THE ATMOSPHERE

1. Introduction.

The atmosphere is an ocean of air surrounding the earth. Aircraft make use of lift derived from the air to sustain flight. Before studying the theory of flight, it is essential to know something of the properties of the atmosphere.

2. Composition.

The air is a mixture of gases in the following proportions:-

NO	Type	Percentage
1	Nitrogen	78.078%
2	Oxygen	20.84%
3	Argon	00.94%
4	Carbon dioxide	00.03%
5	Hydrogen	00.01% & few other gases.

- Varying quantities of water are also held in the lower layers of the atmosphere.

3. Layers of the Atmosphere.

The layers of the atmosphere are shown in Figure- 1:

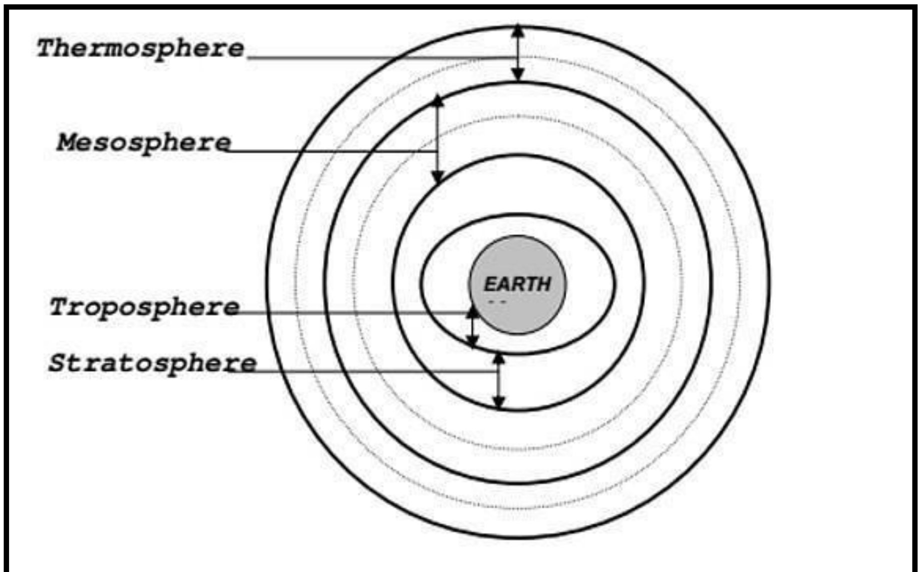
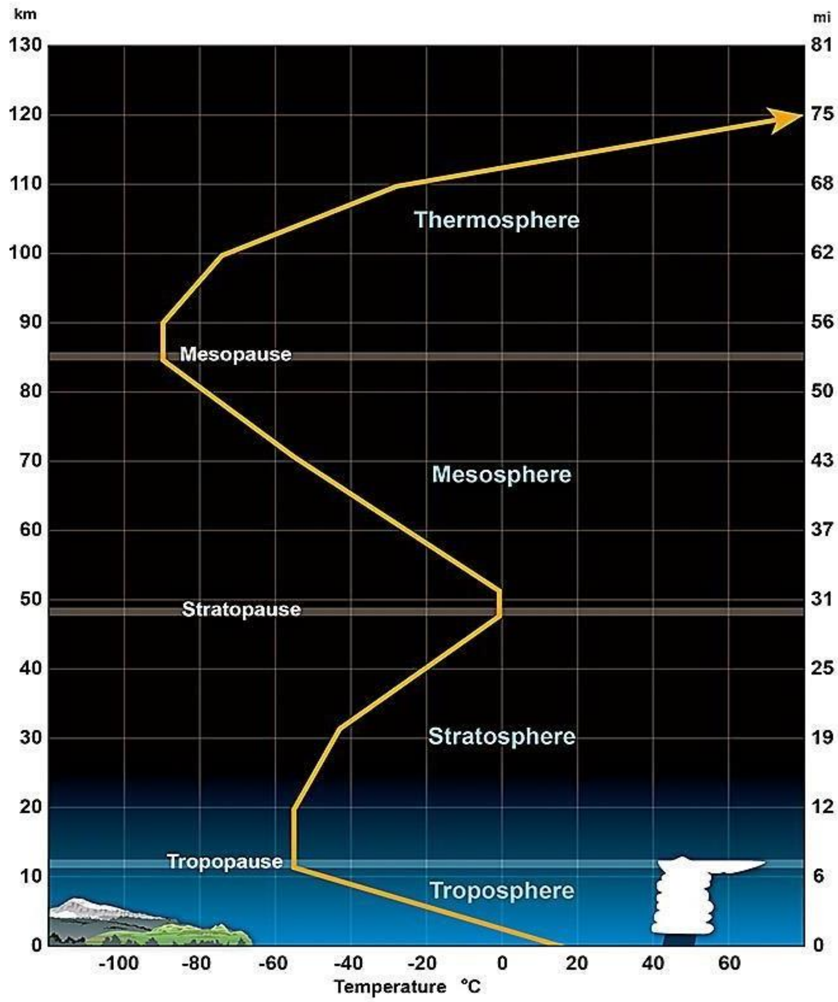


Fig : 1 ATMOSPHERE AROUND THE EARTH

3.1 <u>Troposphere</u> : T

characteristic of the troposphere is that, with the increasing of height decreases the temperature up to approximately 4 miles (6.4 km). In the troposphere, the fall of temperature is uniform. The rate of falling the temperature with increasing height is approximately 1.98 °C per 1000 ft (305m). Most of the weather phenomenon occurs in this zone particularly in the lower half of the troposphere. This zone is called disturbed zone.



The upper boundary of troposphere is known as tropo-pause, which varies with altitude in season and weather situation. The lowest height of the tropo- pause extends 8 to 10 kilometre in Arctic region in winter and highest 16 to 18 km in tropical and equatorial regions. The average height of the tropo-pause is 7 miles (11.3km).

3.2. Stratosphere: It is the region above troposphere. It extends up to about 50 to 55 km from mean sea level. The temperature generally remains practically constant up to 20 km and then increases slowly to about 32 km and finally rises rapidly. The upper boundary of this layer where the temperature is maximum called stratopause. This layer is always cloud less remaining stable and having ideal condition for flying.

3.3. Mesosphere: This is the region of decreasing temperature above stratopause and is called mesosphere. In this region temperature generally decreases up to about 80 to 90 km and reaches the value about -90 °c or below. The upper boundary of this layer where the temperature remains almost constant is called mesopause. In the mesopause the lowest temperature of the atmosphere is found.

3.4. Thermosphere. Above the mesosphere lies the thermosphere whose upper limit is unidentified. It is the region of rising temperature. Above mesopause the temperature increases rapidly with height up to 200 km. thermosphere is divided into two layers as :-

3.4.1 Ionosphere. The lower part of thermosphere is called ionosphere where ionisation is more. Because ions and electrons can remain free for sufficient long time. In this layer the ion and the free electron is high enough to cause reflection of radio wave so making long wave transmission is possible over the earth surface.

3.4.2 Exosphere. The upper part of the thermosphere is called exosphere which extends roughly about 700 km.

4. International Standard Atmosphere.

The average sea level temperature is 15°c (288 k). This decreases with height reaching –56.5°c (216.5k) at the tropopause. In the lower layers of the stratosphere the temperature is constant at 216.5°k. In the higher layers of the atmosphere the temperature varies greatly, exceeding 2000°K in the exosphere.

The rate at which temperature falls with height is known as the Temperature Lapse Rate. In the troposphere, its average value is 6.5 k/km or 1.98°c per 1000 feet. Wide variations from this average occur, and in places the temperature may show a small rise as height increases.

Since the temperature, pressure and density of air at any place depends in its latitude, longitude, altitude and time. Therefore, it is difficult to compare performance of aircraft and aero engines, located at the different places. To overcome these problems an international standard atmosphere is set based on an agreed formula laid down by the International Civil Aviation Organization (ICAO). The standard atmosphere approximates the average condition, which exists at 40° latitude (over Paris). The standard sea level conditions are :-

(1) Temperature ------------------------------(T) 15° c or 59° F.

m^2

m^3,0.00238 t^3

sec^2 ec^2.

5. Terminology

Lapse rate : The rate of falling the temperature, Pressure with increasing height of atmosphere is called Lapse Rate.

Pressure: At sea level the average pressure is 101320 N/m^2 (1013.2 millibars)or 14.7 psi or 29.92 inch Hg. As height increases pressure decreases steadily, such that by 15 km the pressure is about 12000 N/m^2.

Density : The average value of sea level density is 1.225kg/m^3. Density also decreases steadily with height, being about 0.12kg/m^3 at 18km.

6. Temperature variation with altitude

In the standard atmosphere it is assumed that below an altitude of 36,089 ft, (11,000m) there is a constant drop of temperature of 0.00356616 °F / foot of altitude (-6.5 °K/1000m). This is referred to as the lapse rate of the atmosphere, Therefore, the temperature at any given altitude can be written as:

$$T = T_1 + a(h - h_1) \text{.....................} \textbf{(1-1)}$$

Where

T_1 : the reference temperature at altitude h_1(° K)

: reference altitude (m)

a: the lapse rate of the atmosphere (-0.0065 °K/m)

- At sea level h1 =0 and T above an altitude of 11,000 m in the st standard temperature is constant and roughly equal to -56.5 °C.

6. Specifications of standard atmosphere layers.

Type of atmosphere layer	Range	Temperature gradient	Temperature –T-
Troposphere	0-11,000m	-0.0065 ° K/m	------
Stratosphere (lower)	11,000-20,000 m	0 ° K/m	216.66 ° K
Stratosphere (upper)	20,000-32,000 m	0.001 ° K/m	------
Above the upper stratosphere	32,000-47,000m	0.0028 ° K/m	------
Above the previous one	47,000-51,000m	0 ° K/m	270.65 ° K
Mesosphere	51,000-71,000m	-0.0028 ° K/m	-----
Upper Mesosphere	71,000-84,852m	-0.002 ° K/m	-----

7. <u>Standard Atmosphere Equations</u>.

The governing equations for developing the pressure and density distributions with altitude in a standard atmosphere can now be developed. First we will develop the equations for the constant temperature layers, and then for the constant temperature gradient layers.

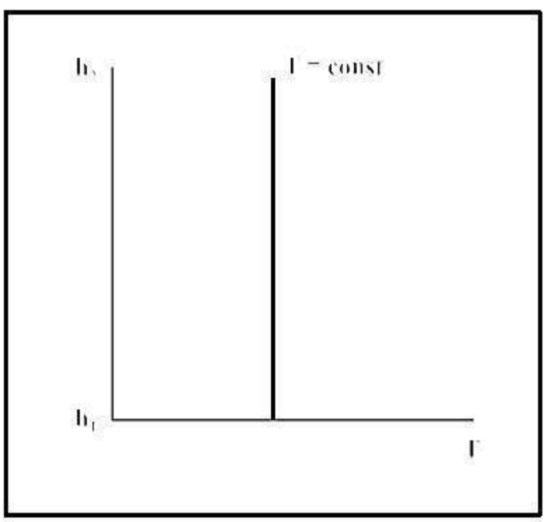
7.1 <u>Assumptions</u>

1. The atmosphere is static (V = 0), Then the differential form of Bernoulli's equation is evaluated with V = 0. The result is

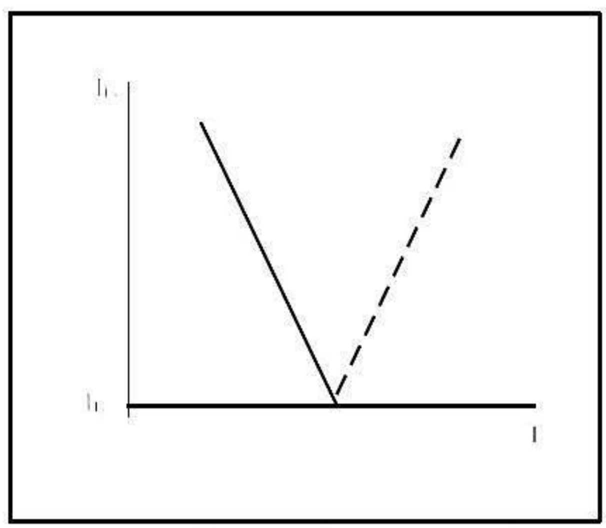
The aero-hydro static equation: --------------► $dp = \rho g_0 dh_G$ ……… **(1-2)**

2. The atmosphere also behaves as a perfect gas and hence satisfies the perfect gas equation: $P = \rho R T$................ **(1-3)**

3. It is assumed that the atmosphere is divided into standard layers that either have constant temperature, or a constant temperature gradient (change in temperature with altitude). The temperature profile would look as shown in one of the following diagrams:



Constant Temperature Layer



Constant Temperature Gradient Layer
_______decreasing with altitude
_ _ _ _ _increasing with altitude

In general the temperature profile (in a given layer) can be expressed as in eq (1-1)

$$T = T_1 + a(h - h_1)$$

Know we have three equations that govern the description of the standard atmosphere, So we can use these equations to find P(h), and ρ(h). The functions $T_{(h)}$ are the means by which we specify the Standard Atmosphere.

To examine how the pressure changes with altitude for the different kinds of temperature layers, the aero-static equation and perfect gas law eq2 are combining to eliminate the density.

$$\frac{dP}{P} = -\frac{g_0 dh}{RT} \dots\dots\dots\dots\dots\dots..(1-4)$$

7.2 <u>Constant temperature layer (T=constant)</u>

Here, T_h = constant = T_1, where T_1 is the temperature at the base of the layer. In constant temperature layers, a = 0 and $T_h = T_1$.. We can substitute into Eq. (4) to obtain:

$$\frac{dP}{P} = -\frac{g_0 dh}{RT_1}$$

Since the left hand side is only a function of P, and the right hand side is constant, other than *dh*, we can easily integrate this equation to obtain the pressure distribution with altitude.

$$lnP \,\Big|_{P_1}^{P} = -\frac{g_0}{RT} h \,\Big|_{h_1}^{h}$$

$$lnP - lnP_1 = -\frac{g_0}{RT_1}(h - h_1)$$

$$\frac{P}{P_1} = e^{-\frac{g_0}{RT_1}(h-h_1)} \dots\dots\dots\dots\dots\dots\dots.(1-5)$$

- Equation 5 tells us how the pressure changes with altitude in constant temperature layer.

From the perfect gas law we have:

$$\frac{P}{P_1} = \frac{\boldsymbol{\rho} RT_1}{\boldsymbol{\rho}_1 RT_1} = \frac{\boldsymbol{\rho}}{\boldsymbol{\rho}_1} = e^{-\frac{g_0}{RT_1}(h-h_1)} \dots\dots\dots\dots.(1-6)$$

- Equation 6 tells us how the density changes with altitude in constant temperature layer.

7.2 Constant temperature gradient layer

We can start with the general equation, Eq. (4) and replace T with the expression that includes the constant gradient:

$$\frac{dP}{P} = -\frac{g_0}{RT}dh = -\frac{g_0}{R}\frac{dh}{[T_1 + a(h - h_1)]}$$

$$\frac{dP}{P} = -\frac{g_0}{R\,a}\frac{a\,dh}{[T_1 + a(h - h_1)]}$$

$$lnP\Big|_{P_1}^{P} = -\frac{g_0}{R\,a}ln[T_1 + a(h - h_1)]\Big|_{h_1}^{h}$$

$$ln\frac{P}{P_1} = -\frac{g_0}{R\,a}\ln\frac{T(h)}{T(h_1)}$$

Finally we have

$$\frac{P}{P_1} = \left(\frac{T(h)}{T_1}\right)^{-\frac{g_0}{R\,a}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1-7)$$

Where

$$T(h) = T_1 + a(h - h_1)$$

From the perfect gas we conclude

$$\frac{P}{P_1} = \frac{\rho RT}{\rho_1 RT_1} = \left(\frac{\rho}{\rho_1}\right)\left(\frac{T}{T_1}\right) \quad =========\rightarrow \quad \frac{\rho}{\rho_1} = \left(\frac{P}{P_1}\right)\left(\frac{T}{T_1}\right)^{-1}$$

$$\frac{\boldsymbol{\rho}}{\boldsymbol{\rho}_1} = \left(\frac{T}{T_1}\right)^{-\left(\frac{g_0}{R\,a}+1\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1-8)$$

Equations (7) and (8) tell us how the pressure and density changes with altitude in a layer of atmosphere with a constant temperature gradient.

Example

By using the constant temperature gradient equations, Calculate the temperature, pressure and density at the tropopause.

Solution:

As we know the Torpopause layer is the boundary between the Trospospher and the next layer stratosphere, the top of the Trospospher. Hence it occurs at 11,000m.

Using the numbers from the previous table, we can write the temperature anywhere in the troposphere as

Temperature Distribution

$T = T_{SL} + a(h-0)$

$= 288.16 - \ {}^{\circ}K/m\ (h)$

$= 288.16 - 0.0065(11,000)$

$= 216.66\ {}^{\circ}K$

Pressure Distribution

$$\frac{P}{P_{SL}} = \left(\frac{T}{T_{SL}}\right)^{-\frac{g_0}{R\,a}}$$

$$\frac{P_{tp}}{P_{SL}} = \left(\frac{216.66}{288.16}\right)^{-\frac{9.81}{287*(-0.0065)}}$$

$$= \left(\frac{216.66}{288.16}\right)^{5.256} = 0.2236$$

=

Density Distribution

$$\frac{\rho}{\rho_{SL}} = \left(\frac{T}{T_{SL}}\right)^{-\left(\frac{g_0}{R\,a}+1\right)}$$

$$\frac{\rho}{\rho_{SL}} = \left(\frac{216.66}{288.16}\right)^{-\left(\frac{9.81}{287*(-0.0065)}+1\right)}$$

$$\frac{\rho}{\rho_{SL}} = \left(\frac{216.66}{288.16}\right)^{(4.256)} \qquad = 0.297$$

= (0.297) = 0.3639 kg/m^3

Aerodynamic forces and moments on aircraft

2.1 The Forces of Flight

Every aircraft, whether an airplane, helicopter or rocket, is affected by four opposing forces: Thrust, Lift, Drag and Weight (Fig. 1). Control surfaces, such as the rudder or ailerons, adjust the direction of these forces, allowing the pilot to use them in the most advantageous way possible.

A force can be thought of as a push or pull in a specific direction. It is a vector quantity, which means a force has both a magnitude (amount) and a direction.

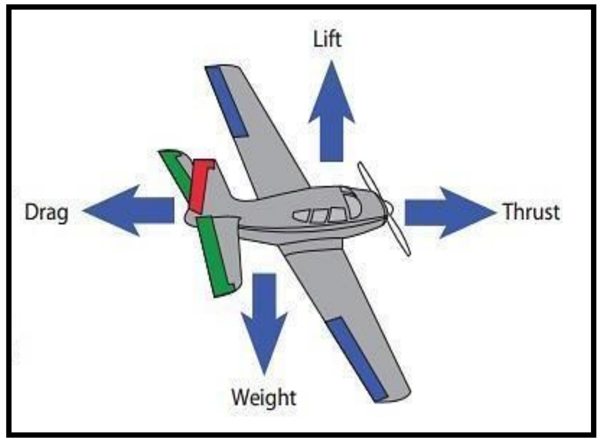


Figure (1-1): Four forces of flight

2.1.1 Thrust

Thrust is produced by an aircraft's propulsion system or engine. The direction of the thrust dictates the direction in which the aircraft will move. For example, the engines on an airliner point backwards, which means that generally speaking, the airplane's thrust vector will point forwards.

2.1.2 Drag

Drag is simply resistance of the aircraft against the air. There are many types of drag, but each is a force opposing thrust.

2.1.3 Lift

Lift is generated by the motion of air passing over the aircraft's wings. The direction of lift is always perpendicular to the flight direction (Fig. 2) and its magnitude depends on several factors, including the shape, size and velocity of the aircraft.

2.1.4 **Weight**

Weight is a force that is always directed toward the center of the earth due to gravity. The magnitude of the weight is the sum of all the airplane parts, plus the fuel, people and cargo. While the weight is distributed throughout the entire airplane, its effect is on a single point called the center of gravity.

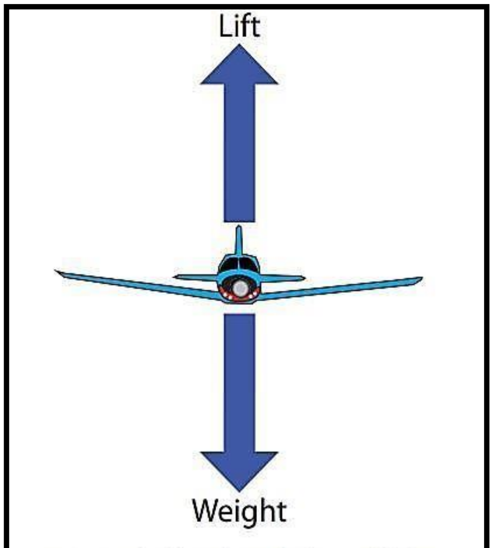


Fig. 2 The lift and weight forces of flight

2.2 **Controlling the Motion of Flight**

In order for an aircraft to reach its destination, the forces of flight have to be precisely manipulated. To do this, the aircraft has control surfaces (Fig. 3) which can direct airflow in very specific ways.

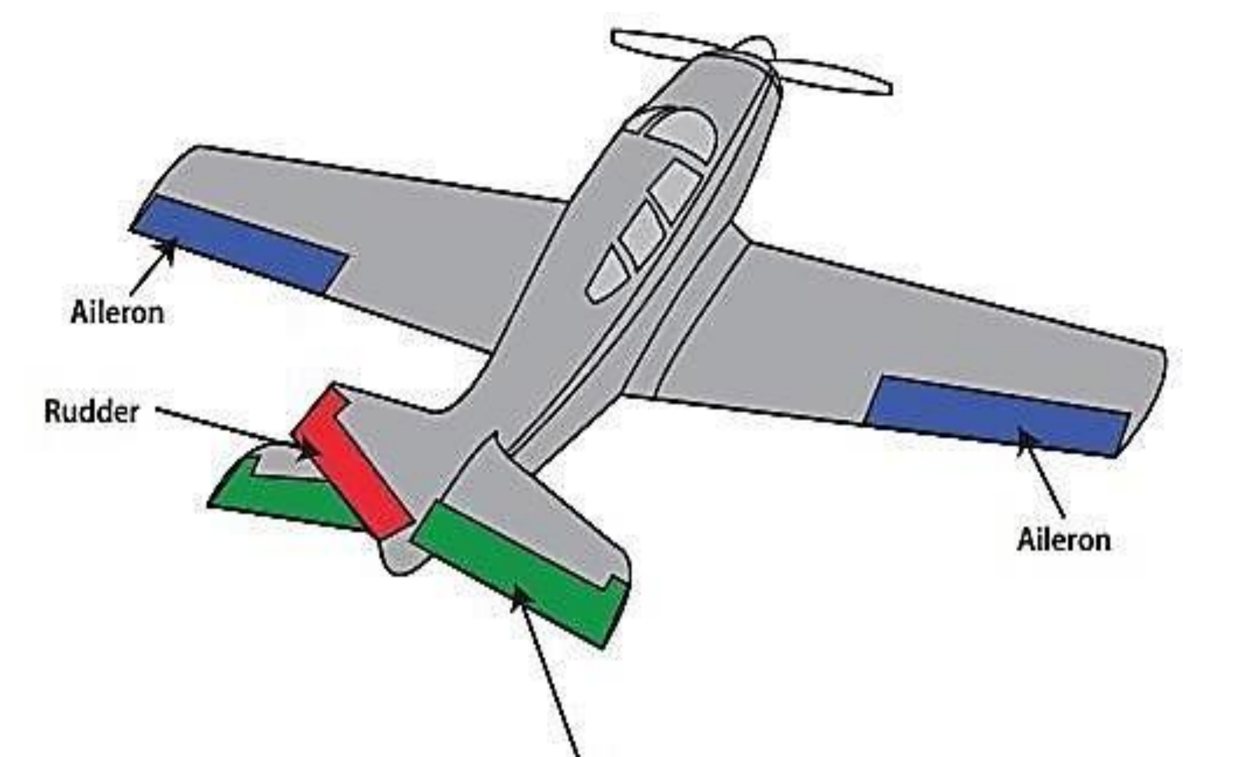


Fig. 3 Aircraft control surfaces

2.2.1 Elevator | Pitching motion

The elevator helps "elevate" the aircraft. It is usually located on the tail of the aircraft and serves two purposes.

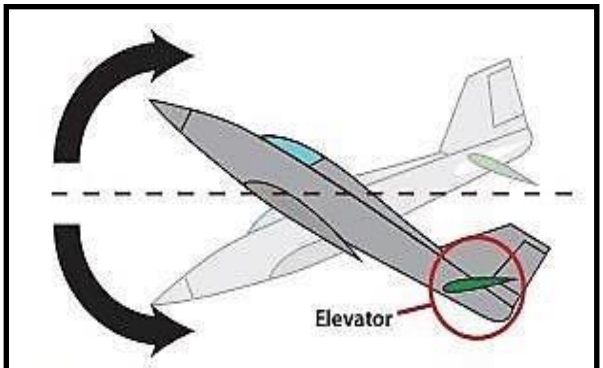


Fig. 4 Elevator and pitch movement

- The first is to provide stability by producing a downward force on the tail. Airplanes are traditionally nose-heavy and this downward force is required to compensate for that.
- The second is to direct the nose of the aircraft either upwards or downwards, known as pitch, in order to make the airplane climb and descend. (Fig. 4).

2.2.2 Ailerons | Rolling motion

The ailerons are located at the rear of the wing, one on each side. They work opposite to each other, so when one is raised, the other is lowered. Their job is to increase the lift on one wing, while reducing the lift on the other. By doing this, they roll the aircraft sideways, which allows the aircraft to turn. This is the primary method of steering a fixed-wing aircraft (Fig. 5).

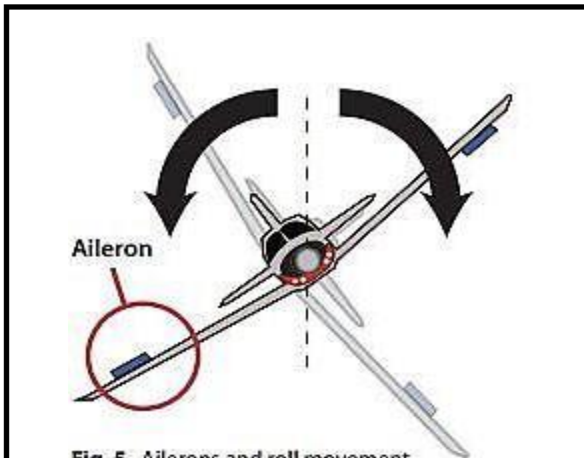


Fig. 5 Ailerons and roll movement

2.2.3 Rudder | Yawing

The rudder is located on the tail of the aircraft. It works identically to a rudder on a boat, steering the nose of the aircraft left and right. Unlike the boat however, it is not the primary method of steering. Its main purpose is to counteract the drag caused by the lowered aileron during a turn. This adverse yaw, as it

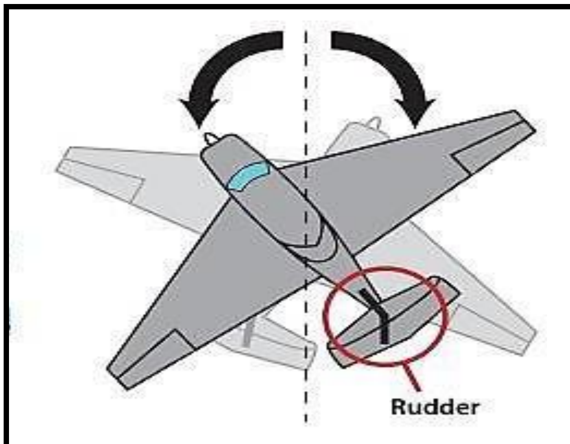


Fig. 6 Rudder and yaw movement

is known, causes the nose of the airplane to point away, or outwards, from the direction of the turn. The rudder helps to correct this by pushing the nose in the correct direction, maintaining what is known as coordinated flight (Fig. 6).

2.3 <u>Airplane axis system</u>

Each axis of flight is an imaginary line around which an airplane can turn. Think of an airplane rotating around an axis like a wheel rotates around an axle. Regardless of the type of aircraft, there are three axes upon which it can move: Left and Right, Forwards and Backwards, Up and Down.

In aviation though, their technical names are the lateral axis, longitudinal axis and vertical axis.

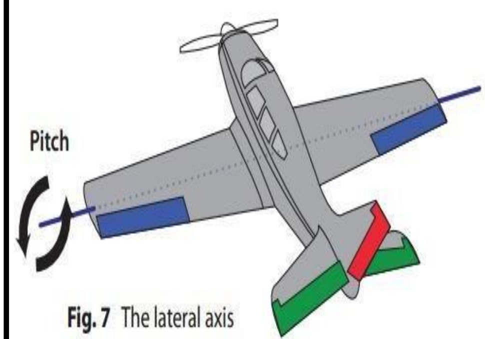


Fig. 7 The lateral axis

2.3.1 <u>The Lateral Axis (Pitch)</u>

The lateral axis runs from wing tip to wing tip. The aircraft pitches around this axis (Fig. 7).

2.3.2 <u>The Longitudinal Axis (Roll)</u>

The longitudinal axis runs from the nose of the aircraft to the tail. This is the axis around which the aircraft rolls (Fig. 8).

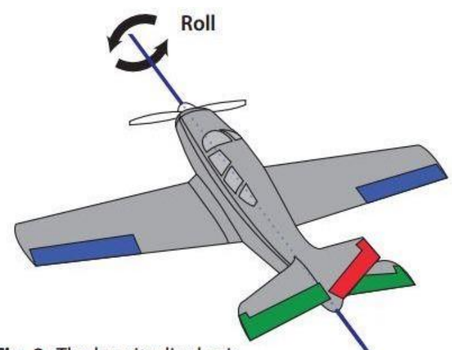


Fig. 8 The longitudinal axis

2.3.3 <u>The Vertical Axis (Yaw)</u>

The vertical axis is slightly different to the others, running vertically through the center of the aircraft. The aircraft yaws around this axis (Fig. 9).

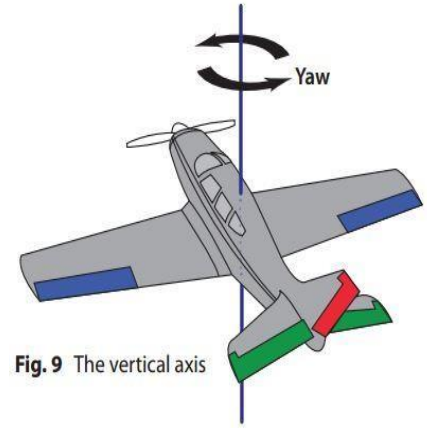


Fig. 9 The vertical axis

2.4 The Center of Gravity

The center of gravity, also known as CG, is the effective point whereby all weight is considered to be. The CG is also the same point where the axes of flight meet (Fig. 10). This point isn't fixed on any aircraft, but moves forwards or backwards along the longitudinal axis, depending on how the aircraft is loaded. It is vital that its center of gravity remain within certain limits however, as an aircraft that is too nose- or tail-heavy will either not fly, or be so difficult to control that it becomes too dangerous to try. These limits are referred to as its operational envelope.

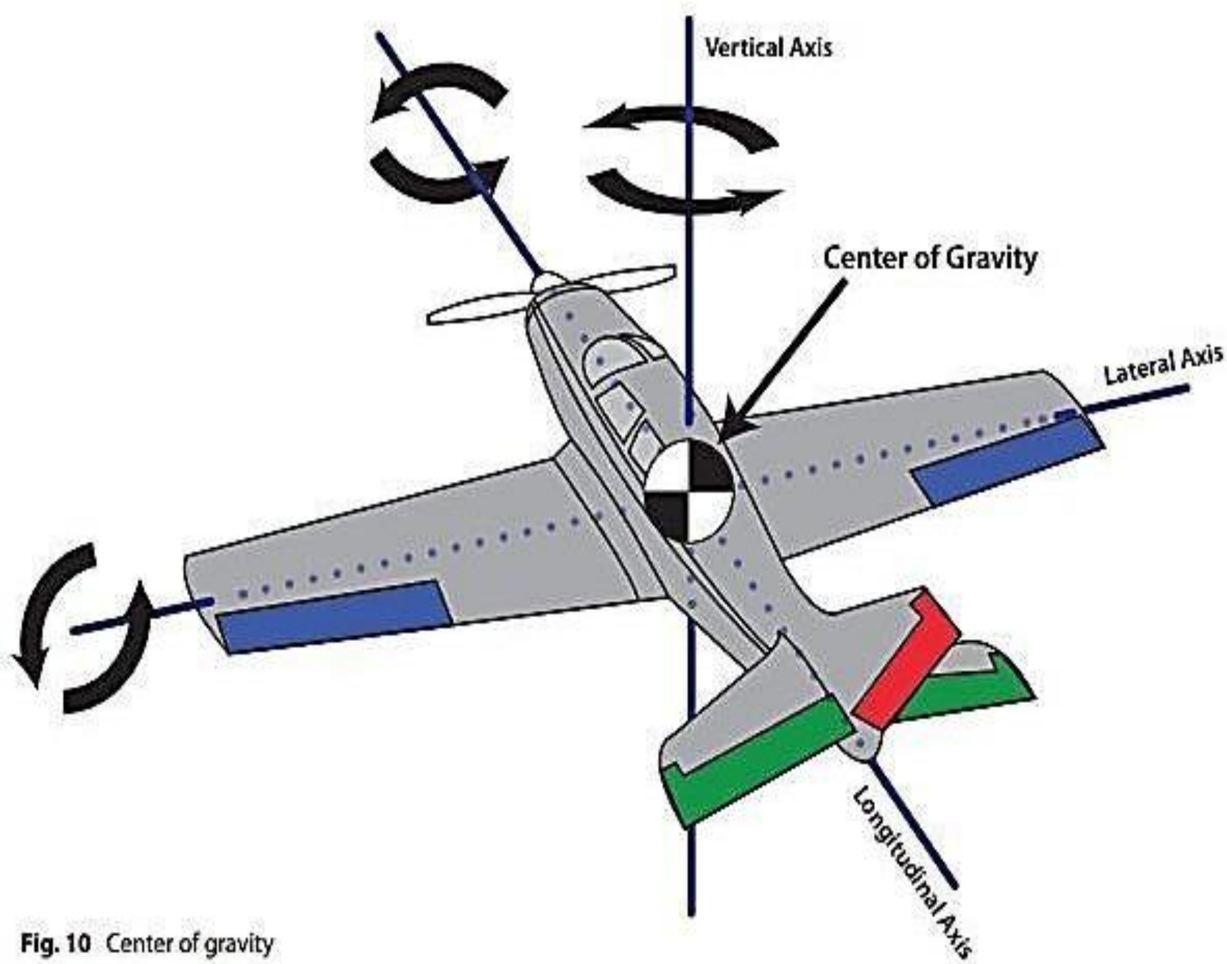


Fig. 10 Center of gravity

LIFT

3. Introduction.

Lift is defined as that component of total air reaction acting on an aerofoil, which is perpendicular to the flight path or the relative air flow direction. The lift is produced due to the difference of pressure across the aerofoil. This difference of pressure is obtained by increasing the velocity of air over the aerofoil and increasing the pressure under the aerofoil. The velocity increased over the aerofoil determines the magnitude of lift and the velocity increase will depend upon the angle of attack and camber ness of the aerofoil.

$$Lift = C_L * \frac{1}{2}\boldsymbol{\rho}V^2 S$$ .... **(Lift Formula)/ (3-1)**

Where

C_L: lift coefficient
ρ: air density (kg/m^3)
V: aircraft speed (m/s)
S: Surface wing area (m^2)

3.1 Factors Affecting on Lift:

Lift force is the component of the Total Air Reaction force and depend on:-

a) Free stream velocity.

b) Air Density

c) Angle of Attack

d) Gross Wing Area

e) Aerofoil shap

f) Condition of the surface of aerofoil.

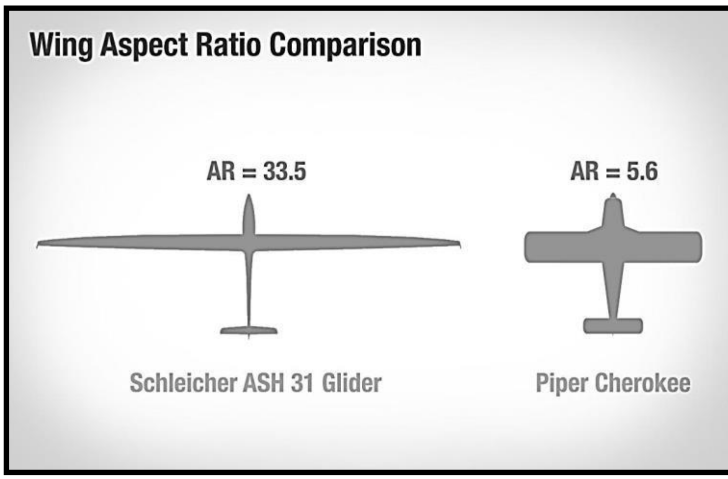
3.1.1 Effect of Air Speed, Density & Wing Area on Lift.

The effect of air density and velocity is observed in the form of dynamic pressure ($\frac{1}{2}\rho V^2$). When dynamic pressure is multiplied by the wing gross area it gives a force ($\frac{1}{2}\rho V^2 S$).From the formula of lift, it is observed that lift is directly proportional to the speed, density and gross wing area.

3.1.2 Effect of Wing Shape on Lift.

The shape of the wing largely determines the airflow over it. If the camber ness of the wing is greater, the airflow over the wing becomes greater. This decreases the pressure over the wing thus increasing the lift. Consequently if the wing camber ness is less, air flow accelerated less and decrease lift.

Aspect ratio also contributes largely on the lift. Greater the aspect ratio, higher is the lift and vice versa. Aspect ratio increases lift not only due to its greater surface area and camber ness but also because the wing tips vortices affect comparatively less area over the wing. (Fig 3-1)



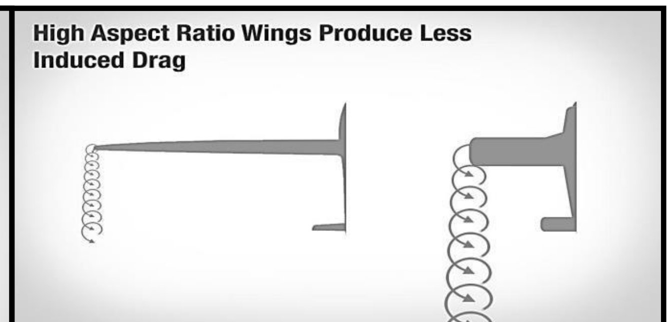


Figure (3-1): Effect of aspect ratio on Lift as teak into consideration wing tip vortices

3.1.3 Effect of Angle of Attack on Lift.

Angle of attack is the angle between the chord line of the aerofoil and the direction of airflow. When the angle of attack is less, the airflow over the aerofoil flows almost to the trailing edge before separation. If the separation point extends towards trailing edge lift effectiveness will not increase much due to less angle of attack. On the other hand at higher angle of attack the separation point moves towards leading edge and increases the total lift. With further increase in angle of attack separation point will travel maximum towards leading edge (beyond 15^0 angle of attack) accompanied by large increase in pressure over the top surface consequently abrupt decrease in lift. The maximum lift is produced at 15^0 angle of attack. Figures (3-2), (3-3).

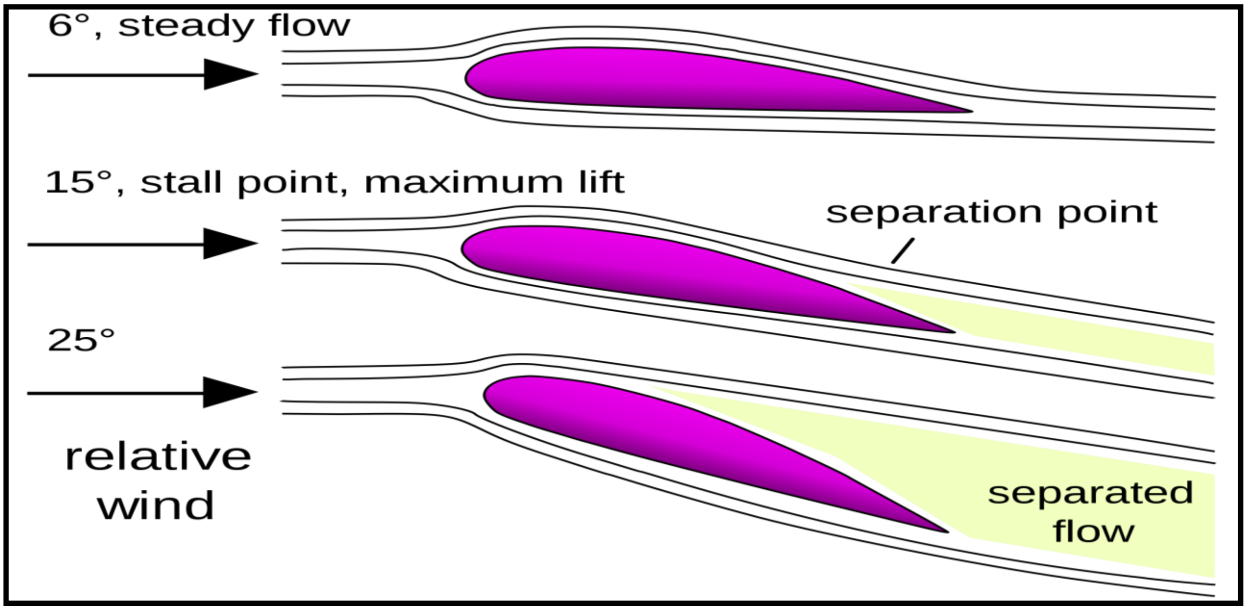


Figure (3-2): Effect angle of attack on lift

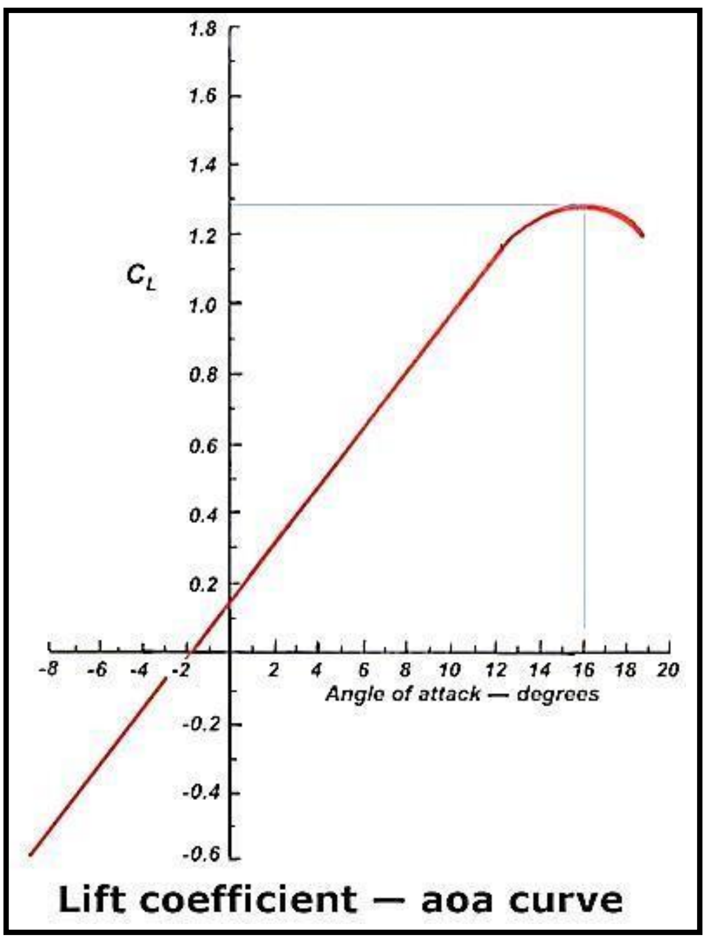


Figure (3-3): Lift coefficient VS Angle of attack

3.1.3 Gross area of wing on Lift.

Gross Wing area is the whole of the wing area of an aircraft including the part which can be considered to be in the fuselage. If the gross area of the wing increases then lift created by the wing will be increases. Fig (3-4)

$$\textbf{\textit{Wing Loading is the ratio}} = \frac{Wing\ Area}{Aircraft\ weight}$$

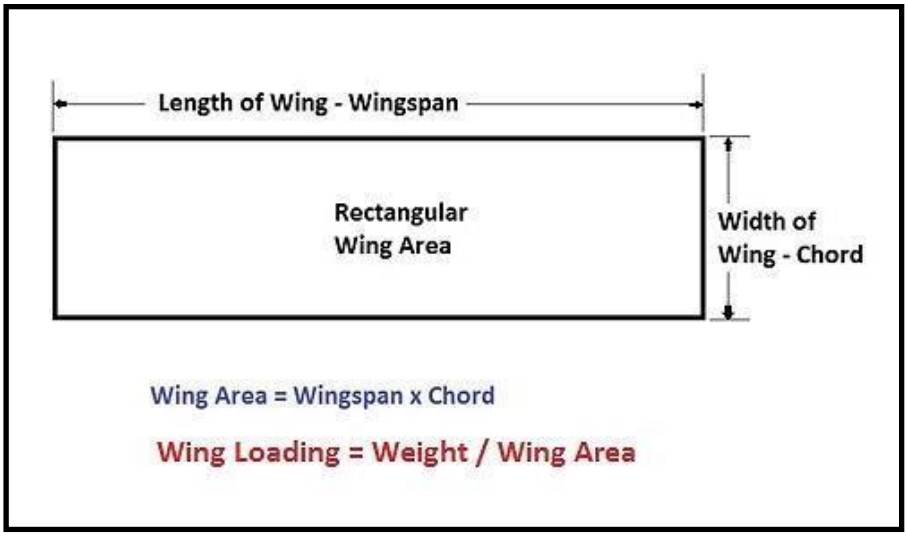


Figure (3-4): Wing gross area

3.1.4 Variation of with Angle of Attack

The example shows that, as speed decreases, C_L must increase to give the same lift force.

There are two ways of changing C_L for an aerofoil:-

a) By changing the aerofoil shape (see use of flaps and slots later)

b) By changing the angle of attack.

On an aircraft the wings are placed at a fixed angle, therefore the attitude of the whole aircraft must be changed in order to change the angle of attack of the wings while flying. We find that C_L increases as angle attack increases and for a plain aerofoil the maximum value at the stalling angle is about 1.0 to 1.5. Beyond the stalling angle C_L decreases sharply. Figure (3-5)

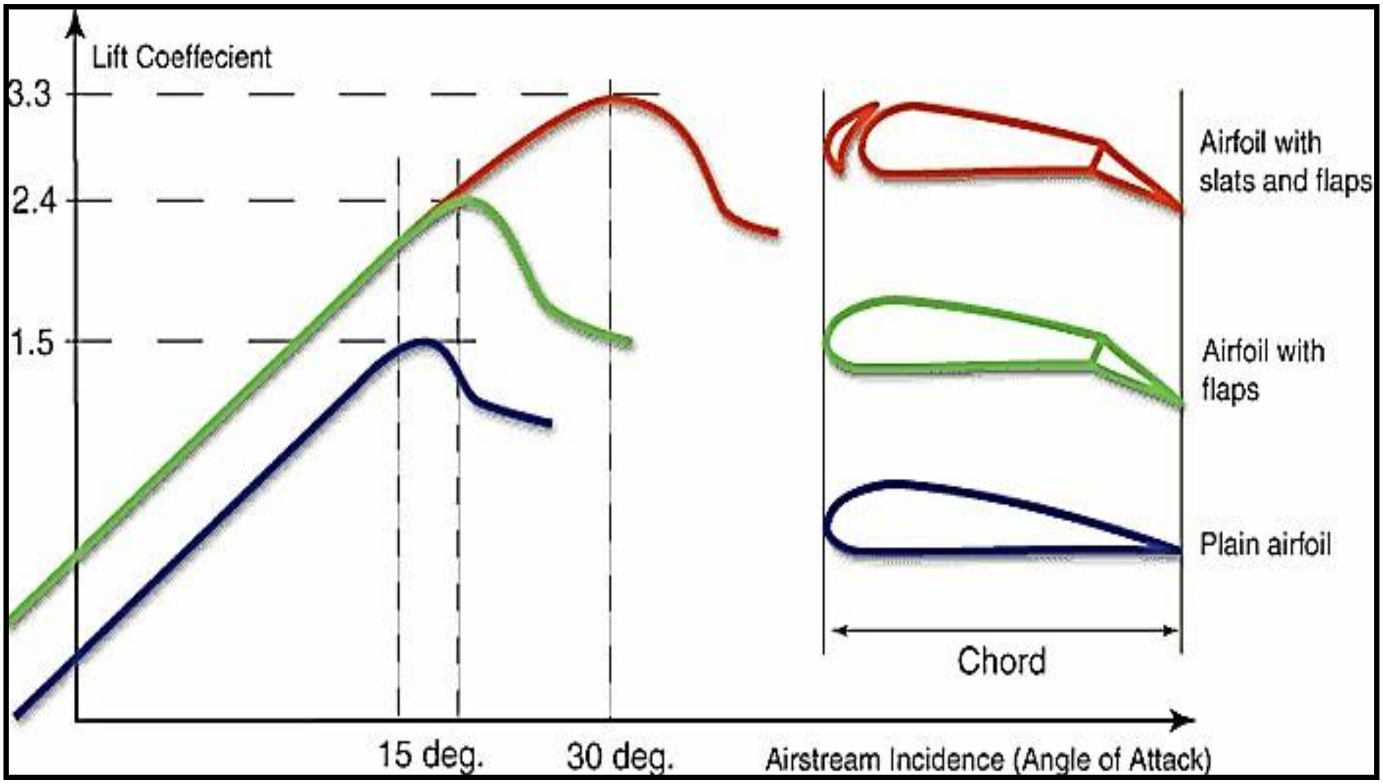


Figure (3-5): effect of secondary control surface on

A cambered aerofoil gives lift (positive value of CL) down to a small negative angle of attack (-3° or -4°). A symmetrical aerofoil, however, gives zero lift at zero angle of attack.

3.1.5 Aerofoil Efficiency (Lift/Drag Ratio)

An aerofoil is most efficient when it produces a lift force which is large in relation to the drag force, i.e. when the Lift/Drag ratio is highest. If we divide the lift equation by the drag equation we get:

$$\frac{Lift}{Drag} = \frac{C_L}{C_D}$$

And we can find the lift/drag ratio by dividing the lift coefficient by the drag coefficient.

- This ratio is a maximum when the angle of attack is small (about 2° - 4°) and most aircraft are designed so that when the fuselage is flying level the wings are meeting the air at approximately this angle. At 4° angle of attack, Lift Drag ratio is maximum and this angle is called optimum angle of attack. Figure (3-6)

- We can see that the aerofoil efficiency increases rapidly up to about +4° angle of attack and beings to decrease after that angle, although the C_L keeps rising to a maximum at 16°. Figure(3-7)
- Aircraft gets stall for two reasons either due to low speed of the aircraft or due to high angle of attack, i.e beyond 15^0 angle of attack.

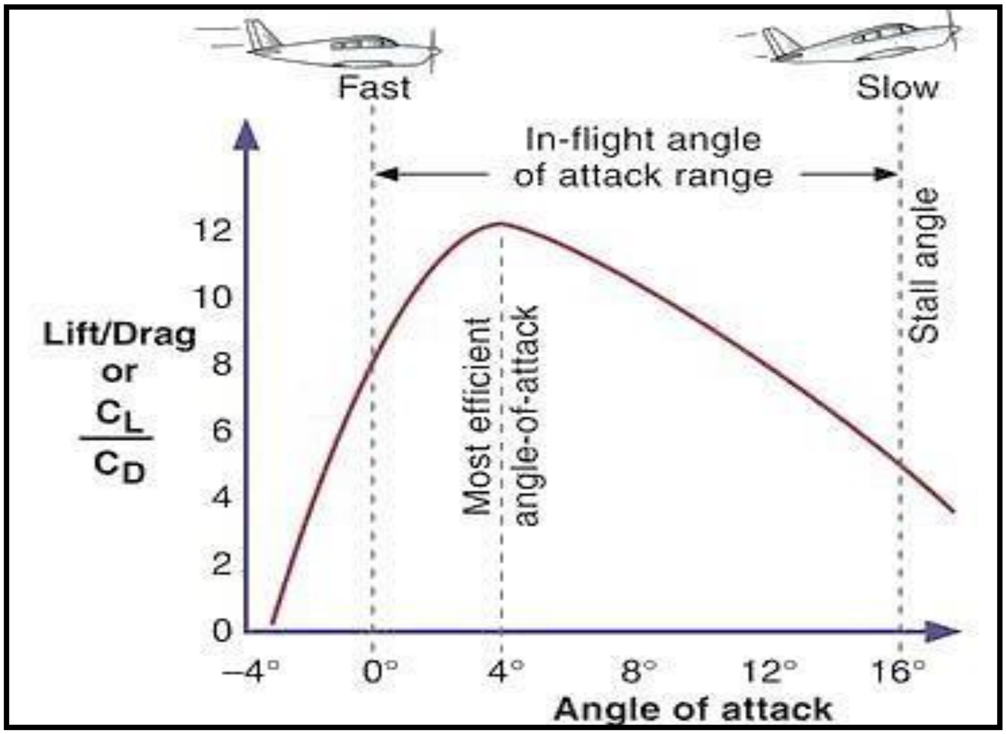


Figure (3-6): Lift/drag ratio VS angle of attack.

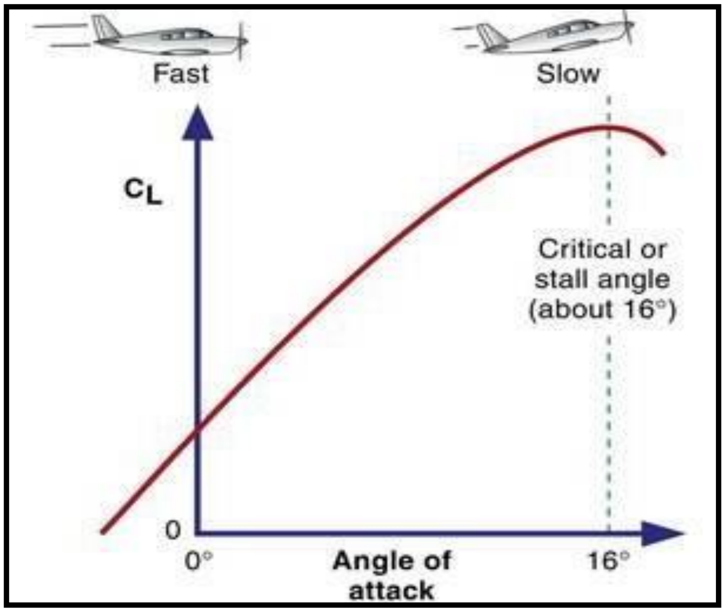


Figure (3-7): illustrate that the maximum value for lift coefficient satisfy when angle of attack equal to 16^0.

DRAG

1. Introduction:

Whenever air strikes a body, air resistance or drag is caused. A cyclist may feel this as a headwind when he moves through the stationary air. Trees may be uprooted by strong winds. In each case the airflow produces a pressure over the surface of the object and this leads to a drag force.

Drag is the resistance to the motion of a body when moving through the air. In other word, drag is that component of total air reaction acting on the AC which is parallel to the flight path.

- Drag can be reduced but cannot be eliminated.
- Drag will vary with stream line shape of the body. If the body is of smooth and stream line shape then there will be less amount of drag. Figure (4-1)

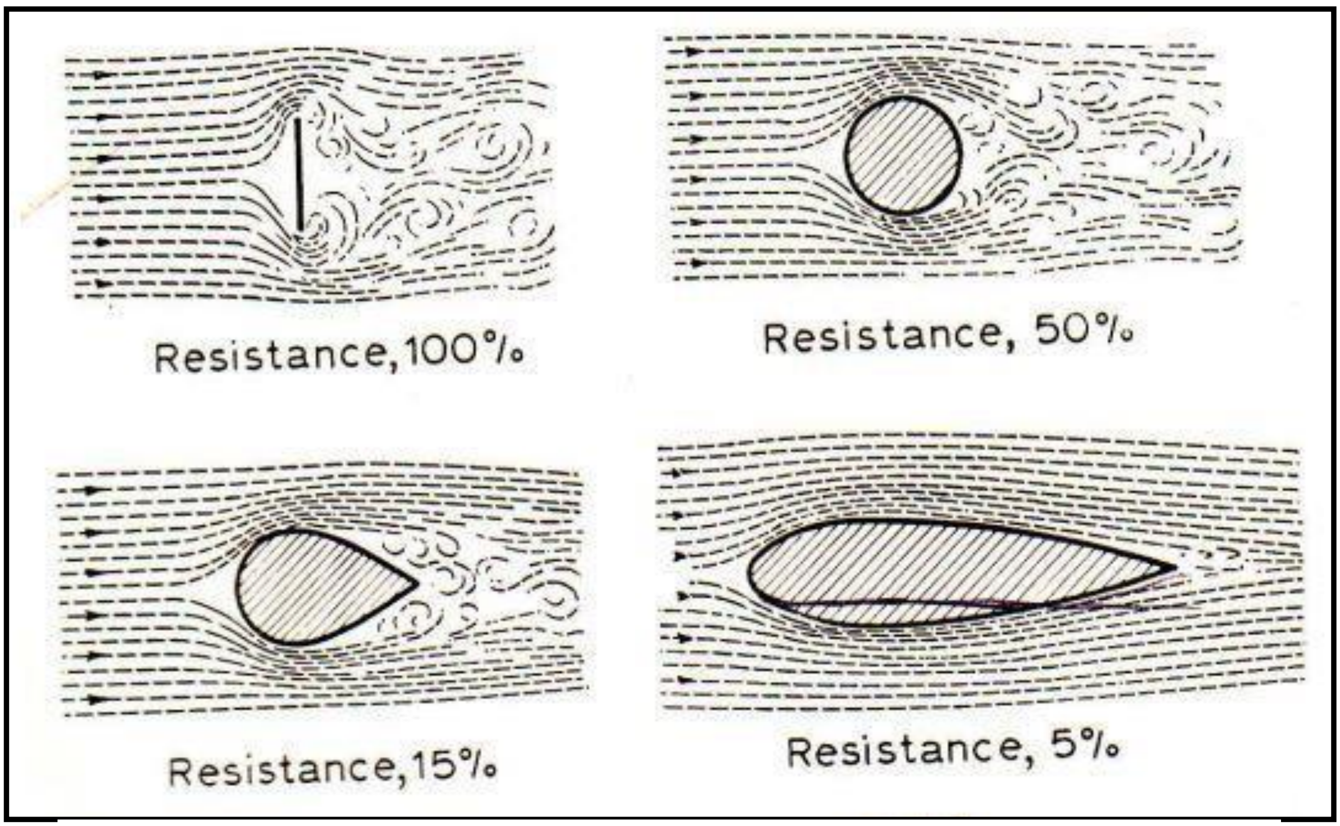


Figure (4-1): effect of streamline shape on drag.

So the Drag can be define as . the force that opposes forward motion through the atmosphere and is parallel to the direction of the free-stream velocity of the airflow. Drag must be overcome by thrust in order to achieve forward motion. Drag can be reduced but cannot be eliminated.

Formula of drag is :-

$$Drag = C_D * \frac{1}{2} \boldsymbol{\rho} V^2 S \text{.......................} \textbf{(Drag Formula)/ (4-1)}$$

Where
C_D: Drag coefficient
ρ: air density (kg/m^3)
V: aircraft speed (m/s)
S: Surface wing area (m^2)

4.1 Dynamic Pressure

The extra pressure caused when air strikes a flat object, and is brought to rest, is called Dynamic Pressure.

Dynamic Pressure varies with:-

a) Speed of flow-V- (m/s); as expected a high speed will cause a high pressure.

b) Density –ρ- (kg/m^3); a jet of water (high density) produces a much higher pressure than a jet of air traveling at an equal speed.

It is found that:

$$\textbf{Dynamic Pressure} = 1/2\, \rho\, v^2\ N/m^2$$

4.2 Types of Drag.

There are various types of drag acting on the aircraft when it is in motion. They can be grouped under two broad categories .These are

1. Paras Drag
2. Induced D ag.

4.2.1 Parasite Drag:

It is the sums of 'form drag and skin friction' drag and produce a large part of the total drag of an A . It is directly proportional to the AC speed.

Parasite drag can be calculated from the formula:

$$\textbf{Parasite Drag (N)} = \frac{1}{2}\rho V^2 S C_{DP}$$

C_{DP}: is the parasite drag coefficient

The way parasite drag varies with aircraft speed is shown overleaf.

4.2.1.1 Variation of Parasite Drag With Speed

Provided that C_{DP} remains constant, it is true to say that parasite drag force increases according to the square of the speed of the aircraft, at constant height. We can represent this on a graph.

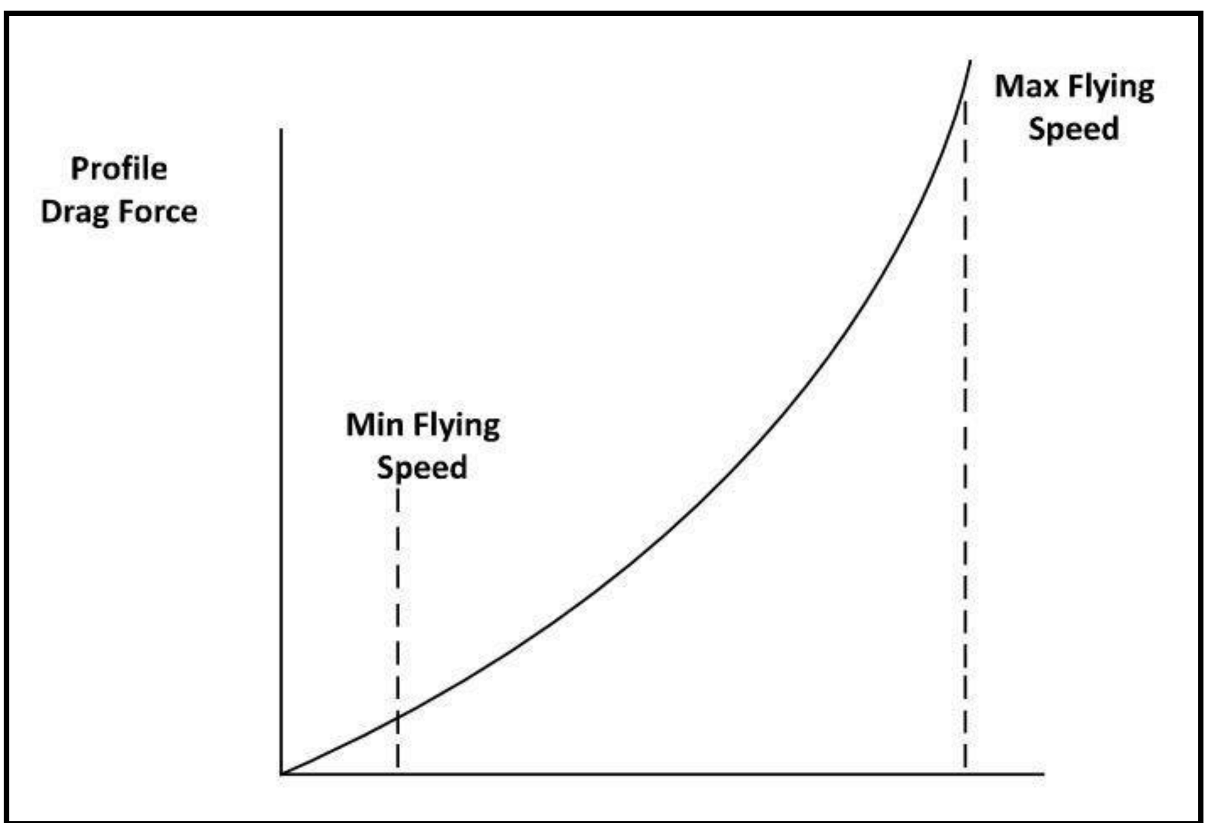


Figure (4-2): Variation of parasite drag with speed.

In fact, C_{DP} does not remain quite constant, because at low flying speed the angle of attack must be made large, with the effect that C_{DP} rises .

This means that the shape of the curve at low speeds is changed slightly.

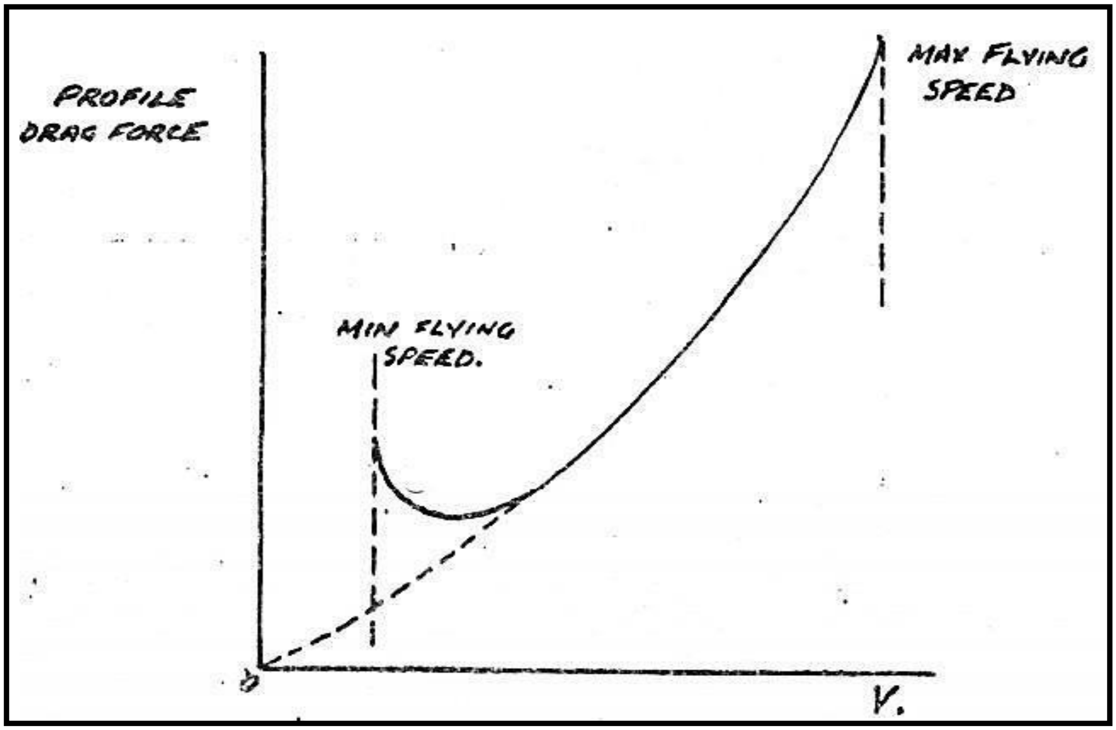


Figure (4-3): Parasite drag at mini flying speed.

This shows that, the parasite drag force may rise slightly as the aircraft comes down to minimum flying speed which is the speed at which the angle of attack has been raised to the stalling angle.

Parasite drag is again two types. These are:

(1) Form Drag:

Form or pressure drag is caused by the air that is flowing over the aircraft or airfoil. The separation of air creates turbulence and results in pockets of low and high pressure that leave a wake behind the airplane or a l (thus the name pressure drag). This opposes forward motion and is a component of the total drag. Since this drag is due to the shape or form of the aircraft, it is also called form drag. Streamlining the aircraft will reduce form drag.

Airplane components that produce form drag include

(1) The wing and wing flaps,

(2) The fuselage,

(3) Tail surfaces,

(4) Nacelles,

(5) Landing gear,

(6) Wing tanks and external stores

(7) E[illegible]nes.

(2) Skin Friction Drag:

Skin friction drag is caused by the actual contact of the air particles against the surface of the aircraft. This is the same as the friction between any two objects or s[illegible] Because skin friction drag is an interaction between a solid (the airplane surface) and a gas (the air), the magnitude of skin friction drag depends on the properties of both the solid and the gas. For the solid airplane, skin fiction drag can be reduced, and airspeed can be increased somewhat, by keeping an aircraft's surface highly polished and clean. Fig (4-4).

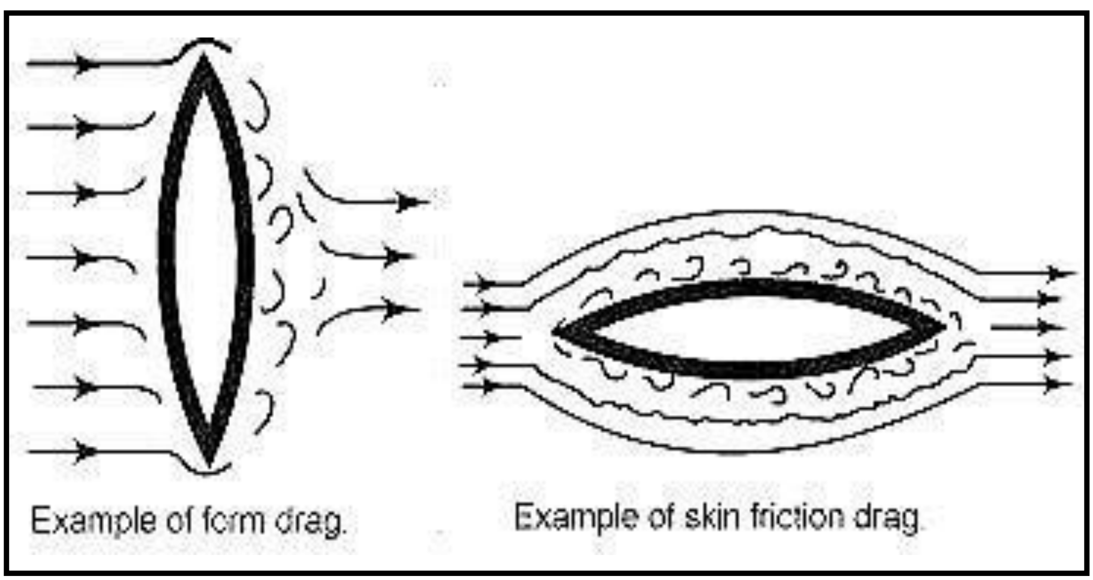


Figure (4-4): Profile drag (skin friction drag + form drag).

(3) Interference Drag

Interference drag comes from the intersection of air streams that creates eddy currents, turbulence, or restricts smooth airflow. For example, the intersection of the wing and the fuselage at the wing root has significant interference drag. It is also very high when two surfaces meet at perpendicular angles.

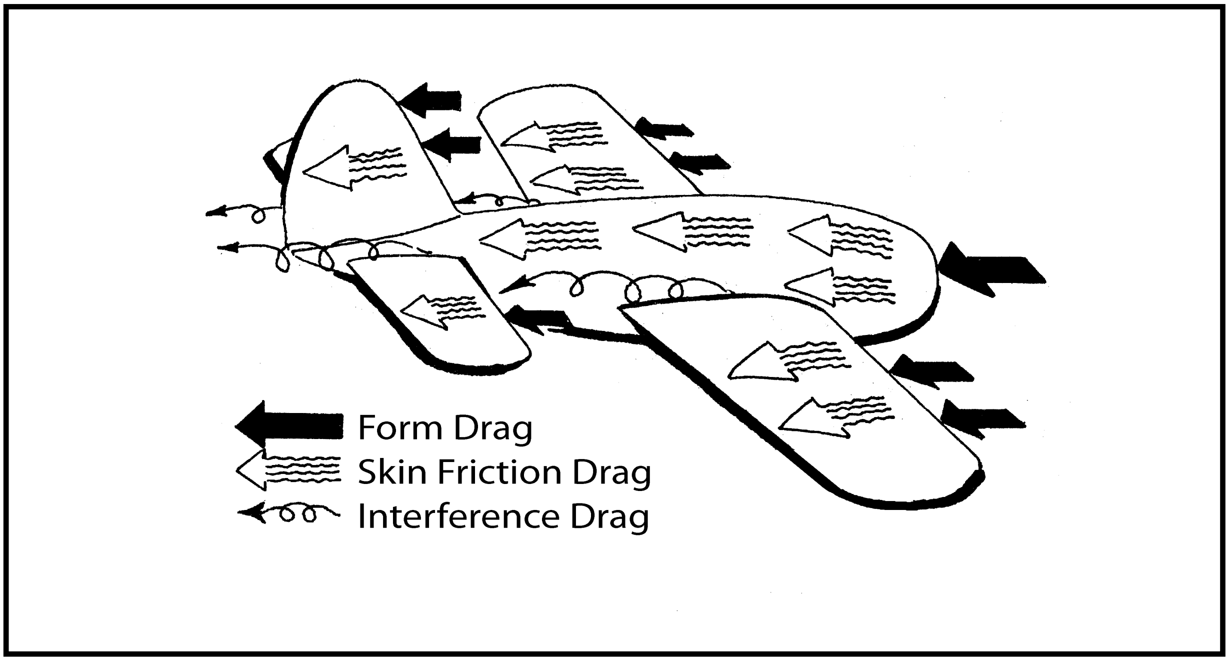


Figure (4-5): Illustrate drag types.

4.2.2 Induced Drag

Induced drag is the drag created due to lift and affected by the vortices at the tip of an aircraft's wing.

The induced drag formula $C_{Di} = \frac{{C_L}^2}{\pi \, AR \, e}$

Where

CDi: Induced drag coefficient

CL: Lift coefficient

AR : Aspect ratio

e : efficiency factor (e=1 for an ellipse and e < 1 *in general*)

The high pressure underneath the wing causes the airflow at the tips of the wings to curl around from bottom to top in a circular motion. This results in a trailing vortex. Figure (4-6) . Induced drag increases in direct proportion to increases in the angle of attack. The circular motion creates a change in the angle of attack near the wing tip which causes an increase in drag. The greater the angle of attack up to the critical angle (where a stall takes place), the greater the amount of lift developed and the greater the induced drag.

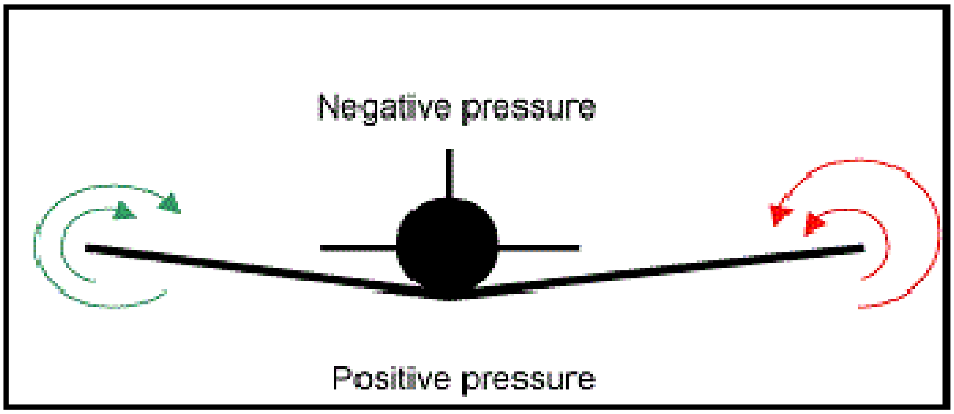


Figure (4-6): Wing tip vortices.

There were three factors which affect the size of the induced drag force:

1. Angle of Attack
2. Aspect Ratio
3. Aircraft Speed

1- When the angle of attack is high and aircraft speed is low, we have seen that the value of C_L must be high. But we have also seen that the vortex must be strong under these conditions. So we can say that induced drag force is high when C_L is high.

2- If we consider two wings of the same area (S), we find that the wing tip vortices are smaller and weaker on the wing of high aspect ratio. Therefore, the induced drag force will be less for an aircraft with long thin wings than for an aircraft with short stubby wings and the same wing area.

3- Induced drag forces becomes less as the aircraft speed increases. As this is a little difficult to understand we must examine the induced drag equation thoroughly. Considering the case of an aircraft flying at different speeds, it can be shown that the induced drag falls even though speed is increased and if this variation is represented on a graph, we obtain the following results:

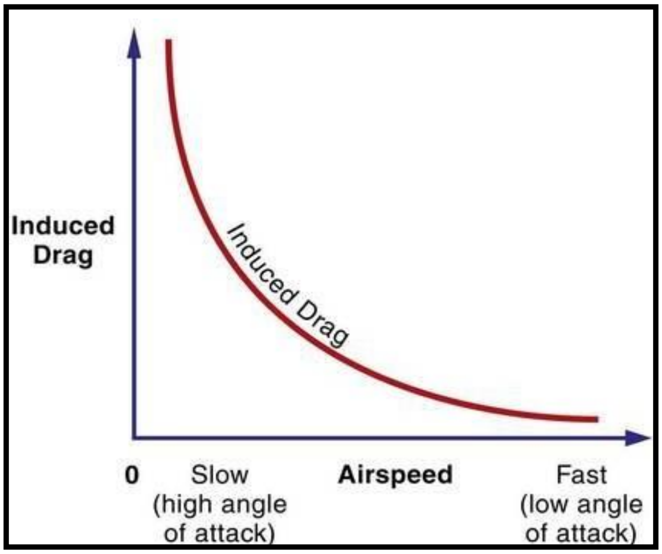


Figure (4-7): Induced drag curve.

4.3 Total Aircraft Drag

If the graphs of Parasite drag force (which increase with speed and induced drag force which decreases with speed) are added together, the graph of total drag force against speed can be drawn.

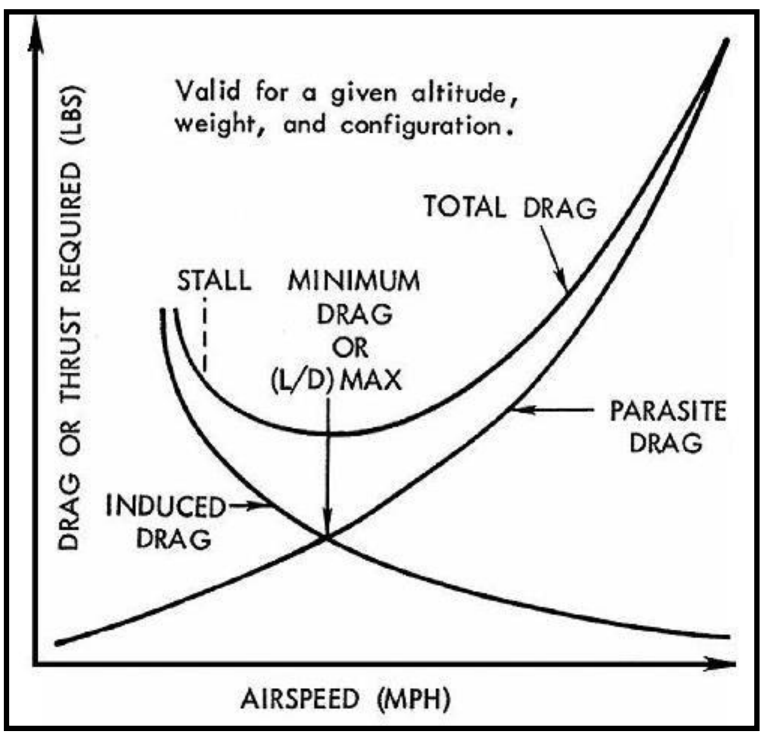


Figure (4-8): Total drag graph.

This graph shows that the minimum drag speed occurs where induced drag force is equal to profile drag force and that total drag force rises as the aircraft slows down below this speed.

4.3 Zero Lift Drag.

When the ac flies at zero lift angle of attack, the resultant of all aerodynamic forces act parallel and opposite to the direction of flight, the drag is produced in this condition is zero lift drag. Zero lift drag consists of Profile drag and Interference drag.

4.4 Wing Tip Vortices.

The difference of pressure across the wing causes high pressure air from the bottom surface to split around the wing tips to top surface of the wing. As the air flows past the wing tips it will get a spiral flow and forms wing tip vortices.

4.5 Trailing Edge Vortices.

When the air flows over the top and bottom surface of the wing and meet at an angle at the trailing edge which causes the air to get a rotary motion and forms trailing edge vortices.

4.6 Variation of C_D with Angle of Attack

The value of C_D does not change very much at small angles of attack and may be least at a small positive angle of attack. As the separation point moves forward, C_D increases and when the flow is completely separated at the stall, the rate of increase becomes more rapid.

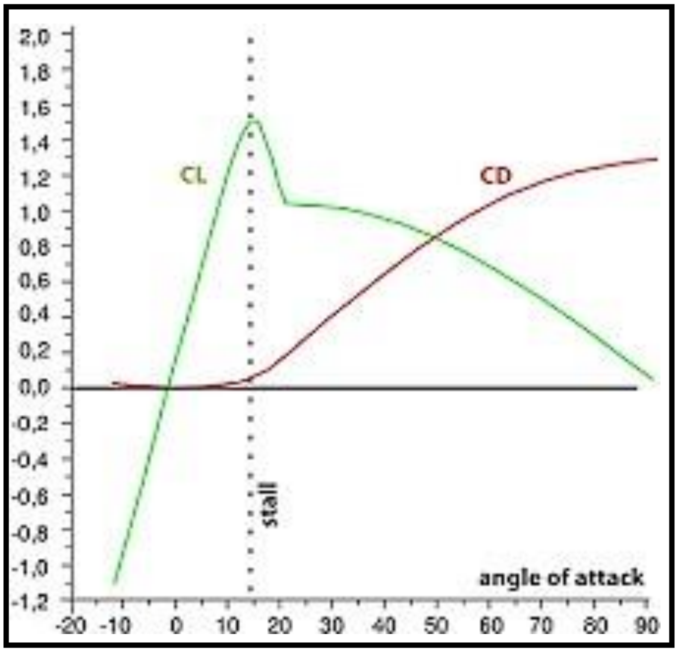


Figure (4-8): Variation of C_D with α.

4.7 Aspect Ratio

Before considering induced drag, it is necessary to define aspect ratio. For an aircraft with a rectangular plan form wing, span (b) and chord length (c).

The aspect ratio = span / chord = b/c

Most aircraft have tapered wing and then the aspect ratio = $\frac{Span}{mean\ chord\ length}$

So, to prevent induce drag, we need high aspect ratio.

It is not necessary to know the mean chord length directly because we can find this by dividing gross wing area by the span (mean chord length = $\frac{S}{b}$)

$$\textbf{Aspect ratio} = \frac{Span}{Mean\ chord\ length} = \frac{b}{\frac{S}{b}} = \frac{b^2}{S}$$

So an aircraft with long thin wings, has a high aspect ratio, an aircraft with short stubby wings has a low aspect ratio. This is very important in considering induced drag.

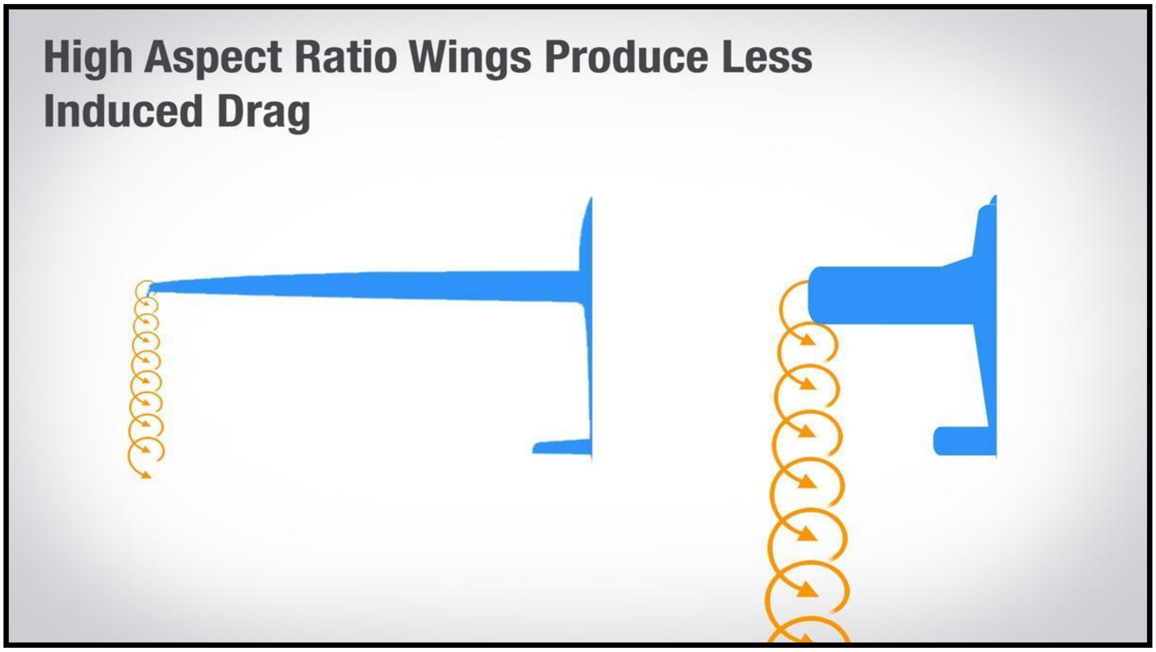


Figure (4-9): Effect aspect ratio on induced drag.

4.8 Wave Drag

Wave Drag is a drag that retards the forward movement of an airplane in both supersonic and transonic flight, as a consequence of the formation of shock waves.

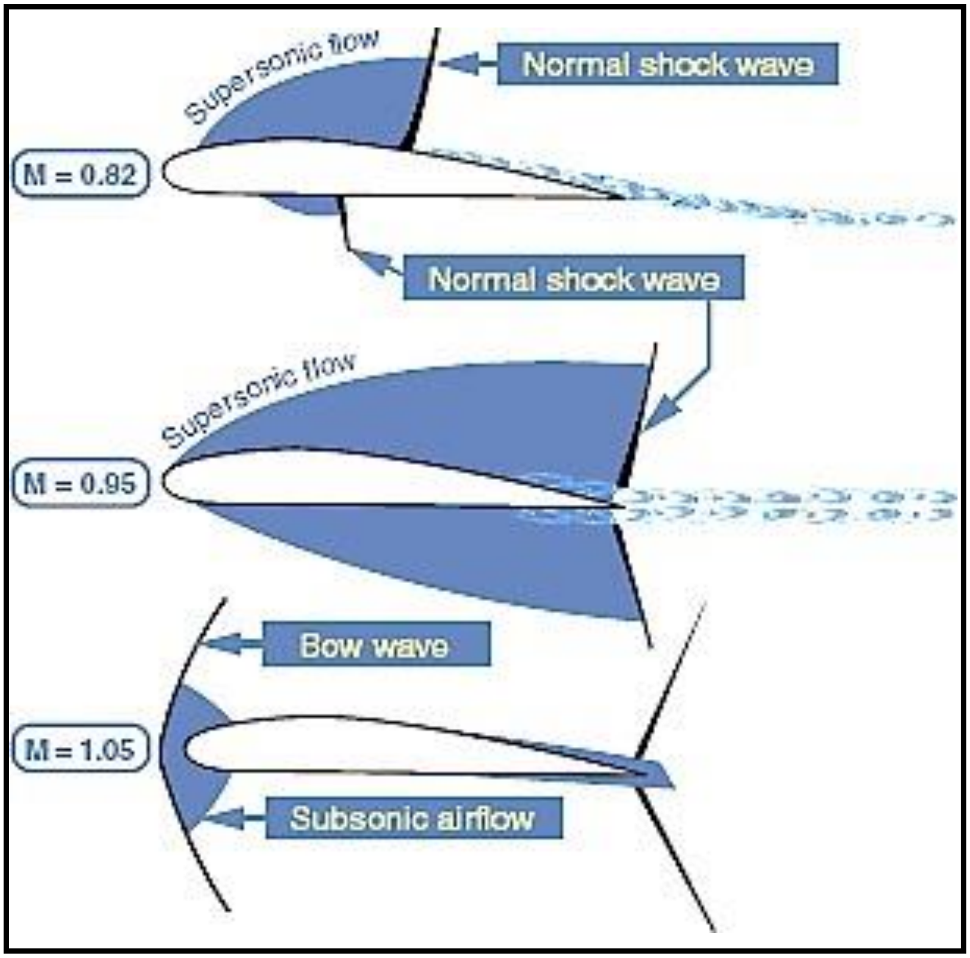


Figure (4-9): Formation of wave Drag.

Stalling

5.1 Introduction .

A stall is a reduction in the lift coefficient generated by a foil as angle of attack increases over the critical angle of attack is typically about 15 degrees but it may vary significantly depending on the fluid, foil, and Reynolds number.

Stalls in fixed-wing flight are often experienced as a sudden reduction in lift as the pilot increases the wing's angle of attack and exceeds its critical angle of attack (which may be due to slowing down below stall speed in level flight). A stall does not mean that the engine(s) have stopped working, or that the aircraft has stopped moving.

5.2 Wing stall

The critical angle of attack is the angle of attack which produces maximum lift coefficient. This is also called the "stall angle of attack".

Below the critical angle of attack, as the angle of attack increases, the coefficient of lift (C_L) increases. Conversely, above the critical angle of attack, as angle of attack increases, the air begins to flow less smoothly over the upper surface of the airfoil and begins to separate from the upper surface. On most airfoil shapes, as the angle of attack increases, the upper surface separation point of the flow moves from the trailing edge towards the leading edge. At the critical angle of attack, upper surface flow is more separated and the airfoil or wing is producing its maximum coefficient of lift. As angle of attack increases further, the upper surface flow becomes more and more fully separated and the airfoil/wing produces less coefficient of lift. Figure (5-1).

The graph shows that the greatest amount of lift is produced as the critical angle of attack is reached "burble point". This angle is 17.5 degrees in this case but changes from airfoil to airfoil. In particular, for aerodynamically thick airfoils (thickness to chord ratios of around 10%), the critical angle is higher than with a thin airfoil of the same camber. Symmetric airfoils have lower critical angles .The graph shows that, as the angle of attack exceeds the critical angle, the lift produced by the airfoil decreases.

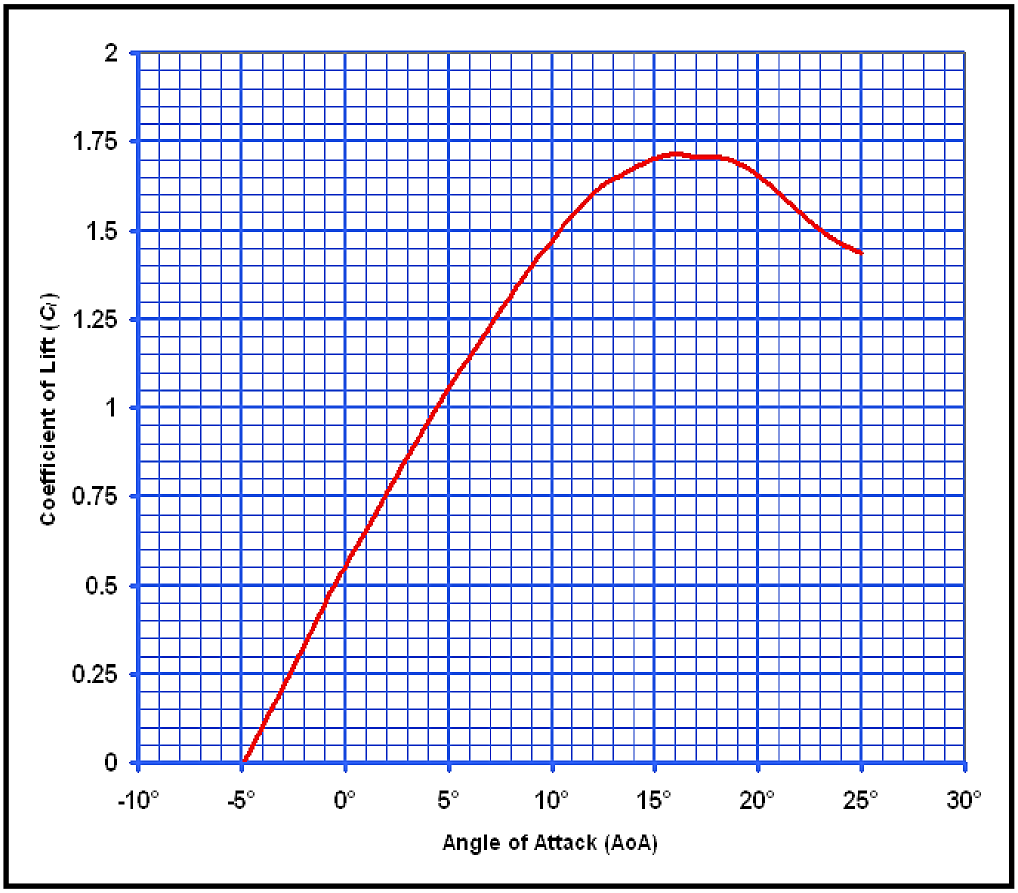


Figure (5-1): Angle of attack vs. lift coefficient

5.3 Stall speed

Stalls depend only on angle of attack, not airspeed. However, the slower an airplane goes, the more angle of attack it needs to produce lift equal to the aircraft's weight. As the speed decreases further, at some point this angle will be equal to the critical (stall) angle of attack. This speed is called the "stall speed". An aircraft flying at its stall speed cannot climb, and an aircraft flying below its stall speed cannot stop descending. Any attempt to do so by increasing angle of attack, without first increasing airspeed, will result in a stall.

The stall speed will vary depending on the airplane's weight, altitude, configuration, and vertical and lateral acceleration.

$$L = 0.5\, C_L\, \boldsymbol{\rho}\, V^2 S \quad \textbf{................(5-1)}$$

Lift is proportional with lift coefficient

$$L = nW = 0.5\, C_L\, \boldsymbol{\rho}\, V^2 S \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots(\;\;\text{-2})$$

Where n is the load factor, therefore the lift coefficient becomes

$$C_l = \frac{2n\, W}{\boldsymbol{\rho}\, V^2\, S} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(5-3)$$

Eq-3 implies that the lift coefficient is inversely proportional with square of air speed for a given aircraft weight, thus higher lift coefficient are required at low speed, and lower lift coefficient are required at higher speed.

Fig. (5-2) shows the relation between lift coefficients with square airspeed for Boeing 747-200 aircraft at 356,000 kg maximum take-off mass.

Note that a lift coefficient of 4.0 is required if the aircraft speed is reduced around 100 knots (185.2 km/hr.). However, this is impossible, because lift coefficient is a limited quantity.

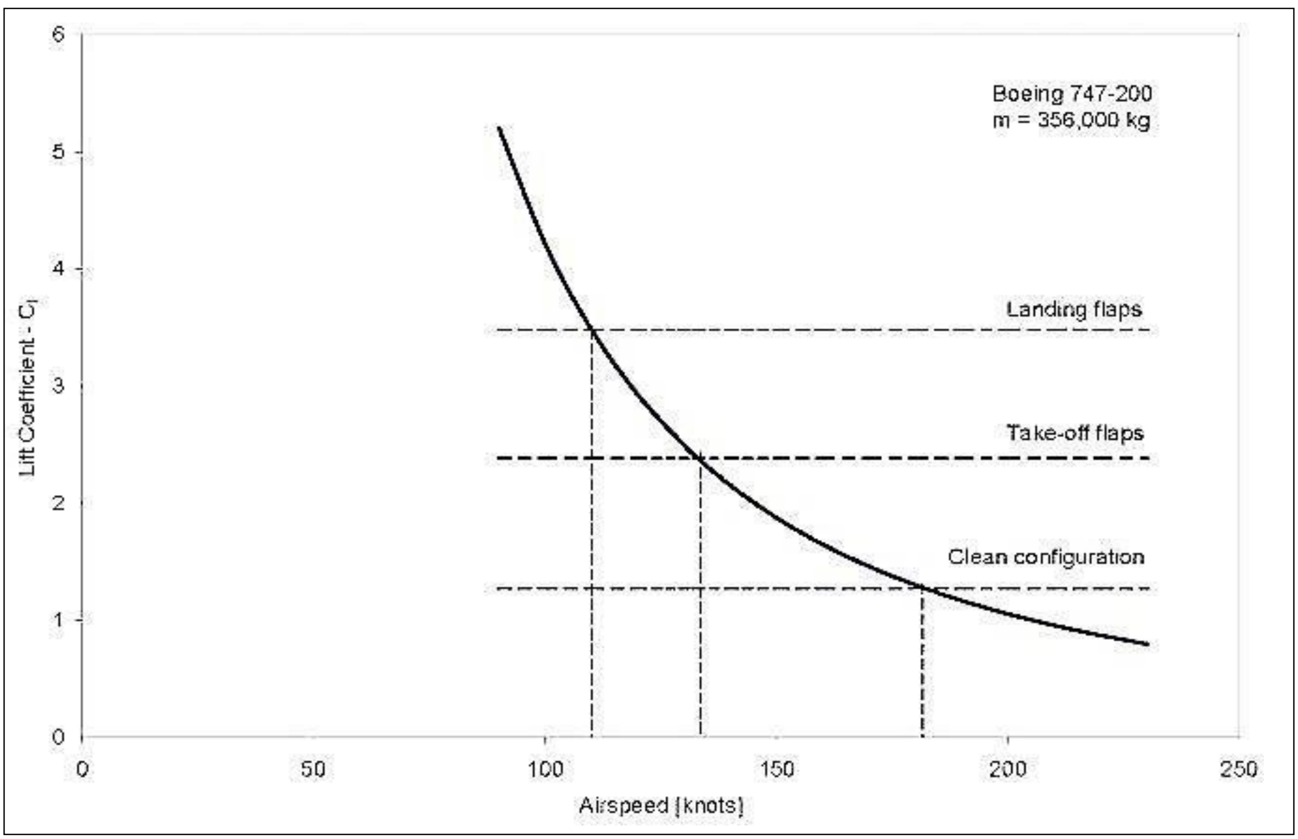


Figure (5-2): Airspeed vs. lift coefficient

Fig. (5-3) shows the airspeeds corresponding to the various lift coefficients for a Boeing 747 size aircraft. Figure implies that slightly below 183 KCAS, the aircraft will require flying with maximum lift coefficient, thus it will stall. The airspeed where the aircraft reaches to the maximum lift coefficient is called the stall speed, because stalling of the wing starts at this point. Since flying below the stall speed will cause a significant lift reduction, stall speed is the minimum flight speed of an aircraft. The maximum lift coefficients of current wing designs are limited around 1.5, so that there is always a minimum flight speed for all aircraft. In summary, the stall speed

$$V_S = \sqrt{\frac{2n\,W}{\boldsymbol{\rho}\, C_{L\,max} S}} \dots\dots\dots\dots\dots\dots\dots (5-4)$$

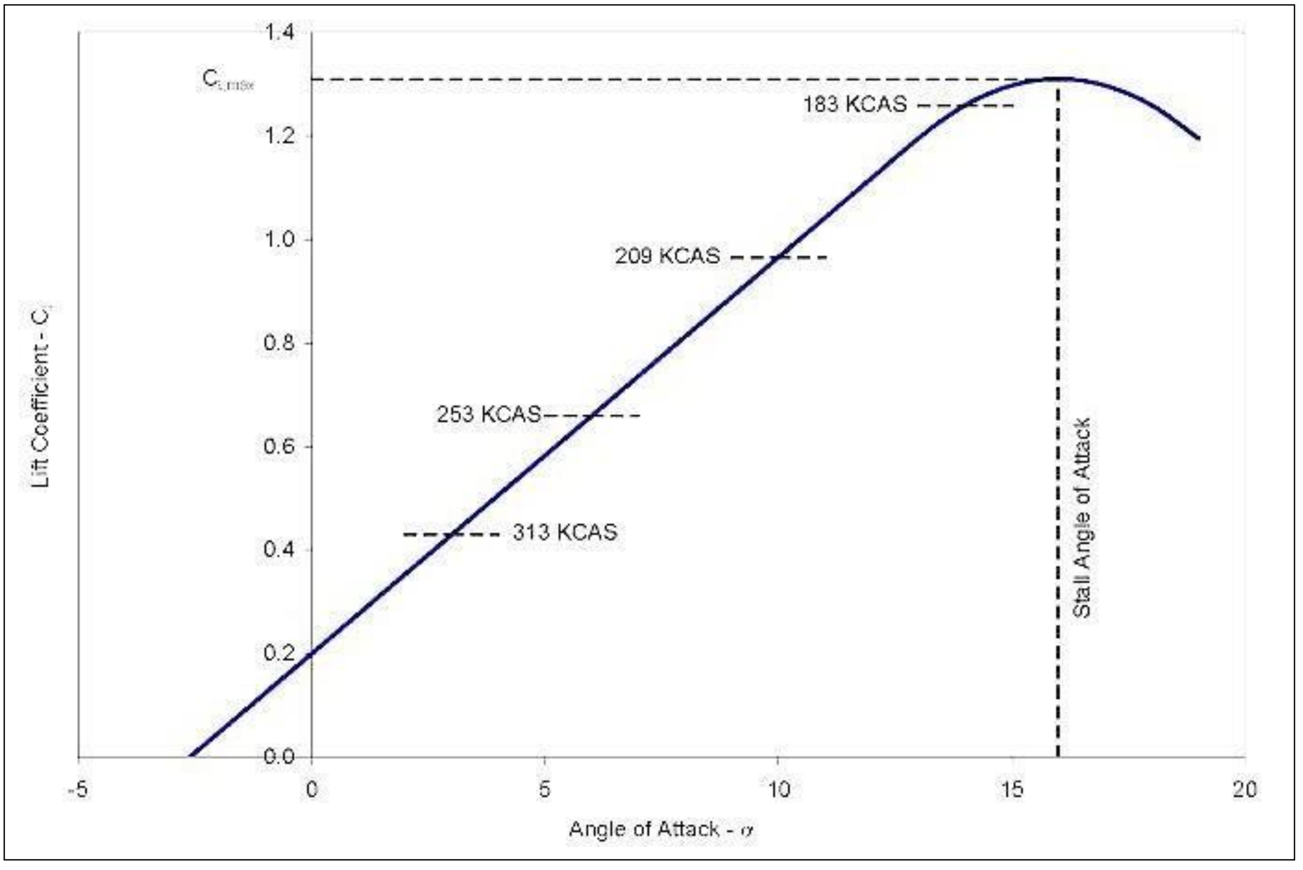


Figure (5-3): Airspeed vs. angle of attack

5.3.1 Factors Affecting the Stall Speed

Eq. (4) well defines the factors affecting the stall speed, in summary;

1- Aircraft Weight
2- Air density
3- Maximum lift coefficient
4- The load factor.

5.3.1.1 Aircraft weight

Stall speed is proportional with the aircraft weight. Stall speed increases, as the weight increases; and decreases as the weight decreases.

5.3.1.2 Air density

Aircraft stall speeds are usually given in terms of calibrated air speed or indicated air speed as an aircraft limitation. However, as it is seen from Eq. (4), it is actually a true airspeed which is inversely proportional with the density. Therefore, although it is constant in terms of CAS, it increases with the altitude because of the density variation. Fig. (5-4) shows how stall speed of Boeing 747 varies with altitude.

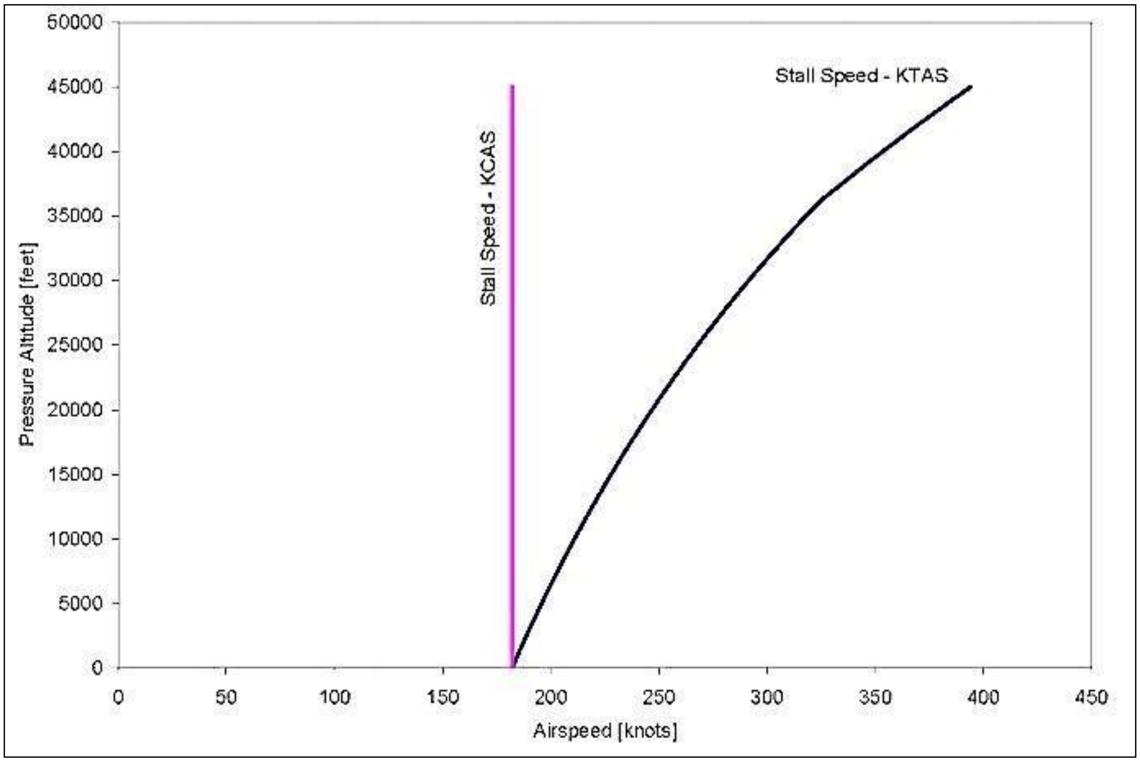


Figure (5-4): Altitude versus stall speed in terms of CAS and TAS.

5.3.1.3 Maximum lift coefficient

Maximum lift coefficient of an airplane can be varied by high lift devices such as flaps and slats. Effects of flaps on the lift and drag characteristics is shown in Fig (5-5). Depending on the angle of attack and flap deflection angle, it is possible to obtain lift coefficients as high as 3.0.

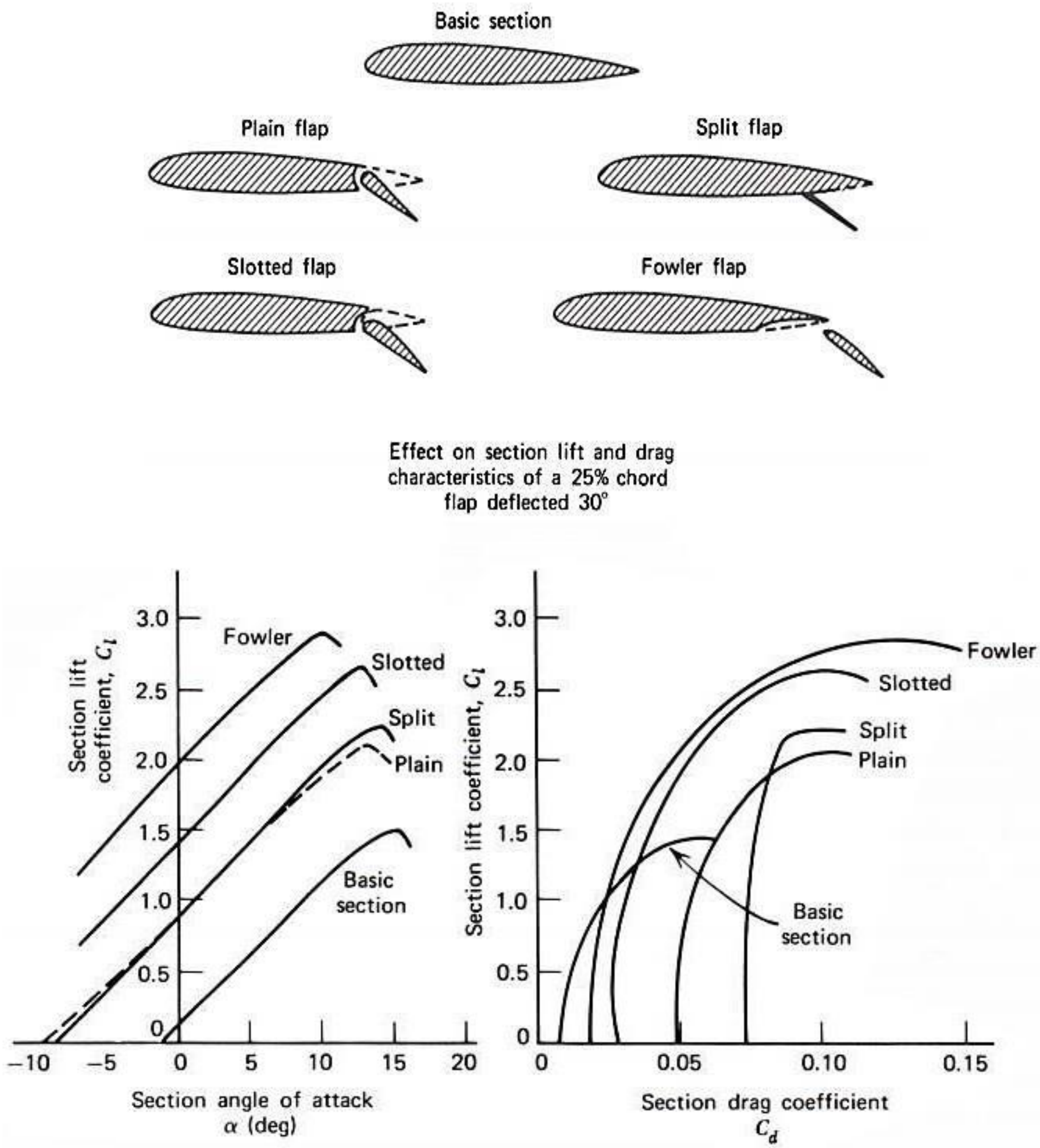


Figure (5-5): Effects of trailing edge flaps on lift and drag characteristics of wing sections

Higher maximum lift coefficients will obviously result in slower stall speeds as seen from Fig. (5-2). Lowest maximum lift coefficient is obtained when flaps are retracted, i.e. airplane in clean configuration, thus highest stall speed occurs in clean configuration. When flaps are deflected, maximum lift coefficient increases and stall speed decreases. However, flap deflection angles are also limited, because airplane drag increases as the flap angles increase. Since higher flap angles are used during landing, stall speeds in the landing configuration are slower.

5.3.1.4 Load factor

Stall speed is proportional with the load factor. It increases as the load factor increases. If V_{SS} is the stall speed of an aircraft in steady level flight, then stall speed during maneuvers will be

$$V_{S_N} = \sqrt{n}\, V_{S_S} \quad \dots \dots \dots \dots \dots \dots \dots (5-5)$$

Or during a turn maneuvering

$$V_{S_N} = \frac{V_{S_S}}{\sqrt{cos\emptyset}} \quad \dots \dots \dots \dots \dots \dots \dots (5-6)$$

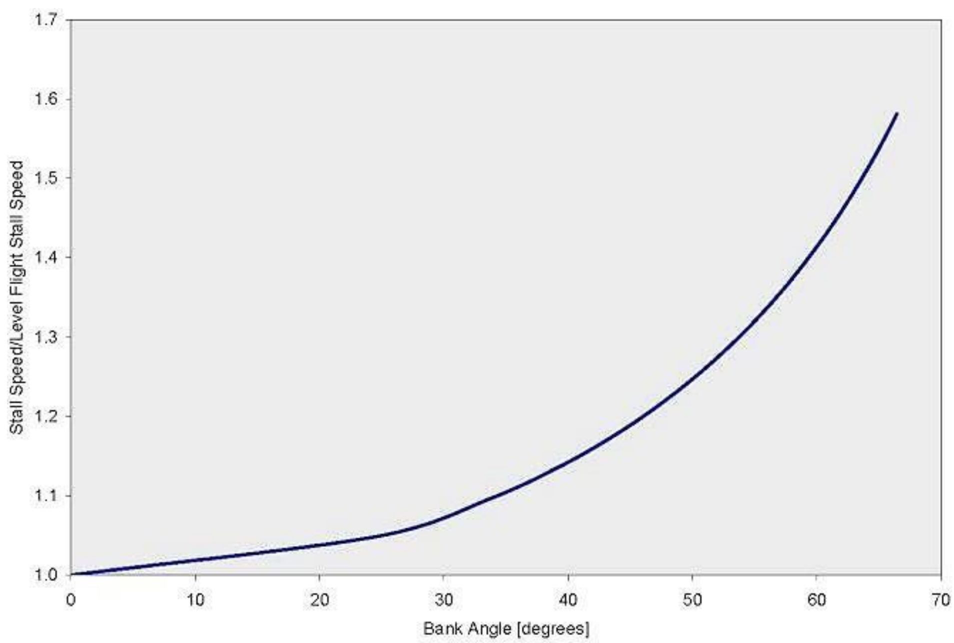


Figure (5-6): Ratio of the stall speed to the level flight stall speed versus bank angle

5.4 High Lift Equipment In Airplane

When an aircraft is landing or taking off, especially high values of lift coefficient are required in order to maintain flight at the desired low speeds.

- Increasing the area S.
- Increasing the lift coefficient C_L by using much more camber.
- Delay the flow separation by controlling the behavior of the boundary layer.

5.4.1 Flaps

The most common high-lift device is the flap, a movable portion of the wing that can be lowered to produce extra lift. When a flap is lowered this re-shapes the wing section to give it more camber. Flaps are usually located on the trailing edge of a wing, while leading edge flaps are used occasionally (only on larger airplanes).

5.4.1.1 Plain Flap

Located in the trailing edge of the wing, where the rear portion of airfoil rotates downwards on a simple hinge mounted at the front of the flap, the plain flap is normally only used where simplicity is required.

- Give increase in maximum lift when required at taking off or landing.
- The lift increase with flap deflection increase.
- Stall angle decrease.

5.4.1.2 Split Flap

The split flap attaches to the bottom of the wing, and deploys downward without changing the top surface of the wing. This type of flap creates more drag than the plain flap because of the increase in turbulence.

- The stalling angle is higher than the corresponding value for a plain flap.
- The increase in lift coefficient is bigger than with a plain flap.
- There will be bigger increase in drag than with a plain flap because of the large wake.

5.4.1.3 Slotted Flap

A gap between the flap and the wing forces high pressure air from below the wing over the flap helping the airflow remain attached to the flap, increasing lift compared to a split flap. Additionally, lift across the entire chord of the primary airfoil is greatly increased as the velocity of air leaving its trailing edge is raised,

- Any flap that allows air to pass between the wing and the flap is considered a slotted flap.

5.4.1.4 Fowler flap

The Fowler flap attaches to the back of the wing using a track and roller system. When it deploys, it moves aft in addition to deflecting downward. This increases the total wing area, in addition to increasing the wing camber and chord line. This type of flap is the most effective of the four types, and it is the type used on commercial airliners and business jets.

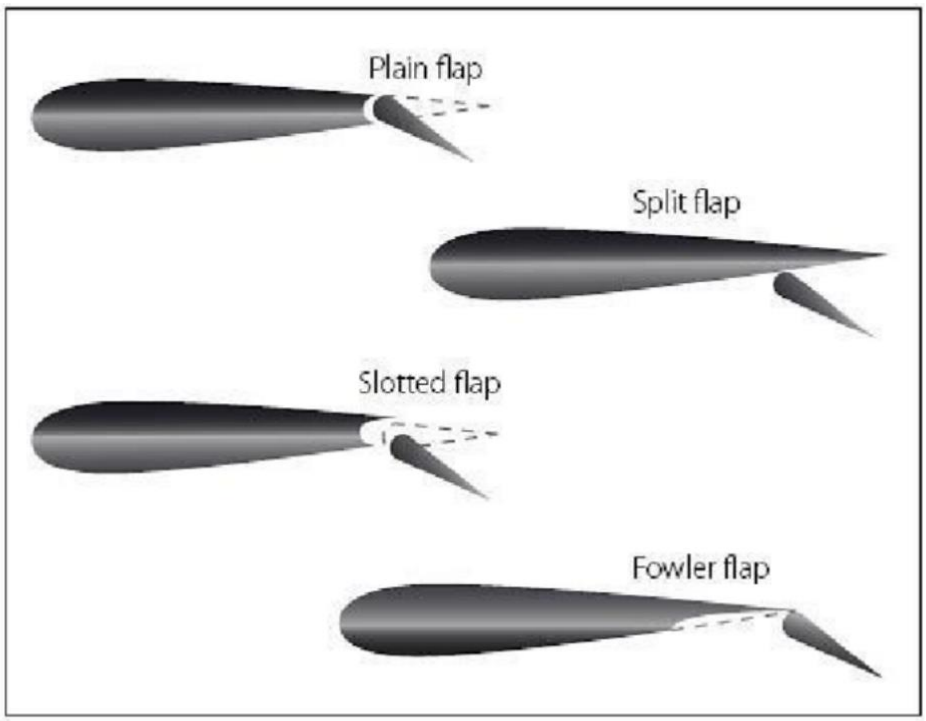


Figure (5-8): Types of wing flap.

5.4.2 Leading edge flap.

The entire leading edge of the wing rotates downward, effectively increasing camber and also slightly reducing chord. Most commonly found on fighters with very thin wings.

5.4.2.1 types of leading edge flap

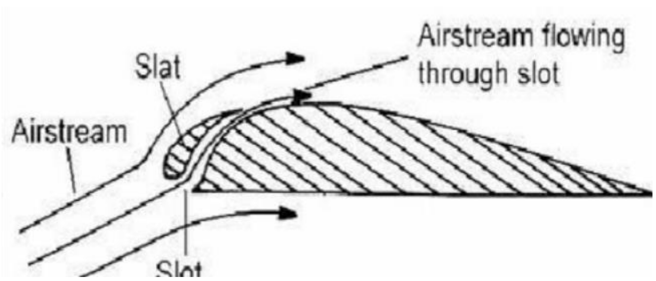
1- Blown flap
2- Flexible flap (FlexFoil)
3- Flaperon

5.4.3 Slots

slots is the air gap between slats and the wing produced due to the extension of the slat, they allow high pressure air from the bottom of the wing to flow to the top of the wing. This ducted air flows over the top of the wing at a high velocity and helps keep the boundary layer air from becoming turbulent and separating from the wing. Slots are often placed on the part of the wing ahead of the ailerons, so during a wing stall, the inboard part of the wing stalls first and the ailerons remain effective.

5.4.4 Slats

Are auxiliary airfoils fitted to the leading edge of the wing, at high angle of attack they automatically move out ahead of the wing, The angle of attack of the slat being less than that of the main plane, there is a smooth airflow over the slat which tends to smooth out the eddies forming over the wing. Slats are usually fitted to the leading edge near the wing tips to improve lateral control.



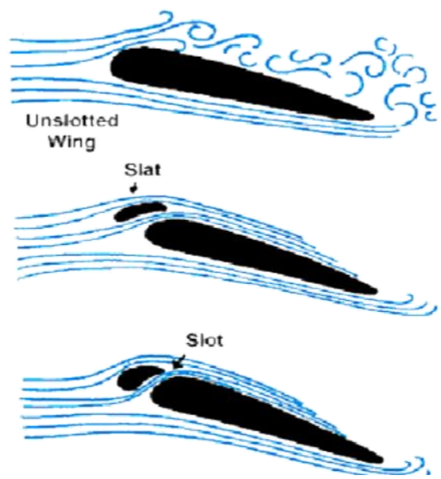
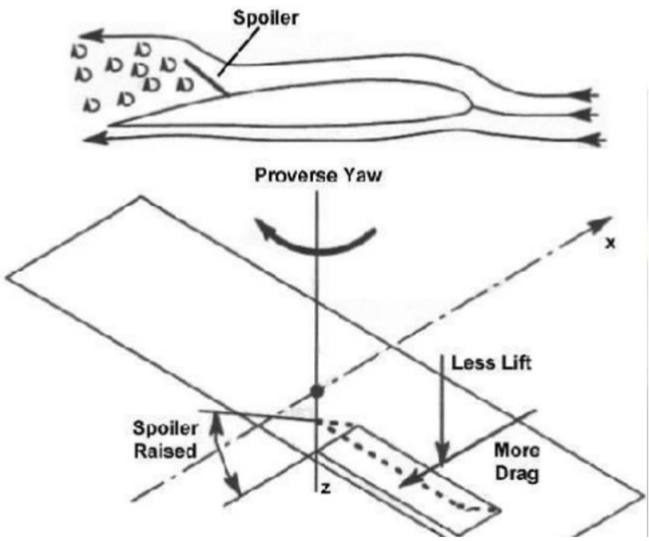


Figure (5-9): Slat and slot.

5.4.5 Spoilers

Spoilers are intended to create drag and reduce lift by "spoiling" the airflow over the wing. Spoilers are usually installed mid chord on the upper surface of the wing, but may also be installed on the lower surface of the wing as well. Fig (5-10).



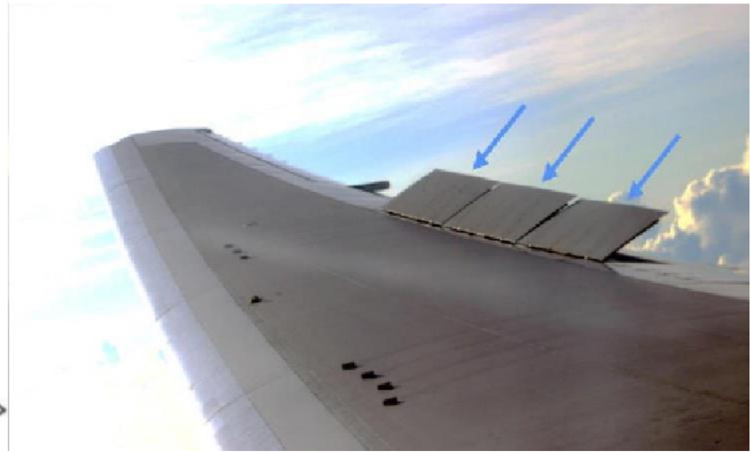


Figure (5-10): Spoilers.

5.4.6 Air brakes

Air brakes are used on high performance combat aircraft to increase drag, allowing the aircraft to decelerate rapidly. When installed on the wings they differ from flaps and spoilers in that they are not intended to modify the lift and are built strongly enough to be deployed at much higher speeds. Fig (5-11).

Figure (5-11): Air breaks.

<u>5.4.7 Ailerons</u>

Ailerons are similar to flaps (and work the same way), but are intended to provide lateral control, rather than to change the lifting characteristics of both wings together, and so operate differentially - when an aileron on one wing increases the lift, the opposite aileron does not, and will often work to decrease lift. Fig (5-12).

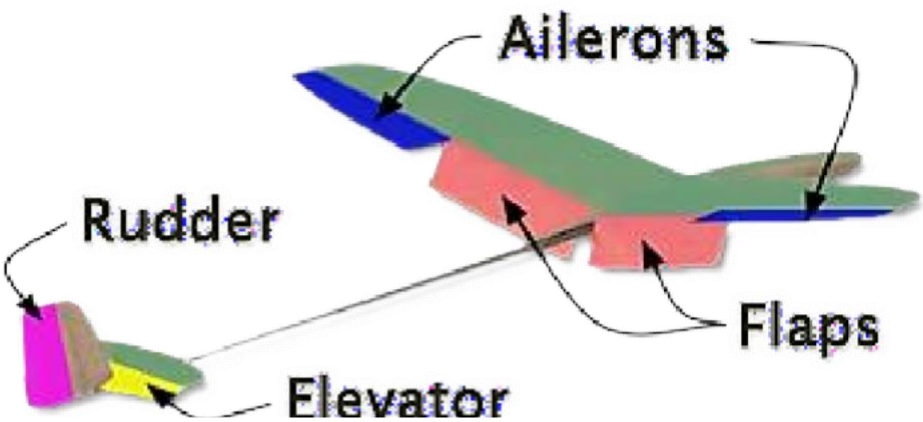


Figure (5-12): Ailerons.

<u>5.4.8 Canard</u>

Canards are lifting planes positioned in front of the main wing.

The weight of the aircraft is shared between the wing and the canard. It has been described as an extreme conventional configuration but with a small highly loaded wing and an enormous lifting tail which enables the center of mass to be very far aft relative to the front surface

Figure (5-13): Canard.

Rotary – Wing aerodynamics

1. Introduction.

Helicopters, unlike fixed-wing airplanes, obtain the required force to oppose weight from rotational movement of blades. Understanding how lift is produced by rotating blades is difficult to some because the airflow which ultimately passes each blade consists of a number of seemingly conflicting flows, produced by:

- Rotation of the blades.
- Induced action.
- Airflow as a result of forward or sideways flight.

Notwithstanding the difficulties, it is important to understand the cause and effects of these flows, and their interaction.

2. Rotational Airflow (V_r).

The rotation of rotor blades as they turn about the mast produces rotational relative wind. The term rotational refers to the method of producing relative wind. Rotational relative wind flows opposite the physical flight path of the airfoil Figure (2-1), striking the blade at 90° to the leading edge and parallel to the plane of rotation Figure (2-2).

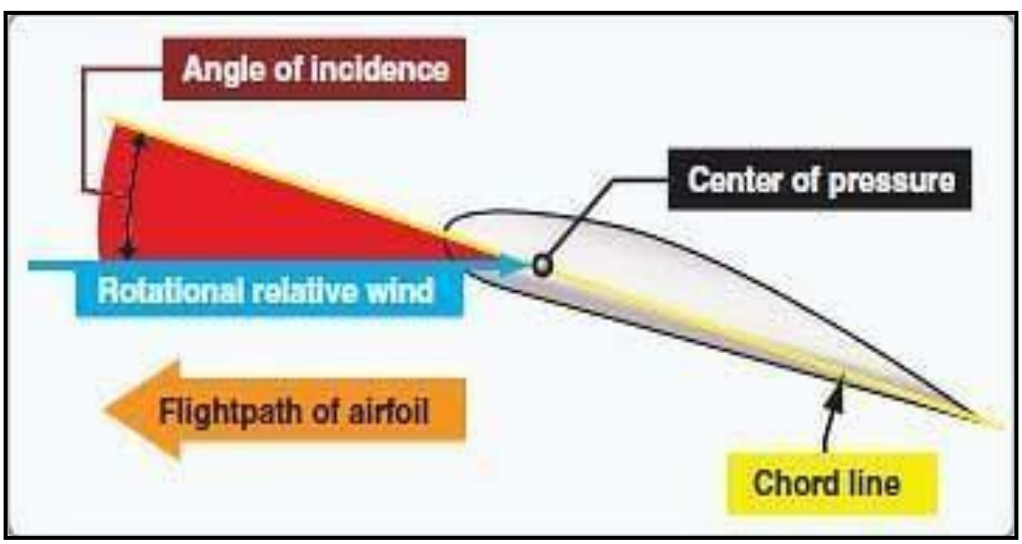


Figure (2-1): Rotational relative wind velocity.

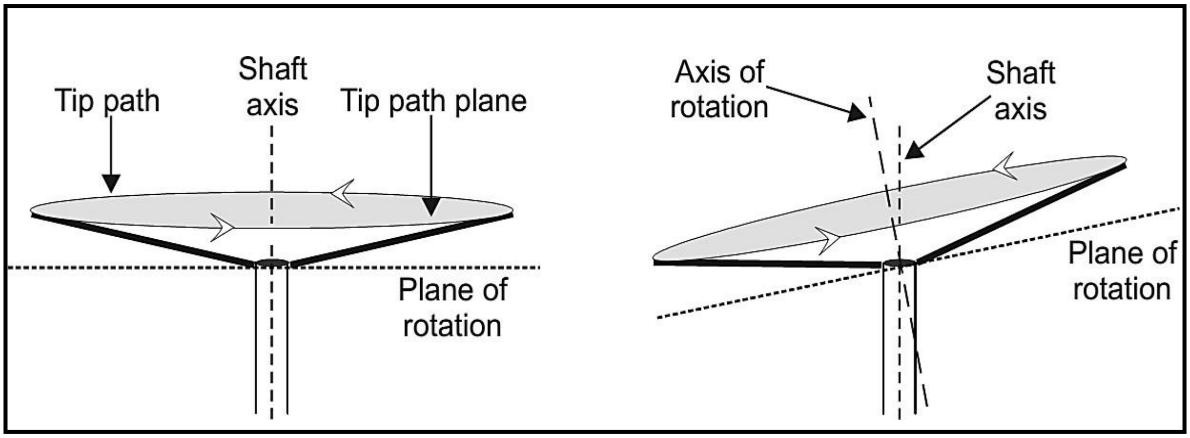


Figure (2-2): plane of rotation and tip path plan.

Rotational relative wind velocity is highest at blade tips, decreasing uniformly to zero at the axis of rotation (center of the mast), At the rotor hub V_r is slower than that at the tip, where the airflow is quite fast. A vector quantity used to represent V_r per blade section for a given rotor rpm, Figure (2-3) shows a large vector (A-B) for flow near the tip in the left diagram and a small vector (A-B) for flow near the hub on the right.

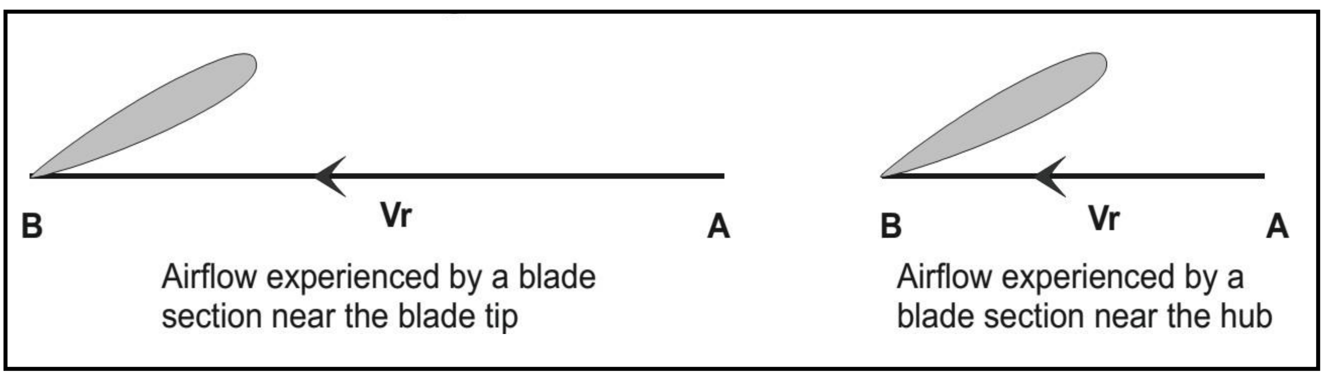


Figure (2-3): Vector quantities of airflow for different blade sections with constant rotor rpm.

The vector for V_r also changes with rotor rpm. If rotor rpm increases the magnitude of V_r increases and if rotor rpm decreases, the magnitude of V_r decreases. In Figure (2-4), vector A-B represents V_r for a given blade section at high rotor rpm in the left-hand diagram and vector A-B represents V_r for the same blade section at low rotor rpm in the diagram on the right.

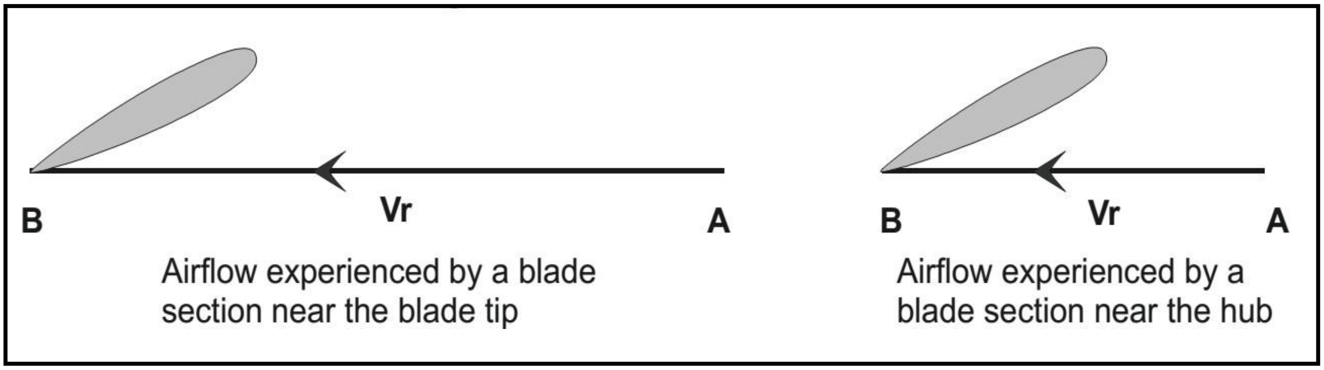


Figure (2-4): Vector quantities of airflow experienced by a given blade section at high and low rotor rpm.

With respect to blade section Vr vectors will be longer or shorter depending on the section considered, as long as the rotor rpm is constant.

With respect to rotor RPM Vr vectors will be shorter or longer depending on rotor rpm, as long as the blade section is at a constant position from the root or tip.

In summary, vectors A-B (V_r) can represent blade section or rotor rpm, but not both, as variable, at the same time.

3. Blade Angle and Angle of Attack.

The angle between the chord of the blade and the plane of rotation (Figure 2-5) is known as the blade angle or pitch angle, and is controlled through the collective pitch control.

If the pilot pulls the collective lever up blade angle increases, and if the pilot pushes the collective lever down, the blade angle decreases.

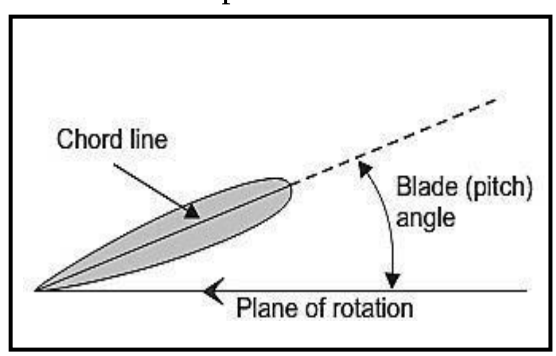


Figure (2-5): Blade / Pitch angle.

The airflow (vector A-B) is in the plane of rotation and as long as no other airflows interfere, the blade angle is also the angle of attack. The blade angle does not affect the direction from which V_r occurs. Whether the plane of rotation is parallel to the ground or tilted, V_r will always be parallel to the plane of rotation.

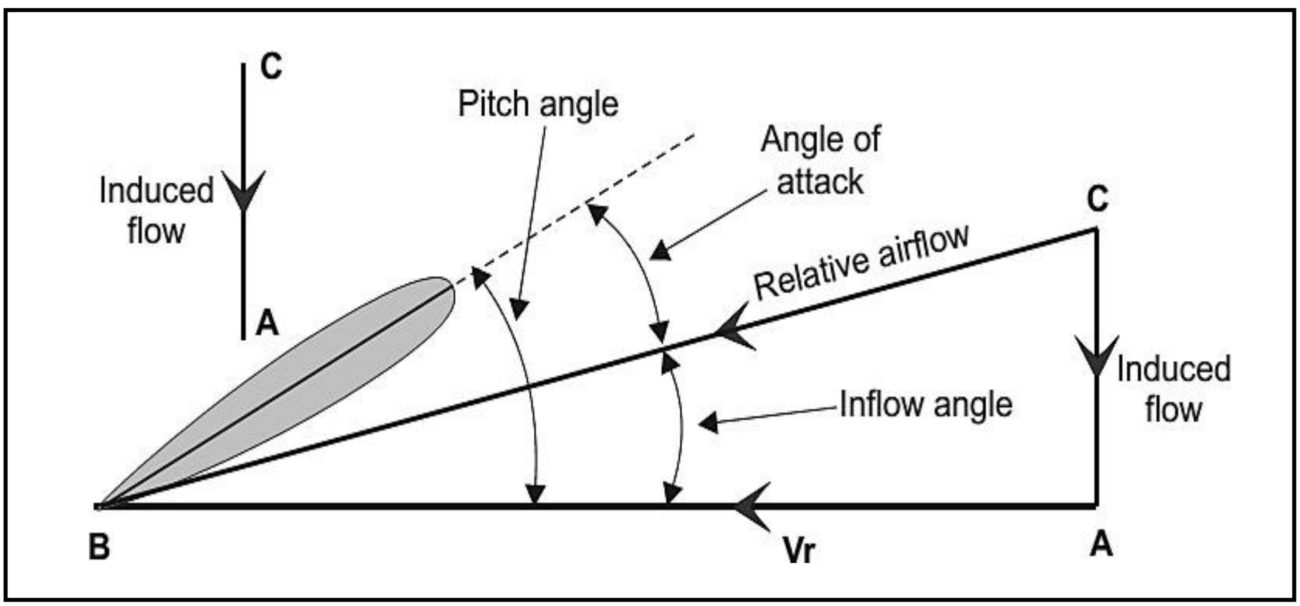
4. Induced Flow.

Newton's law of action and reaction supports the principle that during helicopter flight the rotor must force down a volume of air. This induced flow of air travels down through the rotor when the helicopter is in normal powered flight and is the result of lift that has deflected the airflow downward.

Whereas most of the air molecules will pass through the rotor, those molecules enticed down from some height above the rotor disc may find that when they reach disc height, the helicopter has traveled forward so that they miss the rotor disc altogether.

So, Induced flow is defined as the mass of air that is forced down by the rotor action, most of the air will pass through the rotor but a small part may miss it.

If we take induced flow into consideration now, we see that the rotor blade experiences two airflows, one from straight ahead (vector A-B, V_r) caused by rotation and other from above (vector C-A) caused by induced flow. These two flows create a resultant airflow (vector C-B) onto the blade, and that resultant airflow (or relative airflow, RAF) is no longer parallel to the plane of rotation (see Figure 2-6).



· **Figure (2-6): the effect of induced flow on angle of attack.**

(A-B) Airflow due to rotation.

(C-A) induced flow.

(C-B) combine to produce the relative airflow.

The resultant airflow presents a [illegible] (refer to Figure 2-6)

1. Angle of attack and induced flow are inversely proportional for a given blade section and rotor rpm.

The angle of attack decreases when induced flow becomes established, and is less than the blade angle. When the induced flow increases for a given blade section and rotor rpm, the angle of attack decreases, and when induced flow decreases, the angle of attack increases.

2. Inflow angle and the induced flow are directly proportional for a given Vr, rotor rpm.

The inflow angle is the angle between the plane of rotation and the resultant airflow (RAF). For a given rotor rpm, the inflow angle increases as induced flow increases and decreases as induced flow decreases.

3. For a given induced flow, the inflow angle and rotor rpm are inversely proportional. When the rotor rpm (Vr) increases and the induced flow remain constant, the angle of attack increases and inflow angle decreases. A reduction in rotor rpm (Vr) will decrease the angle of attack and increase the inflow angle.

5. Balance of forces.

5.1 Total Rotor Thrust.

The total reaction (TR) shown in Figure(2-7) is required to provide the opposing force to weight, but the diagram clearly shows that the TR does not act in line with weight; it “leans back” from the vertical. Thus a component of the total reaction must be vectored that does act in line with and opposite to weight. That component vector is called rotor thrust (RT), it is the force produced by each blade section to overcome part of the helicopter’s weight. When the rotor thrusts of all the blade sections are combined, total rotor thrust (TRT) acting through the top of the mast provides the force (or component force) that overcomes the weight of the helicopter.

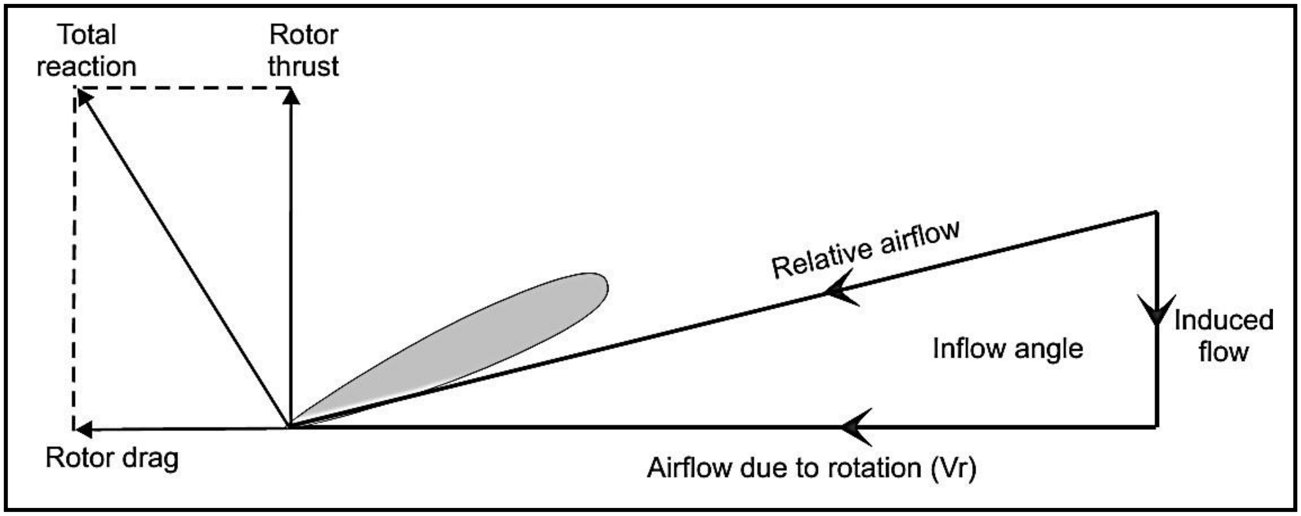


Figure (2-7): Total reaction, rotor thrust and rotor drag forces.

Total rotor thrust acts in line with the axis of rotation at right angles to the plane of rotation. Its magnitude is equal to aircraft weight when the helicopter is hovering in no-wind conditions or in certain un accelerated steady flight conditions, such as stabilized vertical climbs or descents Whenever the rotor disc is not parallel to the earth's surface (such as in forward flight), total rotor thrust is split into a vertical and a forward component. Under those conditions, the vertical component of total rotor thrust must overcome the gross weight of the helicopter (Figure 2-8).

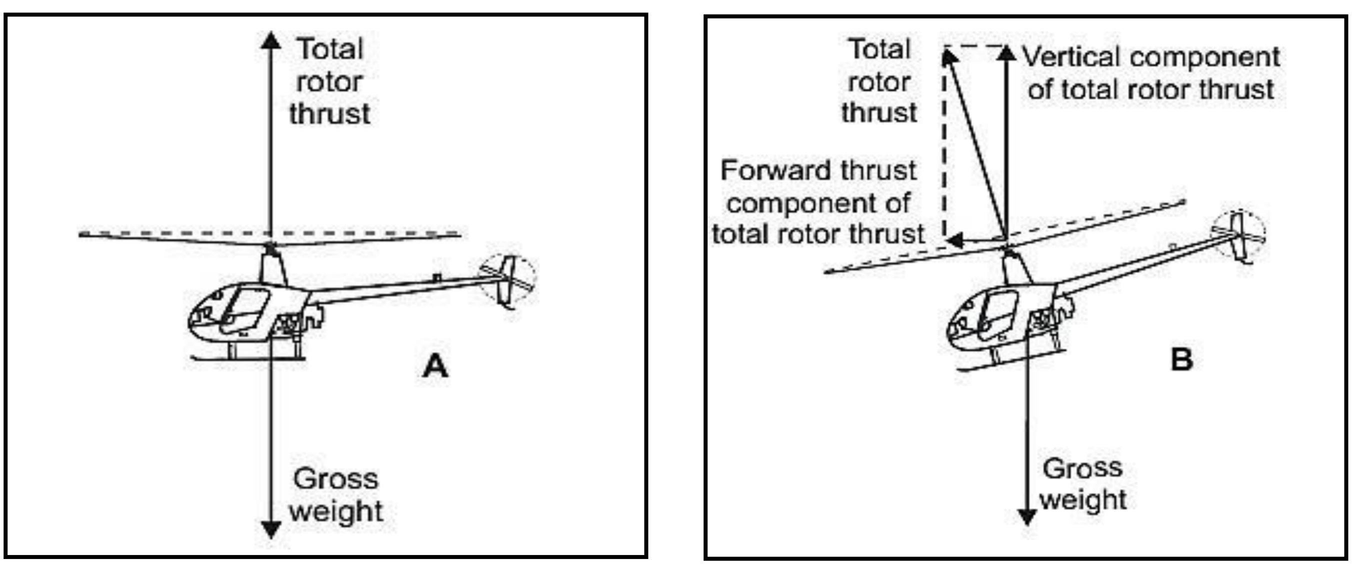


Figure (2-8): Total Rotor Thrust during Hovering (A) and Forward (B) motions.

Figure (2-8) shows

1- In a calm hover (A), total rotor thrust is equal and opposite to the aircraft gross weight.

2- In forward flight (B), the vertical component of total rotor thrust is equal and opposite of the gross weight.

5.2 Rotor Drag (Torque).

Rotor drag is the component of total reaction at right angles to rotor thrust (Figure 2-7). Rotor drag is in the plane of rotation, but in a direction opposite to that of blade travel. Do be careful not to confuse rotor drag (acting in the plane of rotation) with aerodynamic drag (acting in line with the relative airflow). A helicopter in powered flight requires engine power to overcome rotor drag so that the rotor will maintain its rpm. During autorotation flight, rotor drag is overcome by an aerodynamic force.

- Autorotation is a state of flight in which the main rotor system of a helicopter or similar aircraft turns by the action of air moving up through the rotor. Figure (2-9).

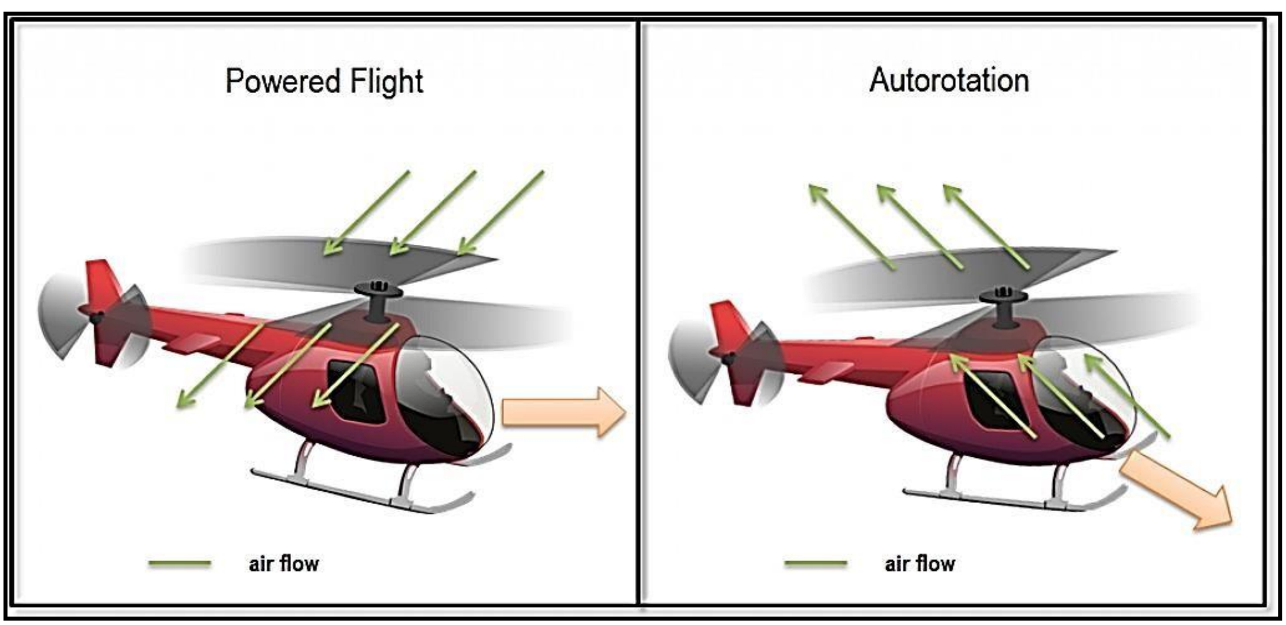


Figure (2-9): Powered and Autorotation flight.

5.3 Angle of Attack and the Rotor Thrust/Rotor Drag Ratio.

Total rotor thrust (TRT) is the force that overcomes weight, but a penalty must be paid for the associated rotor drag (or torque) in terms of power, which is limited.

If we take efficiency in to the consideration, there should be as much total rotor thrust (TRT) and as little rotor drag as possible, that is, the TRT/rotor drag ratio should be as high as possible. In both diagrams of Figure (2-10) we can see once again that the total reaction determines the amounts of rotor thrust and rotor drag.

If the TR leans further away from the axis of rotation, possibly due to a high angle of attack (as in the right hand diagram), the amount of rotor thrust reduces while rotor drag increases. Similarly, if the TR were to “stand up” more, possibly because of a small angle of attack (as in the left hand diagram), the amount of rotor thrust increases and rotor drag decreases. Thus the TRT/rotor drag ratio is entirely determined by the size and orientation of the total reaction (TR).

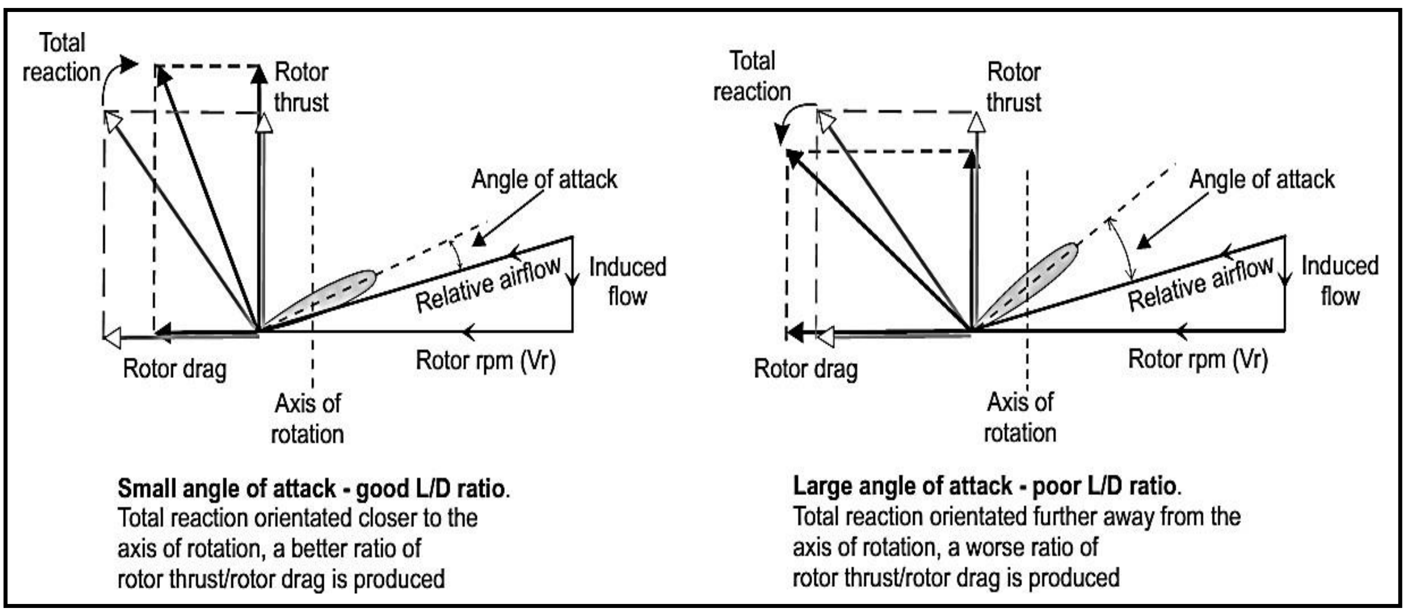


Figure (2-10): Effect of changes in angle of attack on orientation of the total reaction.

Therefore, if the TRT/rotor drag ratio is to be at its best, the total reaction should lean as close as possible to the axis of rotation, the blade should operate at the angle of attack for best L/D ratio, (minimum drag).

5.4 Induced Flow and the Rotor Thrust/Rotor Drag Ratio.

Induced flow also influences the orientation of the total reaction (Figure 2-11). In the right-hand diagram you can see that if the induced flow decreases while rotor rpm stays the same, the inflow angle decreases and the angle of attack increases (if the blade angle is kept constant). To avoid an increased angle of attack the collective control lever is lowered by the pilot, which reduces the blade angle. The smaller inflow angle causes the total reaction to orient itself more to the vertical (towards the axis of rotation). As a result, rotor thrust increases, while rotor drag decreases.

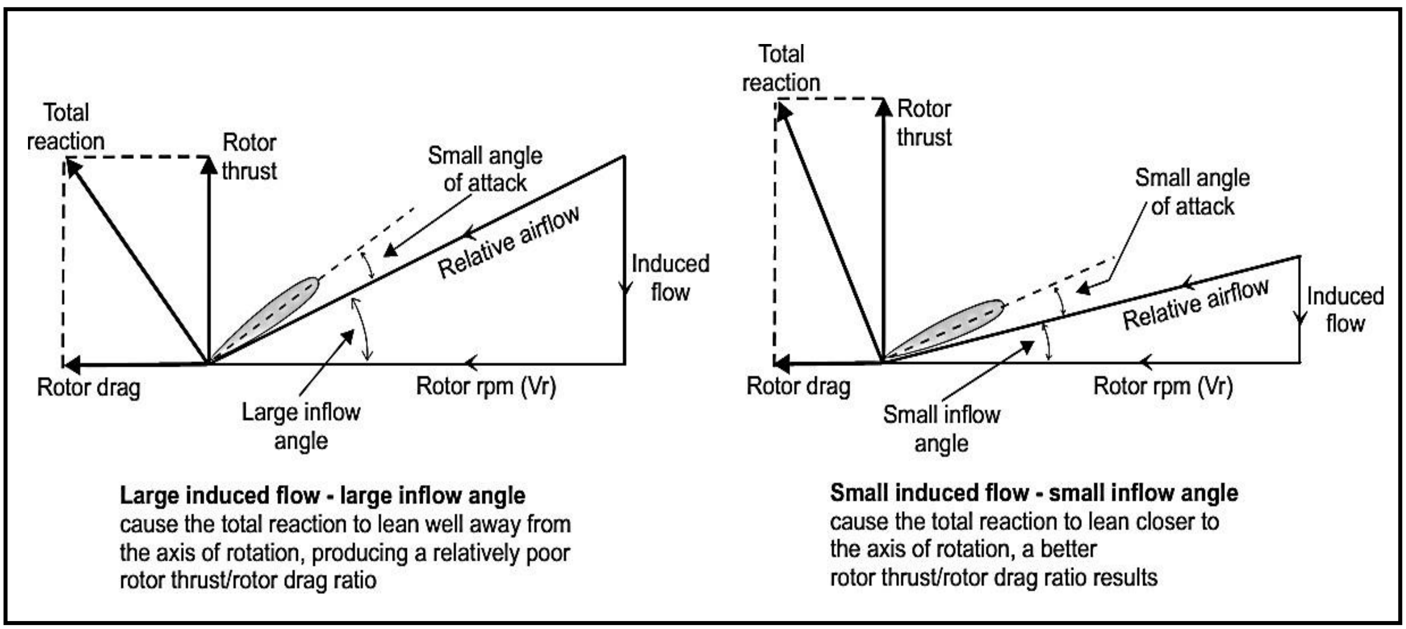


Figure (2-11): Effect of difference in induced flow and inflow angle on the rotor thrust/ rotor drag ratio.

In the left diagram of Figure (2-11), a larger inflow angle and a larger blade angle (high collective setting) can maintain a given angle of attack. However the orientation of the relative airflow and size of the inflow angle cause the total reaction to lean well away from the axis of rotation, resulting in a poor rotor thrust/rotor drag ratio. Note from these explanations the relationship between induced flow and collective lever setting for a given rotor rpm and angle of attack. Let us now consider the influence of both angle of attack and induced flow on the TRT/rotor drag ratio. It can be stated that:

<u>Best efficiency is obtained (maximum TRT/rotor drag ratio) when the angle of attack on the blade produces the least amount of drag and when the collective lever is at the lowest position possible.</u>

5.5 Inflow Angle

Since Vr is more-or-less a constant and the range of angles of attack is relatively small, the inflow angle has a very strong influence on the total reaction, and hence the TRT/rotor drag ratio. In generalized terms, the higher the collective setting, the larger the inflow angle, the greater the amount of rotor drag and the greater the requirement for power. In contrast, the lower the collective setting, the smaller the inflow angle, the less the amount of rotor drag and the less the requirement for power.