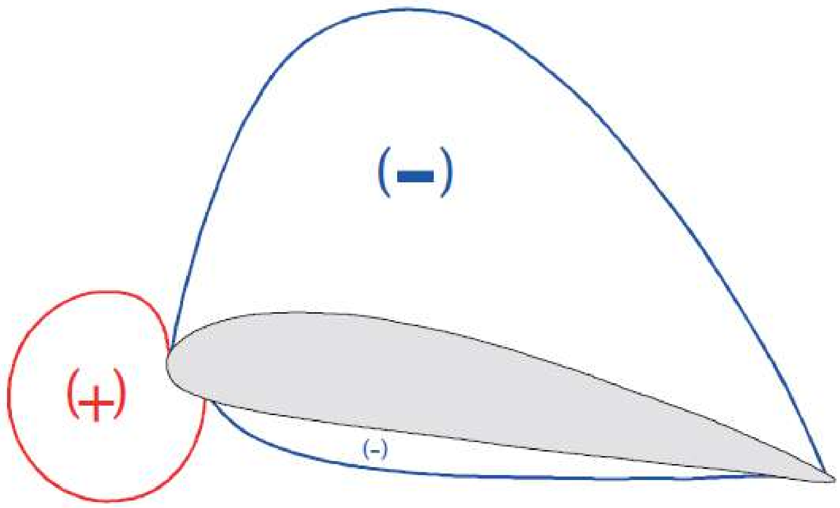


Influence of dynamic pressure (IAS)

If the static pressure on one side of a body is reduced more than on the other side, a pressure differential will exist.

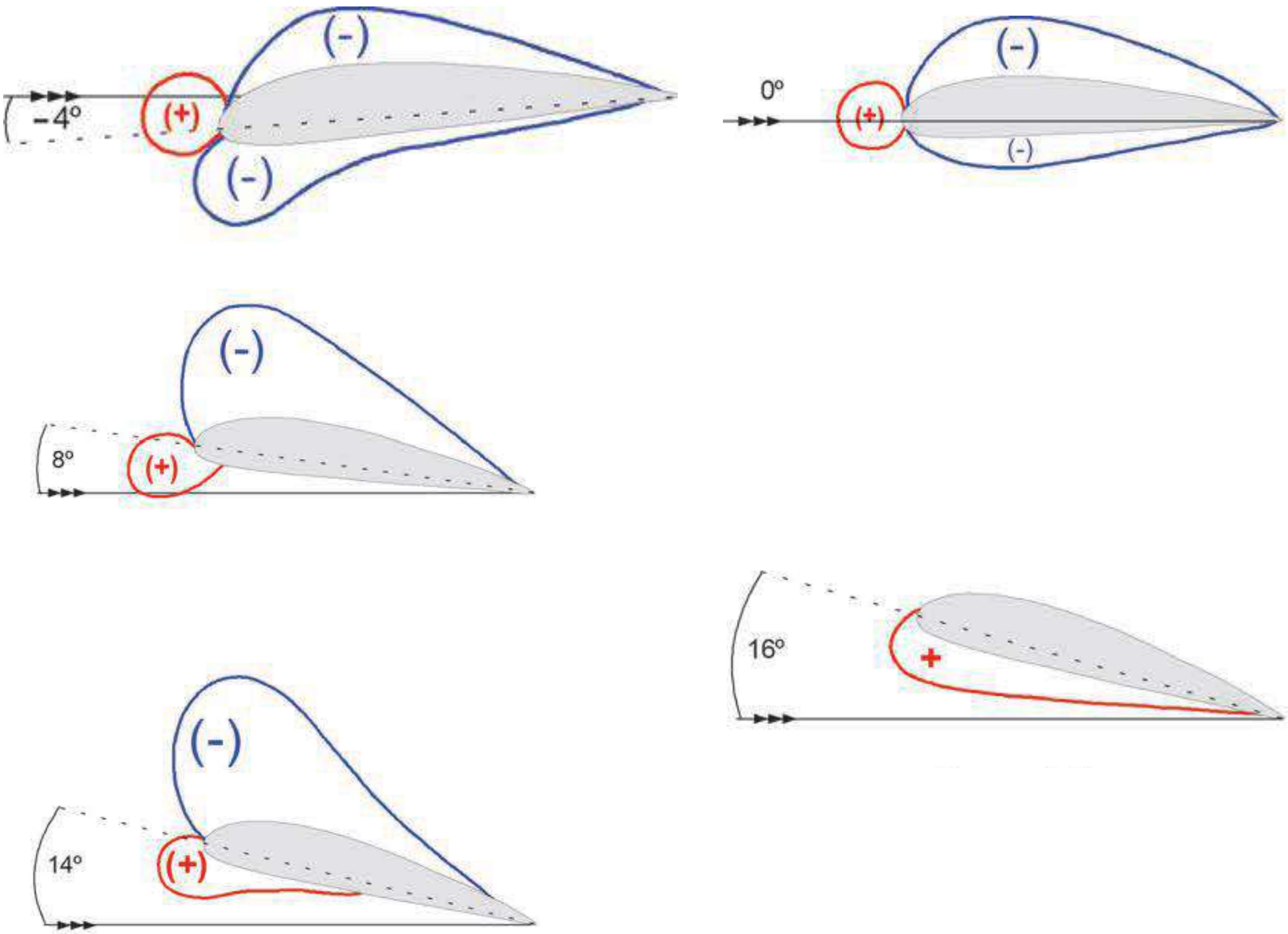


If the dynamic pressure is increased, the pressure differential will increase.



The pressure differential acting on the surface area will produce an upward acting force. If the dynamic pressure (IAS) is increased, the upward force will increase.

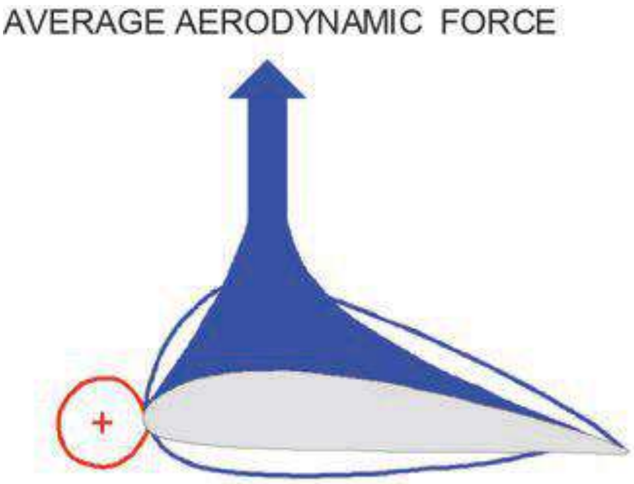
Influence of Angle of Attack

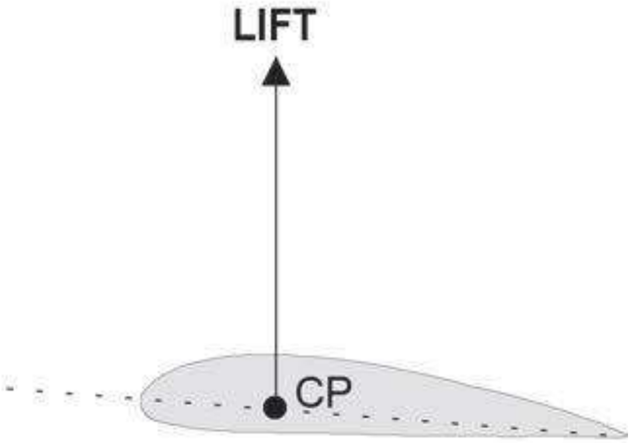


Centre of pressure (CP)

The whole surface of the airfoil contributes to lift, but the point along the chord where the distributed lift is effectively concentrated is termed the Centre of Pressure.

As the angle of attack increases from 0° to 16° the upper 'suction' peak moves forward so the point at which the lift is effectively concentrated, the CP, will move forward. The CP moves forward and the magnitude of the lift force increases with increase in angle of attack until the stall is reached when the lift force decreases abruptly and the CP generally moves back along the chord. Note that the CP is at its most forward location just before the stall.





SUMMARY

Airflow pattern, and ultimately lift and drag, will depend upon:
• Angle of attack - airflow cross-sectional area change
• Airfoil shape (thickness & camber) - airflow cross-sectional area change
• Air density - mass flow of air (decreases with increased altitude)
• Velocity - mass flow of air (changes with aircraft TAS)

The lift force is the result of the pressure differential between the top and bottom surfaces of an airfoil; the greatest contribution to overall lift comes from the top surface.

Anything (ice in particular, but also frost, snow, dirt, dents and even water droplets) which changes the accurately manufactured profile of the leading portion of the upper surface can seriously disrupt airflow acceleration in that area, and hence the magnitude of the lift force will be affected.

An increase in dynamic pressure (IAS) will increase the lift force, and vice versa.
An increase in angle of attack will increase the lift force, and vice versa, (0° to 16°).

The centre of pressure (CP) of a cambered airfoil moves forward as the angle of attack increases.

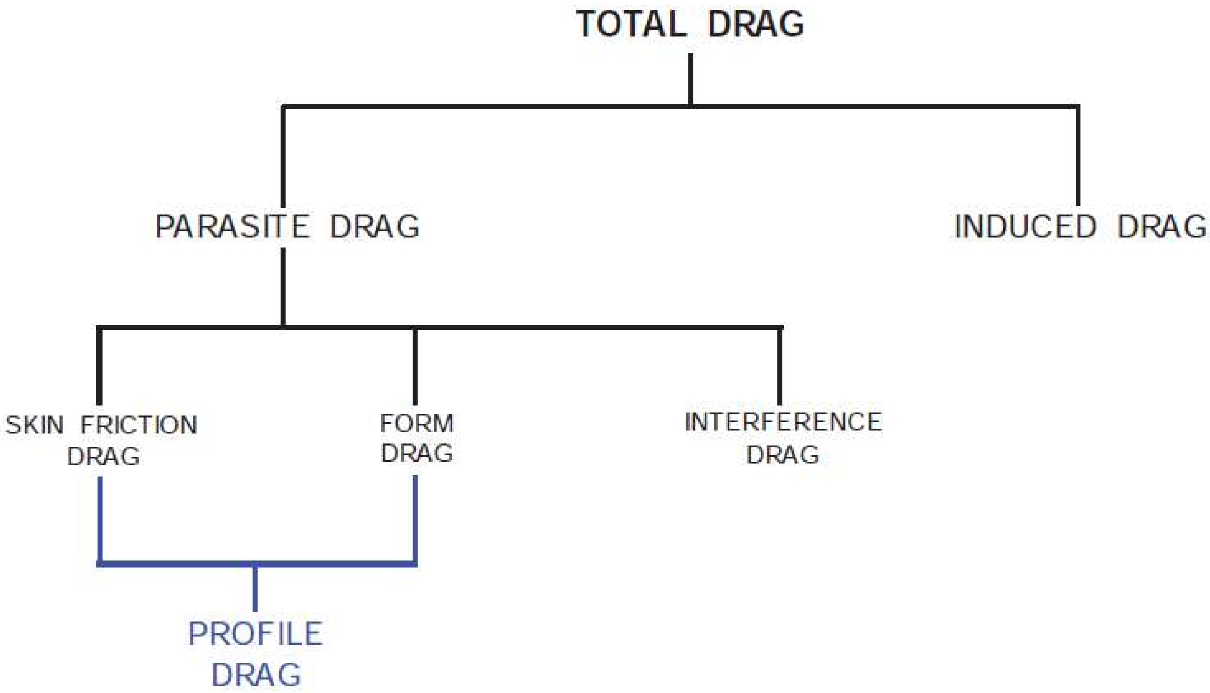
The coefficient of lift (CL) is the ratio between lift per unit wing area and dynamic pressure.
As the angle of attack increases from -4°, the leading edge stagnation point moves from the upper surface around the leading edge to the lower surface.
The greatest positive pressure occurs at the leading edge stagnation point, where the relative flow velocity is zero.

Form (pressure) drag is the result of the pressure differential between the leading edge and trailing edge of the airfoil.

An increase in dynamic pressure (IAS) will increase form drag, and vice versa.

The coefficient of drag (CD) is the ratio between drag per unit wing area and dynamic pressure.

3. DRAG

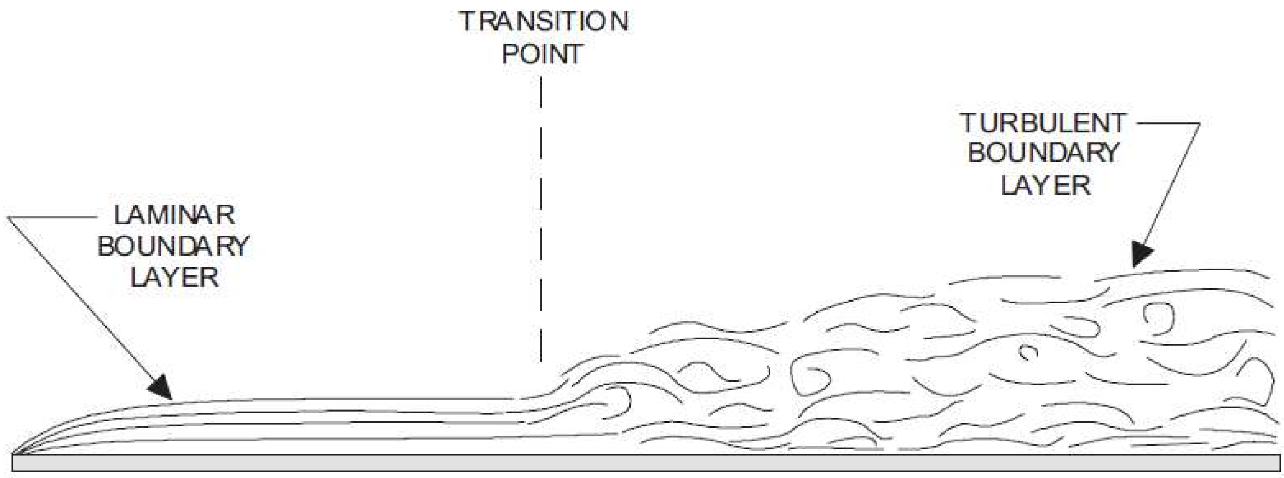


Parasite drag is independent of lift generation, while induced drag is the result of lift generation.

SKIN FRICTION DRAG

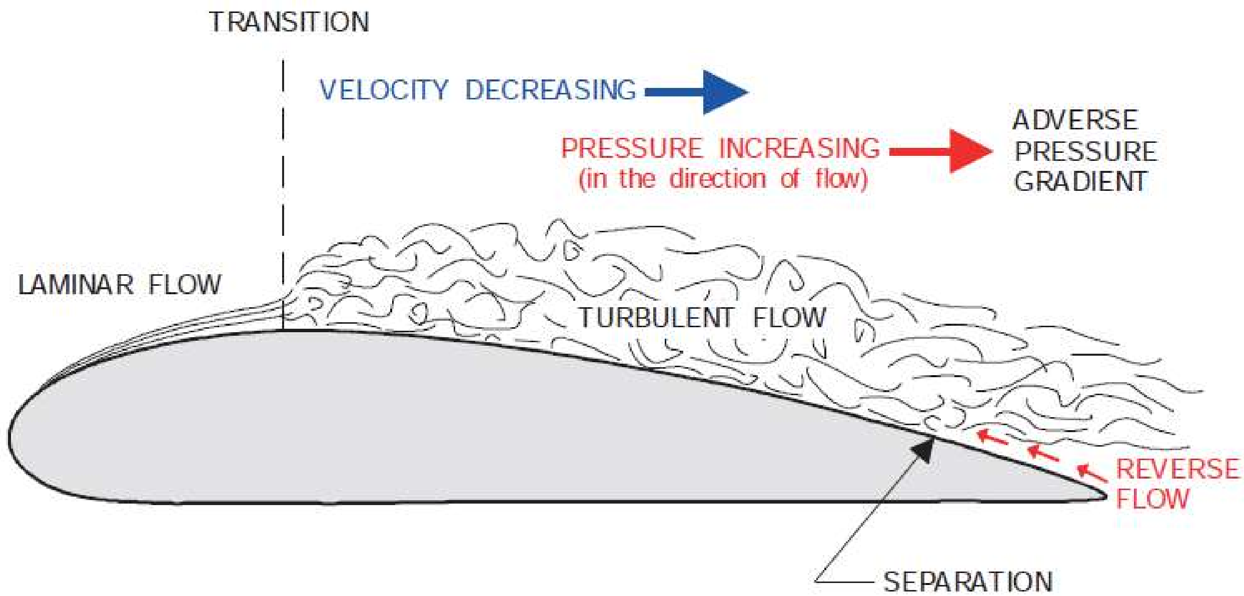
Particles of air in direct contact with the surface are accelerated to the speed of the aircraft and are carried along with it. Adjacent particles will be accelerated by contact with the lower particles, but their velocity will be slightly less than the aircraft because the viscosity of air is low. As distance from the surface increases, less and less acceleration of the layers of air takes place. Therefore, over the entire surface there will exist a layer of air whose relative velocity ranges from zero at the surface to a maximum at the boundary of the air affected by the presence of the aircraft. The layer of air extending from the surface to the point where no viscous effect is detectable is known as the boundary layer.

The boundary layer will exist in two forms, either laminar or turbulent. In general, the flow at the front will be laminar and become turbulent some distance back, known as the transition point. The increased rate of change in velocity at the surface in the turbulent flow will give more skin friction than the laminar flow. A turbulent boundary layer also has a higher level of kinetic energy than a laminar layer.



FORM DRAG (or pressure drag)

Form (pressure) drag results from the pressure at the leading edge of a body being greater than the pressure at the trailing edge. Overall, skin friction causes a continual reduction of boundary layer kinetic energy as flow continues back along the surface. The adverse pressure gradient behind the transition point will cause an additional reduction in kinetic energy of the boundary layer. If the boundary layer does not have sufficient kinetic energy in the presence of the adverse pressure gradient, the lower levels of the boundary layer stop moving. The upper levels of the boundary layer will overrun at this point (separation point) and the boundary layer will separate from the surface at the separation point. Also, surface flow aft of the separation point will be forward, toward the separation point - a flow reversal. Because of separation, there will be a lower pressure at the trailing edge than the leading edge. An aerodynamic force will act in the direction of the lower pressure; this force is called form drag.



INTERFERENCE DRAG

When considering a complete aircraft, parasite drag will be greater than the sum of the parts. Additional drag results from boundary layer ‘interference’ at wing/fuselage, wing/engine nacelle and other such junctions.

FACTORS AFFECTING PARASITE DRAG

- IAS: parasite drag varies directly with the square of indicated airspeed

- Configuration: parasite drag varies directly in proportion to the frontal area presented to the airflow.

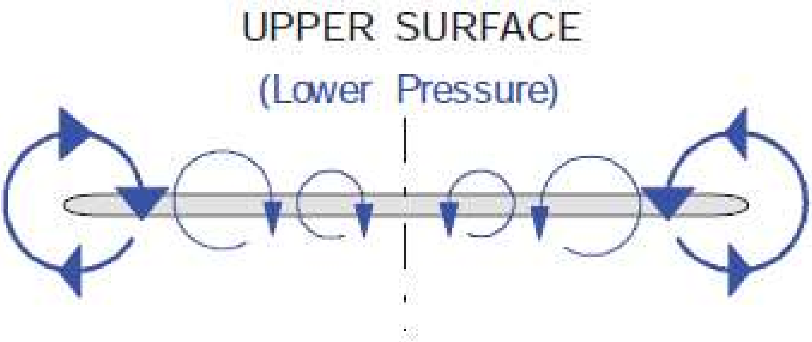
- Airframe contamination: any contamination will increase the parasite drag coefficient and, in case of severe contamination, also the frontal area presented to the airflow will increase.

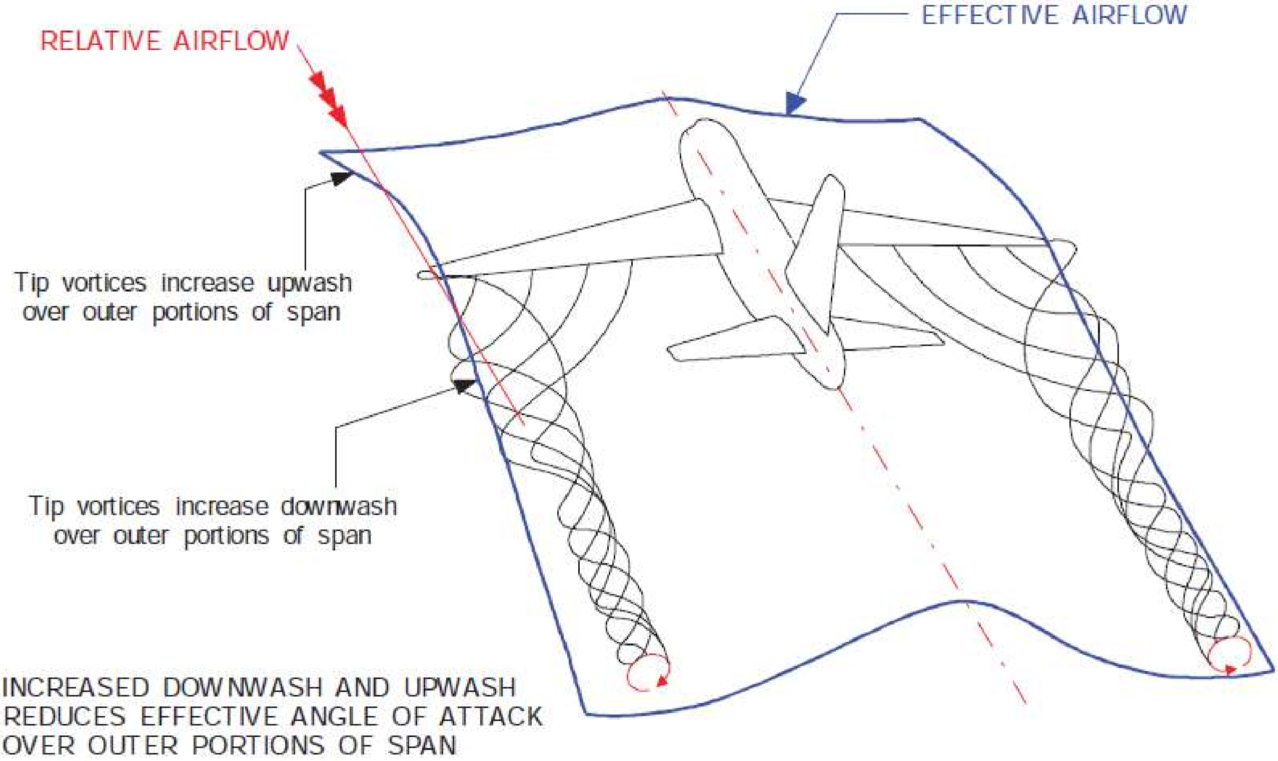
INDUCED DRAG

Induced drag is an undesirable by-product of lift. Wing tip vortices modify upwash and downwash in the vicinity of the wing which produces a rearward component to the lift vector known as induced drag.

The lower the IAS, the higher the angle of attack - the stronger the vortices.

The stronger the vortices - the greater the induced drag.




RELATIVE AIRFLOW
EFFECTIVE AIRFLOW
Tip vortices increase upwash over outer portions of span
Tip vortices increase downwash over outer portions of span
INCREASED DOWNWASH AND UPWASH REDUCES EFFECTIVE ANGLE OF ATTACK OVER OUTER PORTIONS OF SPAN

4. LIFT

The important factors for aerodynamic forces are:

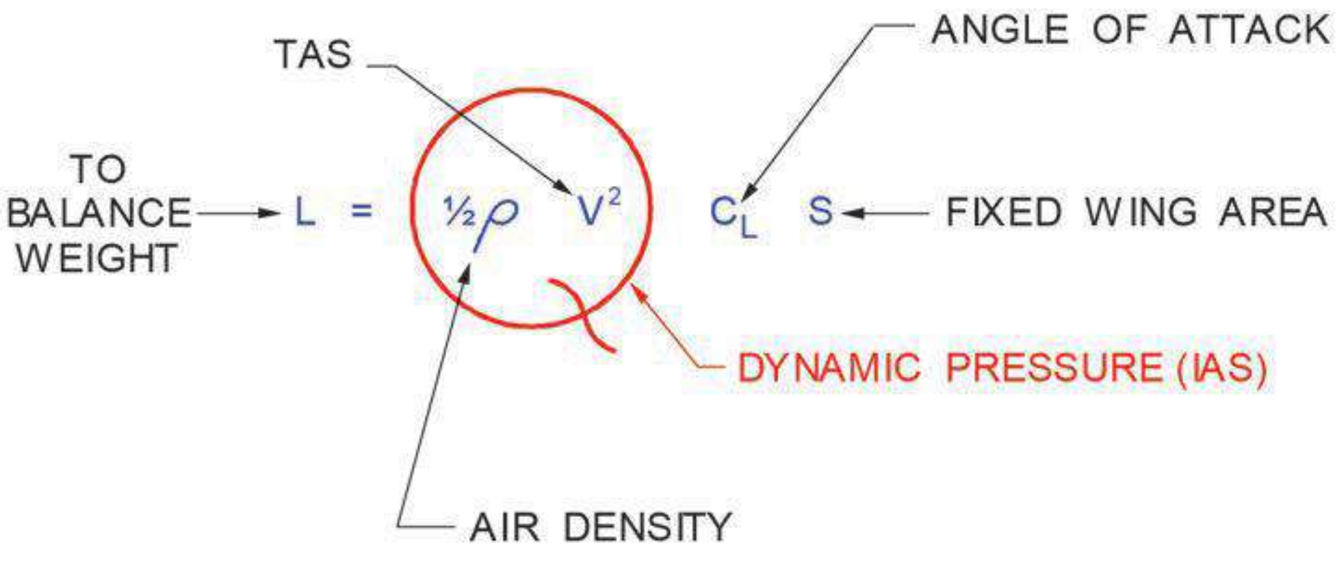
- Dynamic pressure:
  - Airstream velocity
  - Air density

- Pressure distribution: (CL)
  - Shape or profile of the surface
  - Angle of attack

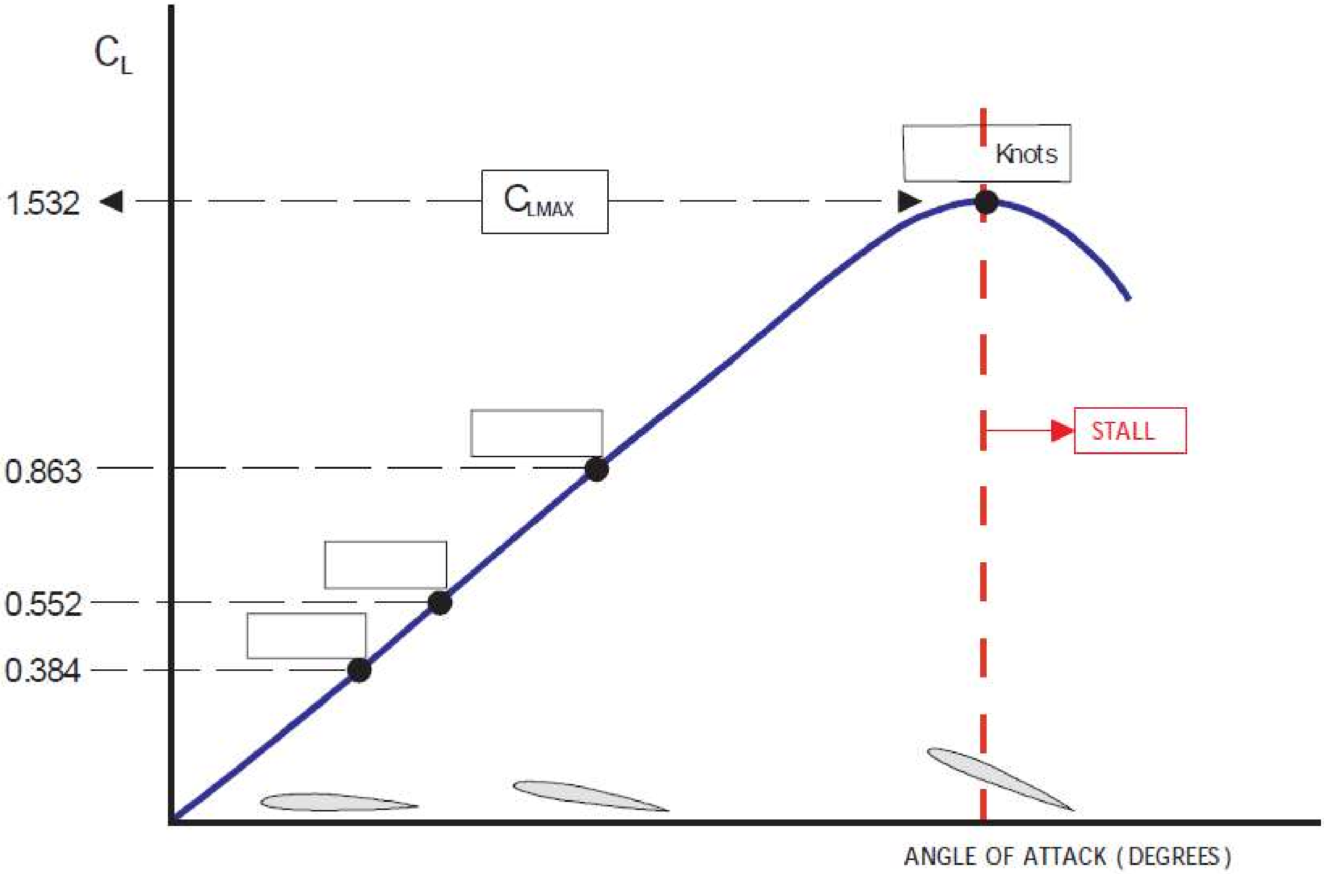
- Surface area

- Condition of the surface

- Compressibility effect (not considered in this chapter)



LIFT CURVE



The figure shows the lift curve of a symmetrical airfoil section, with lift coefficient (CL) plotted against angle of attack.

To generate a constant lift force, any adjustment in dynamic pressure must be accompanied by a change in angle of attack. (At CL less than CLMAX).

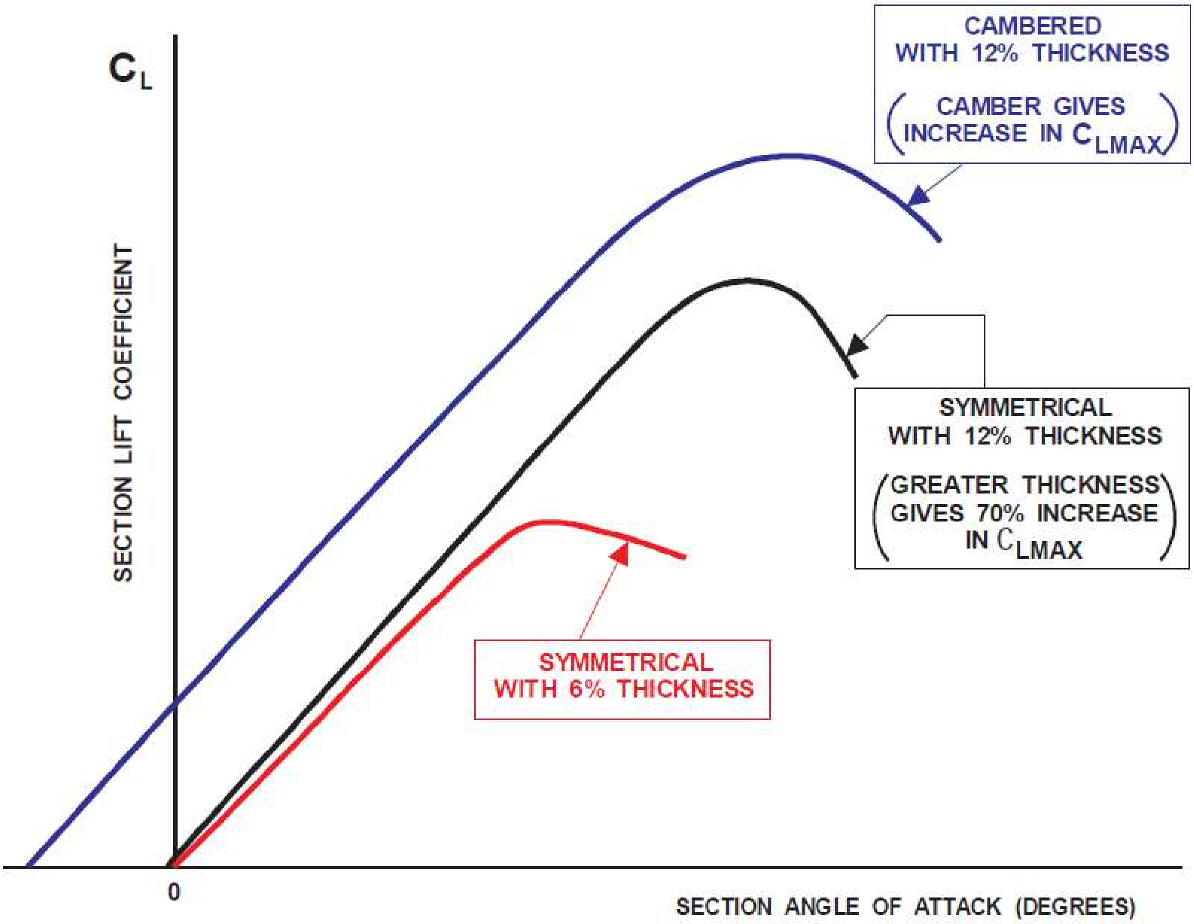
For a constant lift force, each dynamic pressure requires a specific angle of attack.

Minimum dynamic pressure is determined by the maximum lift coefficient (CLMAX), which occurs at a specific angle of attack (approximately 16°).

The angle of attack for CLMAX is constant. (This is true for a given configuration).

If more lift is required due to greater operating weight, a greater dynamic pressure is required to maintain a given angle of attack.

We can easily see the difference between a symmetrical airfoil and a cambered airfoil.



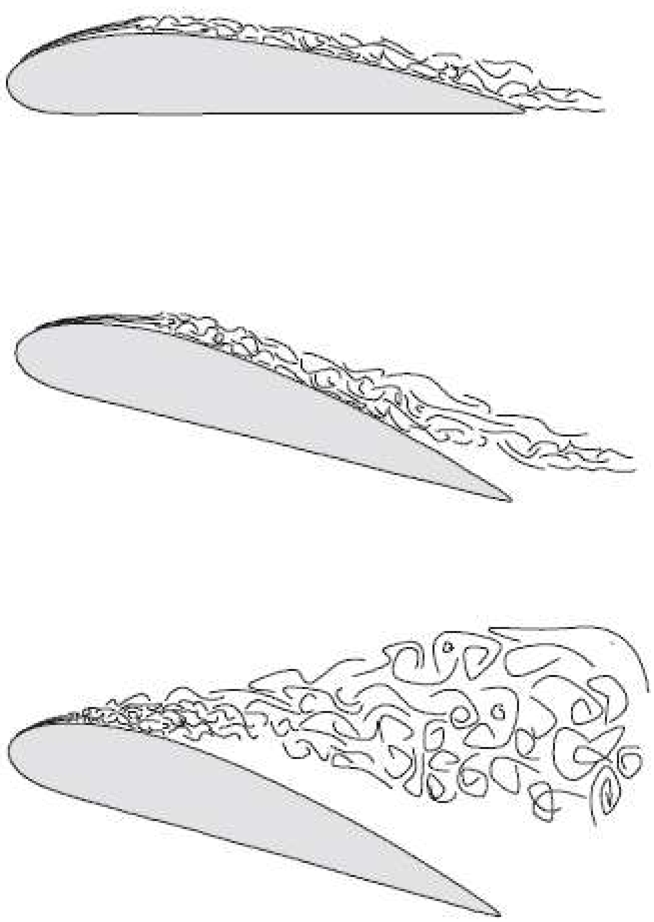
5. STALL AND HIGH LIFT DEVICES

STALL

Stalling is a potentially hazardous manoeuvre involving loss of height and loss of control. A pilot must be able to clearly and unmistakably identify an impending stall so that it can be prevented. Different types of aircraft exhibit various stall characteristics, some less desirable than others. Airworthiness authorities specify minimum stall qualities that an aircraft must possess.

CAUSE OF STALL

The CL of an airfoil increases with angle of attack up to a maximum (CLMAX). Any further increase above this stalling angle, or critical angle of attack, will make it impossible for the airflow to smoothly follow the upper wing contour, and the flow will separate from the surface, causing CL to decrease and drag to increase rapidly.



It is important to remember that the angle of attack is the angle between the chord line and the relative airflow.

Therefore, if the angle of attack is increased up to or beyond the critical angle, an airplane can be stalled at any airspeed or flight attitude.

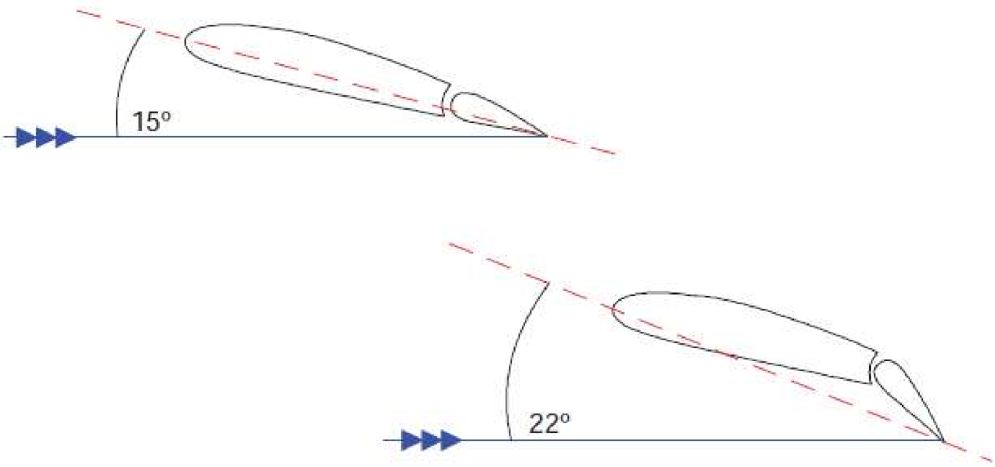
STALL RECOVERY

To recover from a stall or prevent a full stall, the angle of attack must be decreased to reduce the adverse pressure gradient. This may consist of merely releasing back pressure, or it may be necessary to smoothly move the pitch control forward, depending on the aircraft design and severity of the stall.

Allow airspeed to increase and recover lost altitude with moderate back pressure on the pitch control. Pulling too hard could trigger a secondary stall, or worse, could exceed the limit load factor and damage the aircraft structure. As angle of attack reduces below the critical angle, the adverse pressure gradient will decrease, airflow will re-attach, and lift and drag will return to their normal values.

USE OF FLIGHT CONTROLS CLOSE TO THE STALL

At low speeds normally associated with stalling, dynamic pressure is at a very low value and greater control deflection will be required to achieve the same response; also, the flying controls will feel unresponsive or "mushy". If an accidental stall does occur, it is vitally important that the stall and recovery should occur without too much wing drop. Moving a control surface modifies the chord line and, hence, the angle of attack. An aircraft being flown close to the stall angle may have one wing that produces slightly less lift than the other; that wing will tend to drop. Trying to lift a dropping wing with aileron will increase its angle of attack and may cause the wing to stall completely, resulting in that wing dropping at an increased rate. At speeds close to the stall, ailerons must be used with caution.



STALL RECOGNITION

The airplane is considered stalled when the behavior of the airplane gives the pilot a clear and distinctive indication of an acceptable nature that the airplane is stalled.

Acceptable indications of a stall, occurring either individually or in combination, are:
1) A nose-down pitch that cannot be readily arrested;
2) Buffeting, of a magnitude and severity that is a strong and effective deterrent to further speed reduction;
3) The pitch control reaches the aft stop and no further increase in pitch attitude occurs when the control is held full aft for a short time before recovery is initiated.

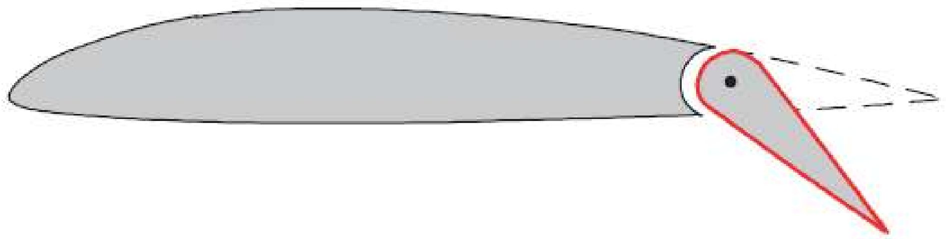
HIGH LIFT DEVICES

Aircraft are fitted with high lift devices to reduce the take-off and landing distances. This permits operation at greater weights from given runway lengths and enables greater payloads to be carried.

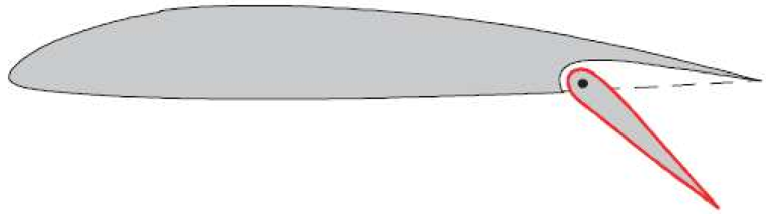
FLAPS

A flap is a hinged portion of the trailing or leading edge which can be deflected downwards and so produce an increase of camber.

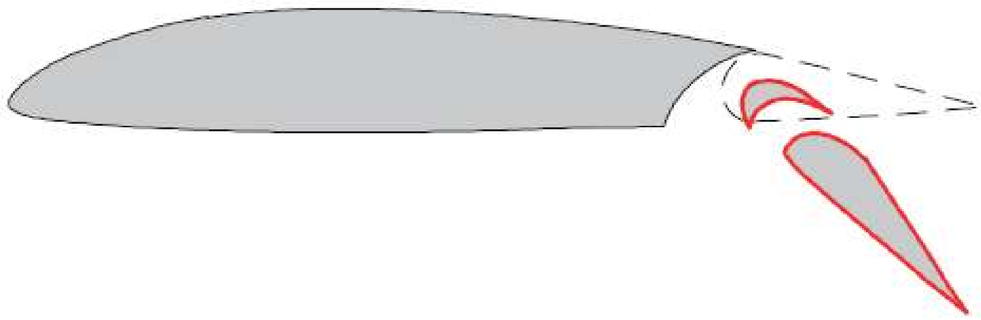
PLAIN FLAP



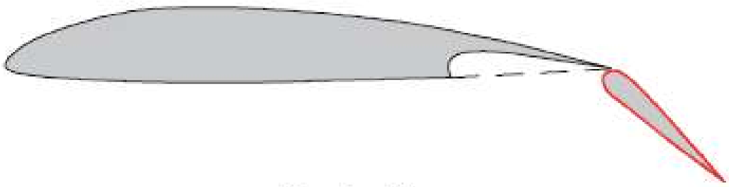
SPLIT FLAP



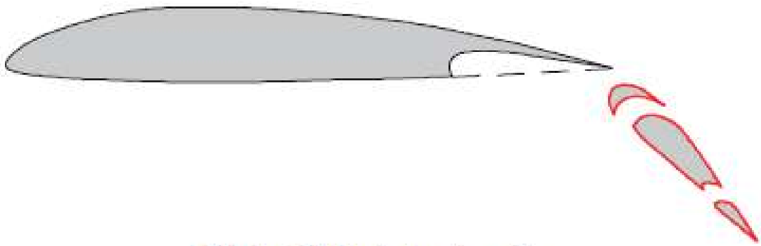
SLOTTED AND MULTIPLE SLOTTED FLAP



FOWLER FLAP

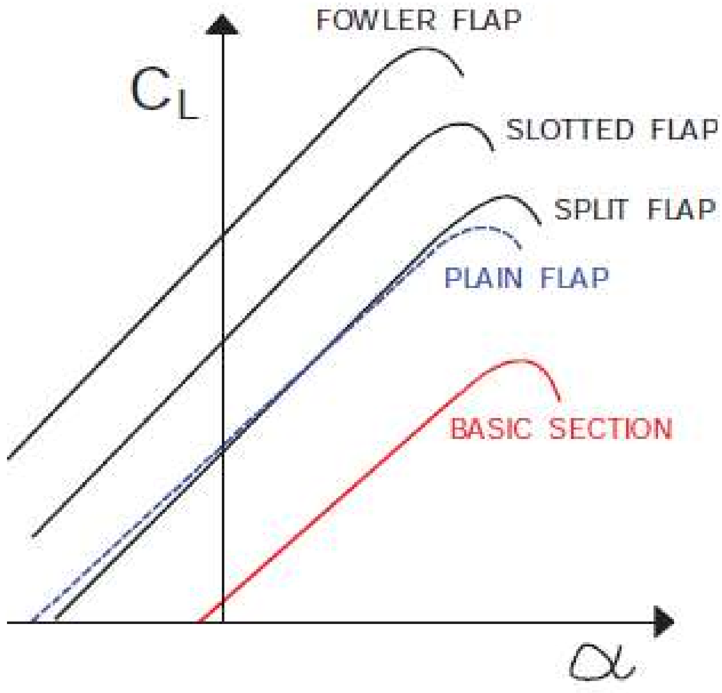


Fowler Flap

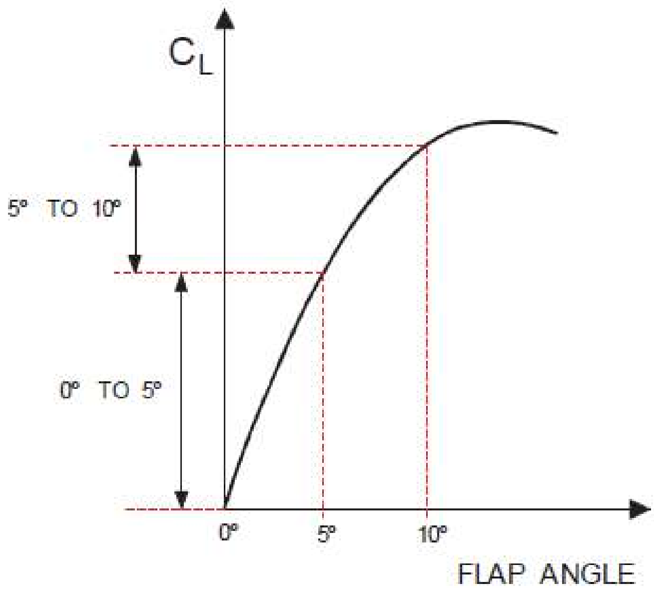


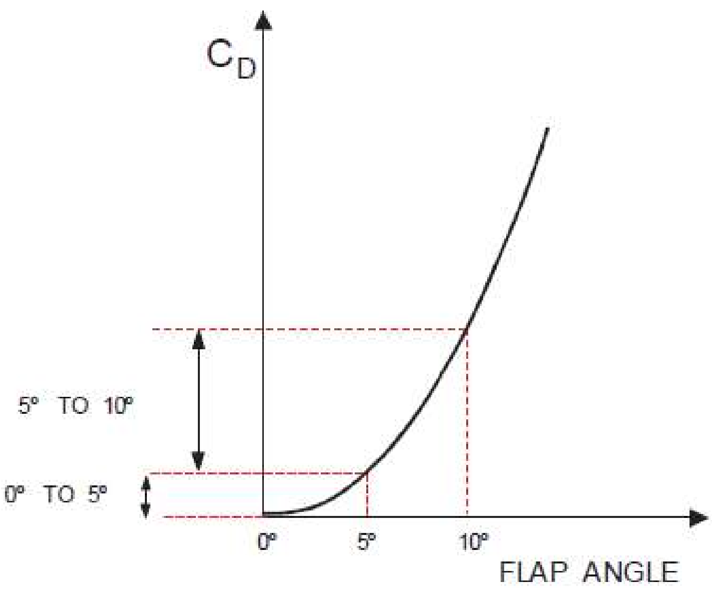
Triple Slotted Fowler Flap

COMPARISON



VARIATION OF LIFT AND DRAG

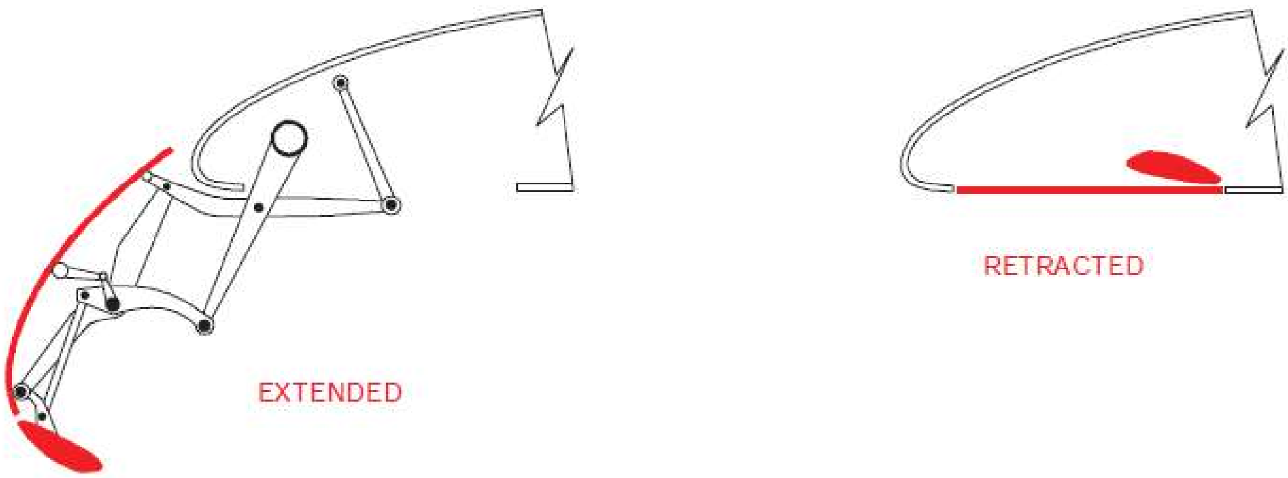




LEADING EDGE HIGH LIFT DEVICES

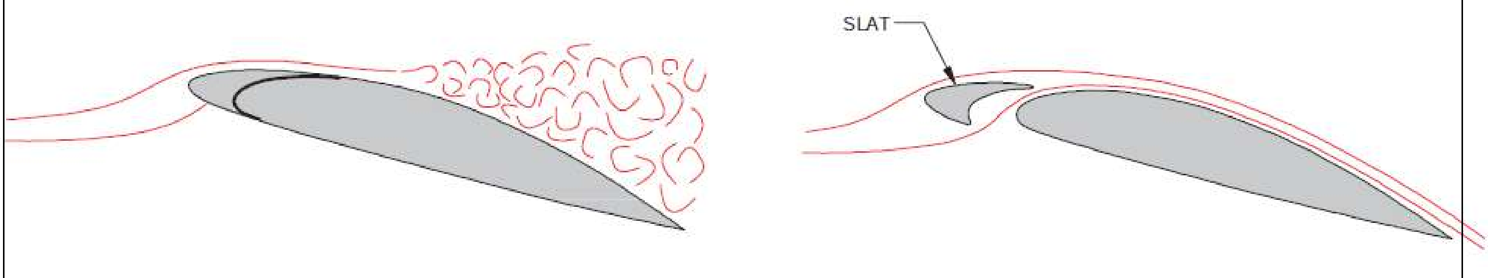
There are two forms of leading edge high lift device commonly in use: the leading edge flap and the leading edge slot or slat.

LEADING EDGE FLAPS: KRUEGER FLAP



LEADING EDGE SLATS

A slat is a small auxiliary airfoil attached to the leading edge of the wing, Figure 8.14. When deployed, the slat forms a slot which allows passage of air from the high pressure region below the wing to the low pressure region above it. Additional Kinetic Energy is added to the airflow through the slot by the slat forming a convergent duct, so when slats are deployed, the boundary layer is re-energized.
If Kinetic Energy is added to the boundary layer, boundary layer separation will be delayed to a much higher angle of attack.



6. STABILITY AND CONTROL

Stability is the tendency of an aircraft to return to a steady state of flight without any help from the pilot, after being disturbed by an external force.
An aircraft must have the following qualities:

• Adequate stability to maintain a uniform flight condition.

• The ability to recover from various disturbing influences.

• Sufficient stability to minimize the workload of the pilot.

• Proper response to the controls so that it may achieve its design performance with adequate maneuverability.

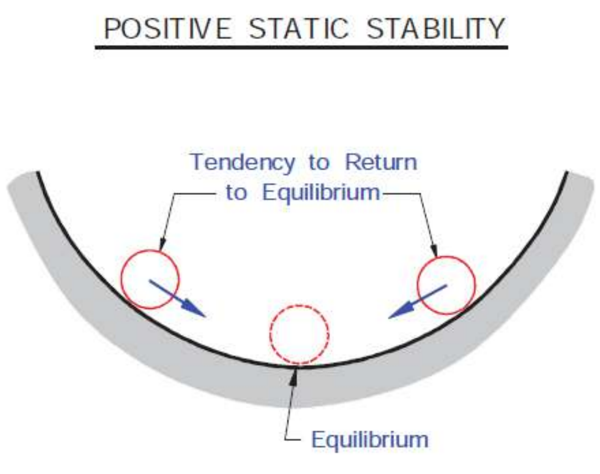
STATIC STABILITY

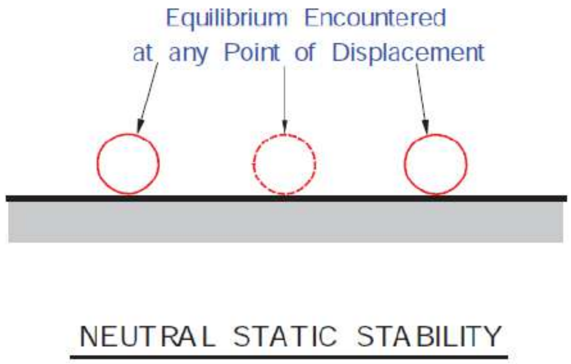
An aircraft is in a state of equilibrium (trim) when the sum of all forces is zero and the sum of all moments is zero; there are no accelerations and the aircraft will continue in steady flight. If equilibrium is disturbed by a gust, or deflection of the controls, the aircraft will experience accelerations due to an unbalance of moments or forces.
The type of static stability an aircraft possesses is defined by its initial tendency, following the removal of some disturbing force.

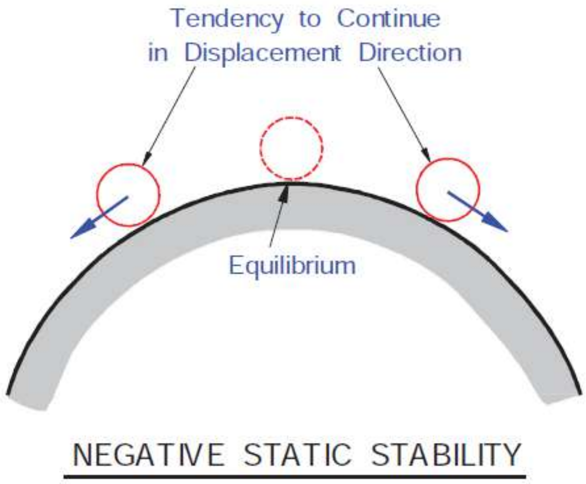
• Positive static stability (or static stability) exists if an aircraft is disturbed from equilibrium and has the tendency to return to equilibrium.

• Neutral static stability exists if an aircraft is subject to a disturbance and has neither the tendency to return nor the tendency to continue in the displacement direction.

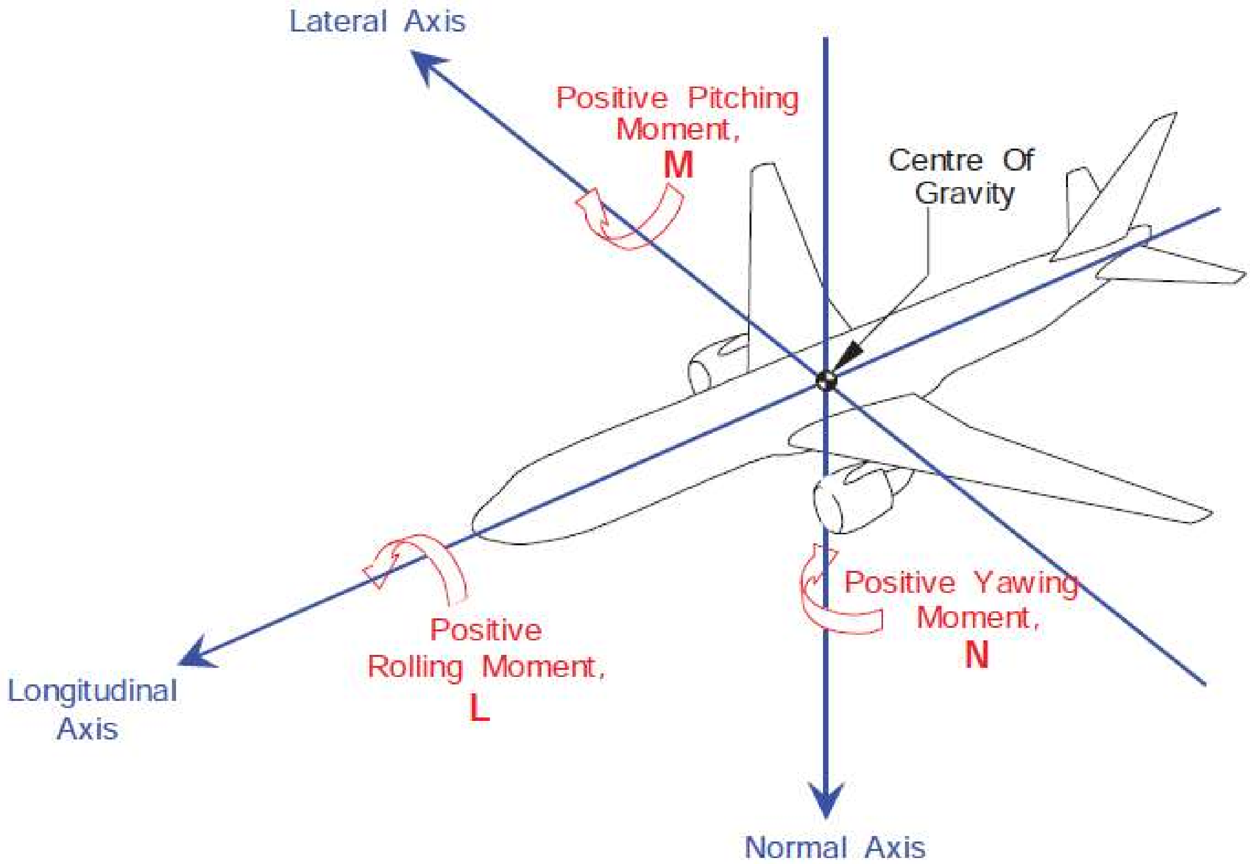
• Negative static stability (or static instability)







AIRPLANE REFERENCE AXIS



CONTROLLABILITY

An aircraft is said to be trimmed (in trim) if all moments in pitch, roll, and yaw are equal to zero. The establishment of trim (equilibrium) at various conditions of flight may be accomplished by:

- pilot effort
- trim tabs
- variable incidence trimming tailplane
- moving fuel between the wing tanks and an aft located trim tank, or
- bias of a surface actuator (powered flying controls)

The term controllability refers to the ability of the aircraft to respond to control surface displacement and achieve the desired condition of flight. Adequate controllability must be available to perform take-off and landing and accomplish the various manoeuvre in flight. A contradiction exists between stability and controllability. A high degree of stability gives reduced controllability.

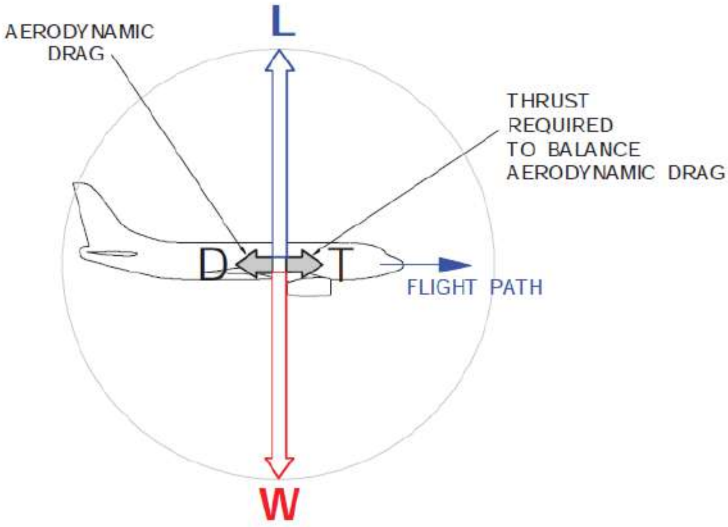
7. FLIGHT MECHANICS

Flight Mechanics is the study of the forces acting on an aircraft in flight and the response of the aircraft to those forces. For an aircraft to be in steady flight, the following conditions must exist:

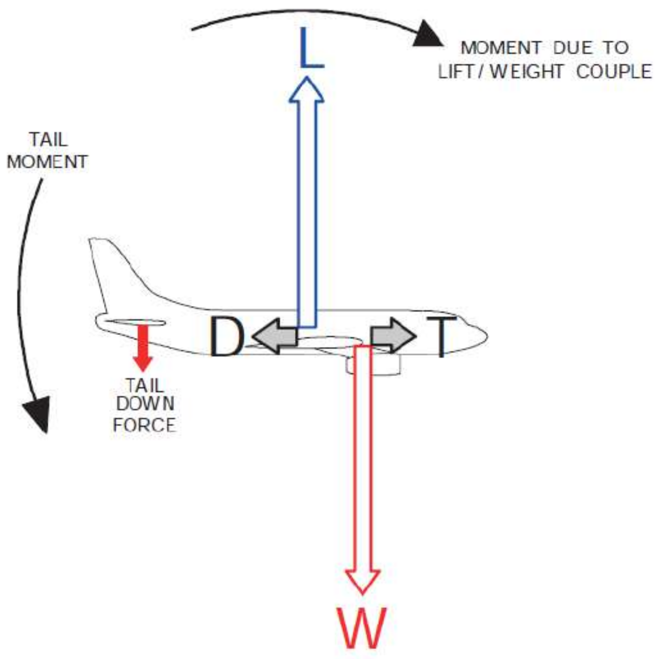
- the forces acting upward must exactly balance the forces acting downward
- the forces acting forward must exactly balance the forces acting backward
- the sum of all moments must be zero

This condition is known as equilibrium.

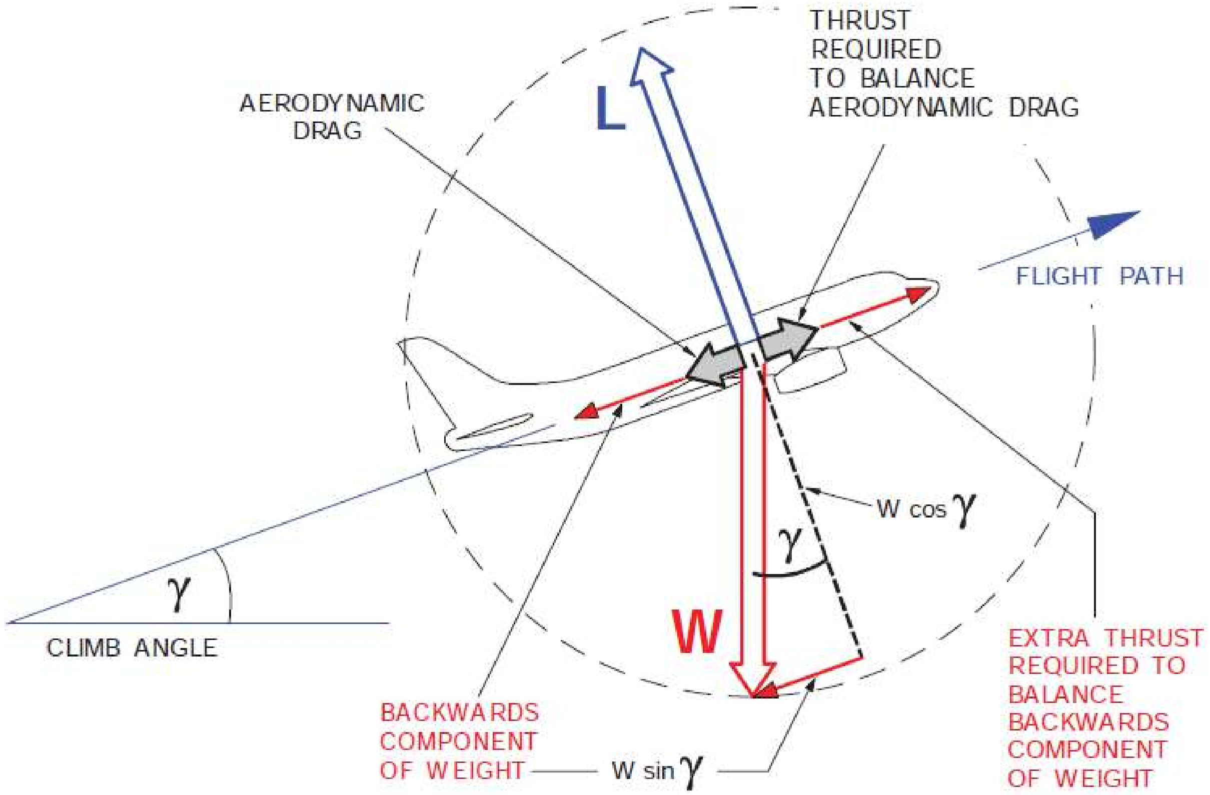
STRAIGHT HORIZONTAL STEADY FLIGHT



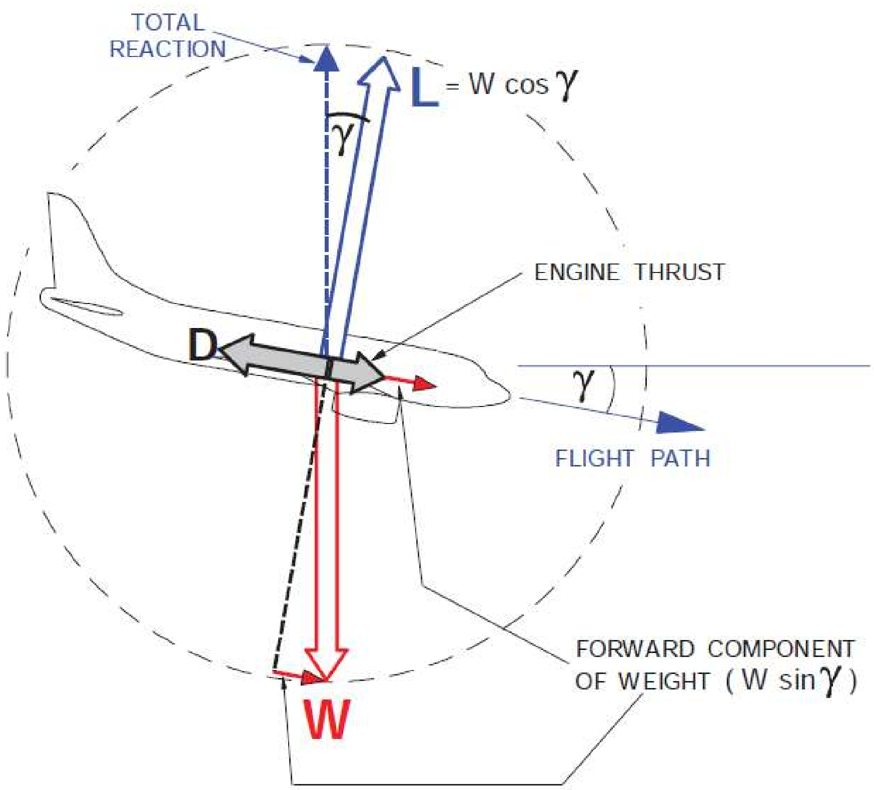
TAILPLANE AND ELEVATOR



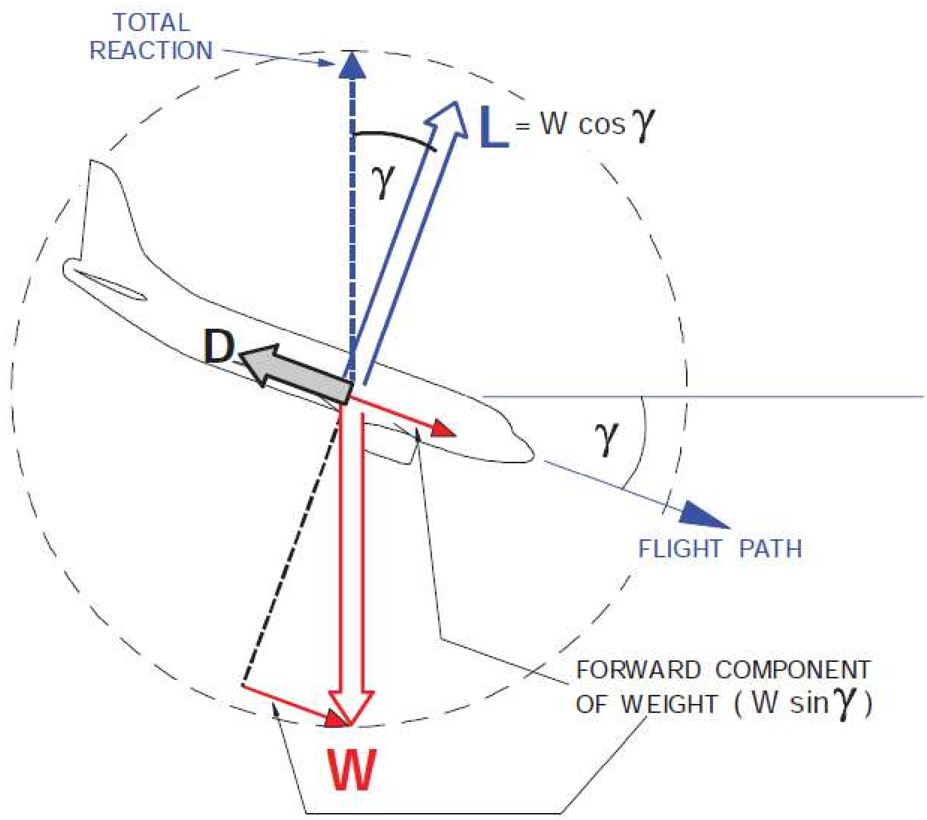
STRAIGHT STEADY CLIMB



POWER-ON DESCENT

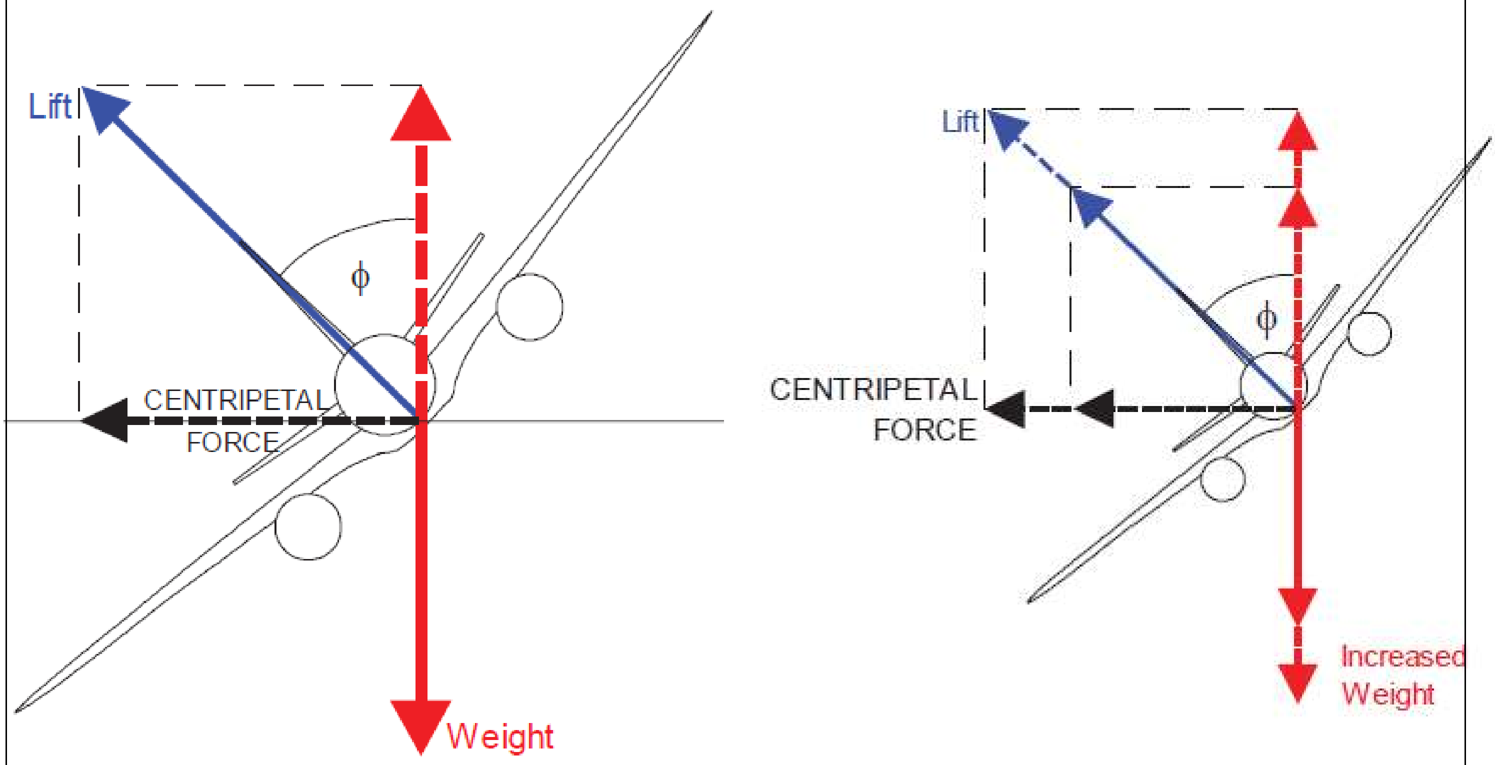


GLIDE

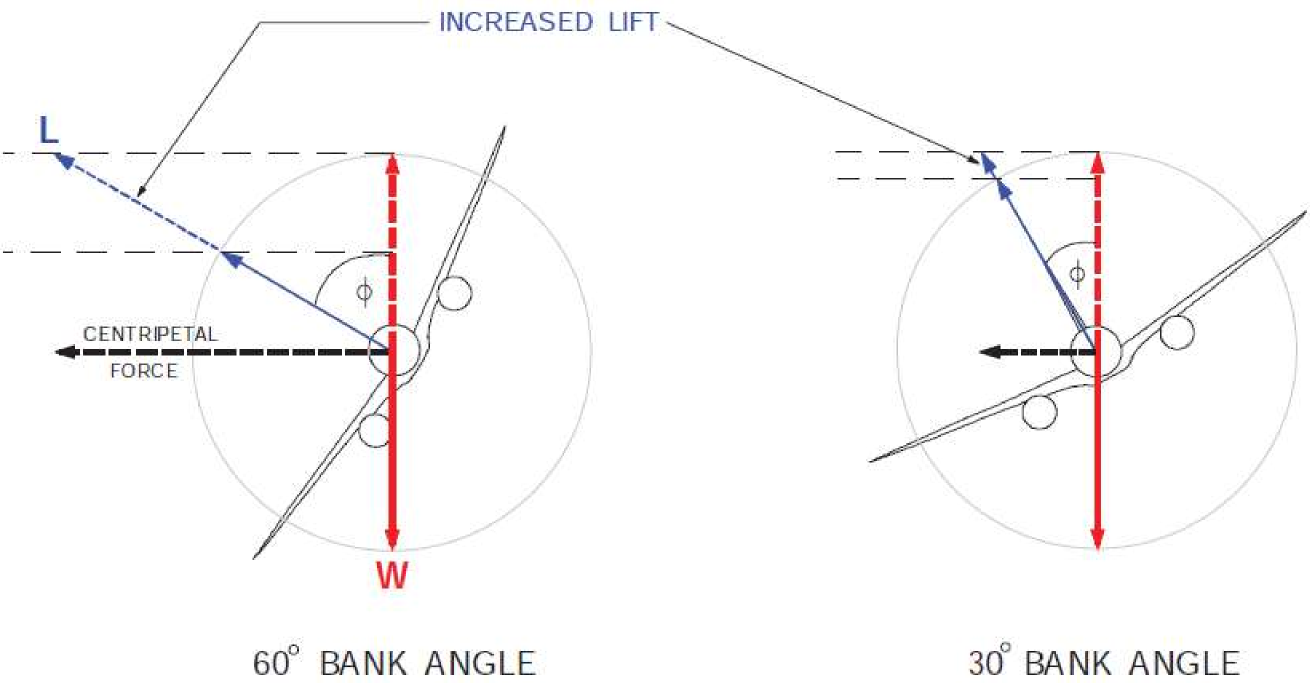


TURN

Effect of weight



Load Factor


INCREASED LIFT
L
CENTRIPETAL
FORCE
W
ϕ
ϕ
60° BANK ANGLE
30° BANK ANGLE

8. HIGH SPEED FLIGHT

Studying high speed flight we must start to consider air compressibility.
When an aircraft moves through the air infinitesimally small pressure disturbances, or waves, are propagated outward from the aircraft in all directions, but only the waves travelling ahead of the aircraft are significant for the study of high speed flight.

SPEED OF SOUND
The speed of sound changes with temperature only.
At 15°C the speed of sound is 340 meters per second.

MACH NUMBER
As the speed of an aircraft increases, there is a decrease in the distance between the aircraft and the influence of the advancing pressure waves.
At higher speeds there is also a change in the flow and pressure patterns around the aircraft.
Lift and drag, maneuverability and the stability and control characteristics will all be changed.

It is vitally important that the flight crew know the speed of the aircraft in relation to the potential effects of 'compressibility'. If the aircraft speed through the air (TAS) and the speed of sound in the air through which it is flying (the local speed of sound) is known, this will give an indication of the degree of compressibility. This relationship is known as the Mach number and Mach number is a measure of compressibility.

Mach number (M) is the ratio of the true airspeed (V) to the local speed of sound (a).

$$M = \frac{V}{a}$$

Mach number will increase if altitude is increased at constant IAS; the lower the temperature, the lower the speed of sound.

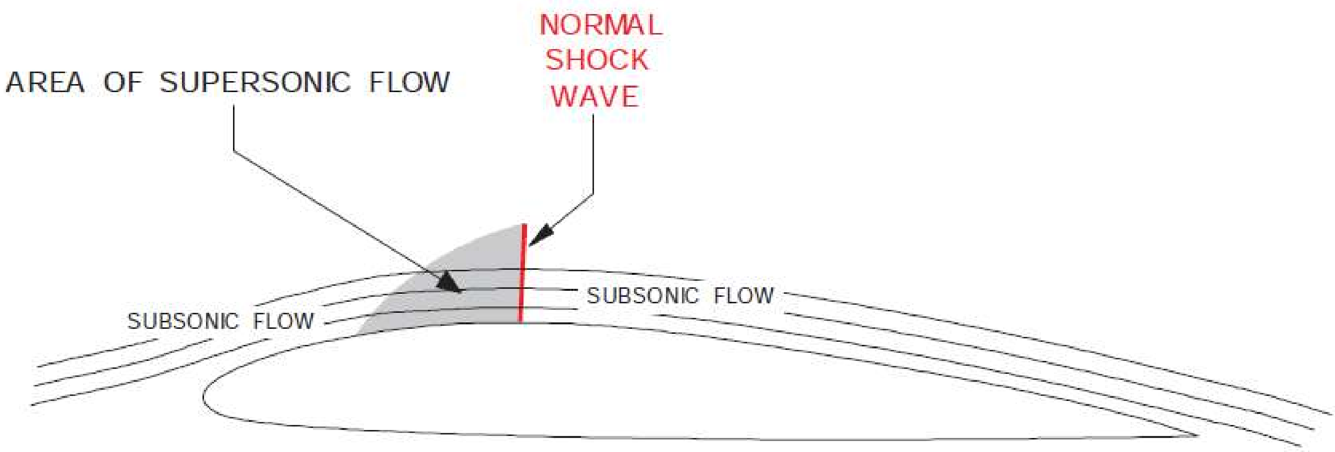
CRITICAL MACH NUMBER

An airfoil generates lift by accelerating air over the top surface. At small angles of attack the highest local velocity on an aircraft will usually be located at the point of maximum thickness on the wing.

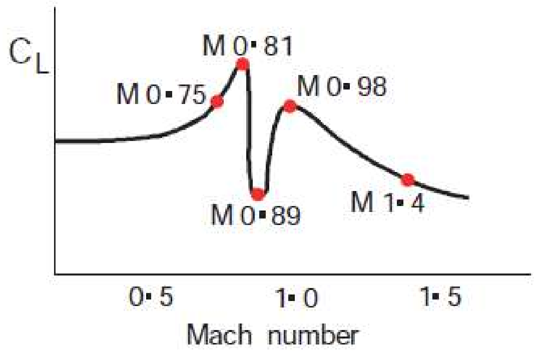
As the free stream speed increases, the maximum speed on the aerofoil will reach the local speed of sound first. The free stream Mach number at which the local velocity first reaches Mach 1.0 (sonic) is called the Critical Mach number.

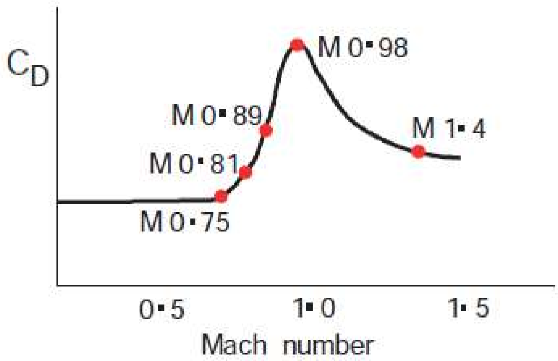
Critical Mach number is the highest speed at which no parts of the aircraft are supersonic.

At speeds just above the critical Mach number there will be a small region of supersonic airflow on the upper surface, terminated by a shock wave.



LIFT AND DRAG WITH INCREASING MACH NUMBER





9. LIMITATIONS

OPERATING LIMIT SPEEDS

An aircraft in flight must observe certain speed limitations; these can be maximum speeds or minimum speeds. The limits may be set by various considerations, but the main ones are:

- Strength of the aircraft structure
- Stiffness of the aircraft structure
- Adequate control of the aircraft

Note: Strength is the ability of the structure to withstand a load, and stiffness is the ability to withstand deformation.

LOADS AND SAFETY FACTORS

- Limit load: the maximum load to be expected in service
- Ultimate load: the failing load of the structure
- Factor of safety: the ratio of ultimate load to limit load

For aircraft structures the factor of safety is 1.5.

LOAD FACTOR

$$\text{Load Factor (n)} = \frac{\text{Lift}}{\text{Weight}}$$

It is also known as “g”.
Example: in straight level flight the load factor is 1.0 (1 g), in a turn with a bank angle of 60 degrees the load factor is 2.0 (2g).

The aircraft must be made strong enough to withstand also negative load factors (or negative g forces).

NEGATIVE STALL
If the angle of attack is increased in the negative direction it will reach an angle at which it will stall.

FLAP SPEED LIMIT
Flaps are designed to reduce take-off and landing distances and are used when airspeed is relatively low. The flaps, operating mechanism and attachment points to the structure are not designed to withstand the loads which would be applied at high airspeeds (dynamic pressure).

www.simmerdream.com