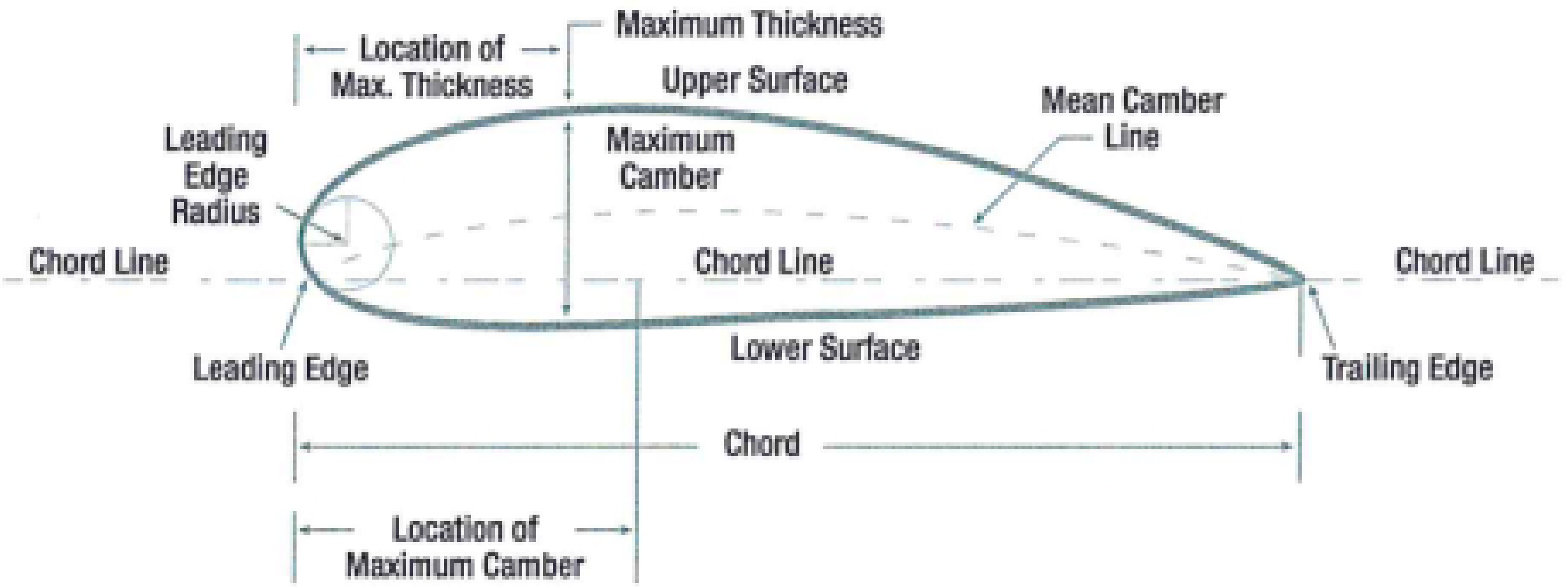
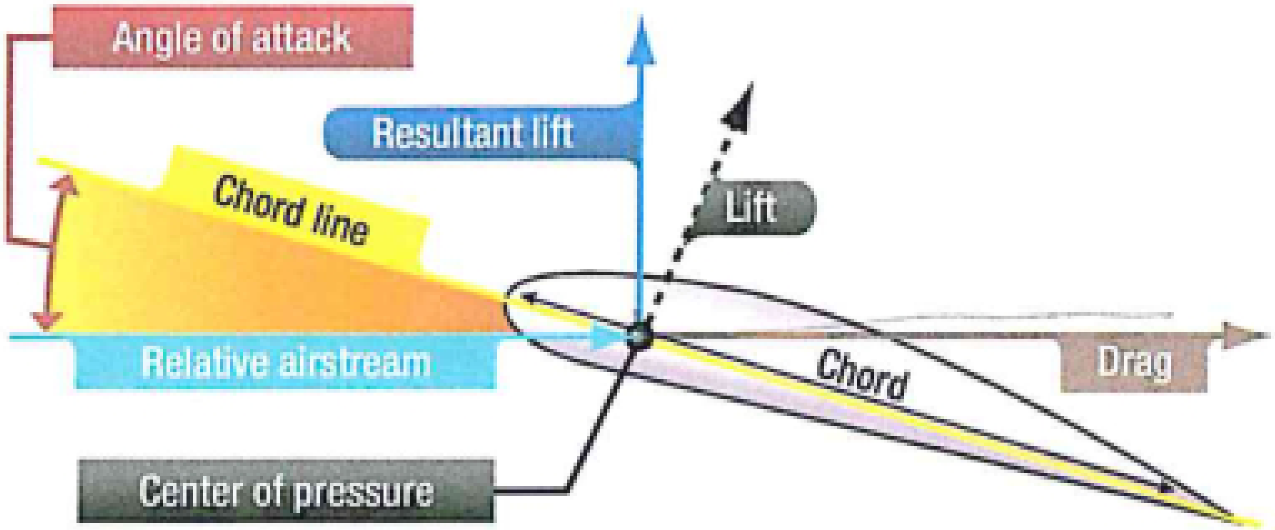
Aerodynamics

Airfoil terminology

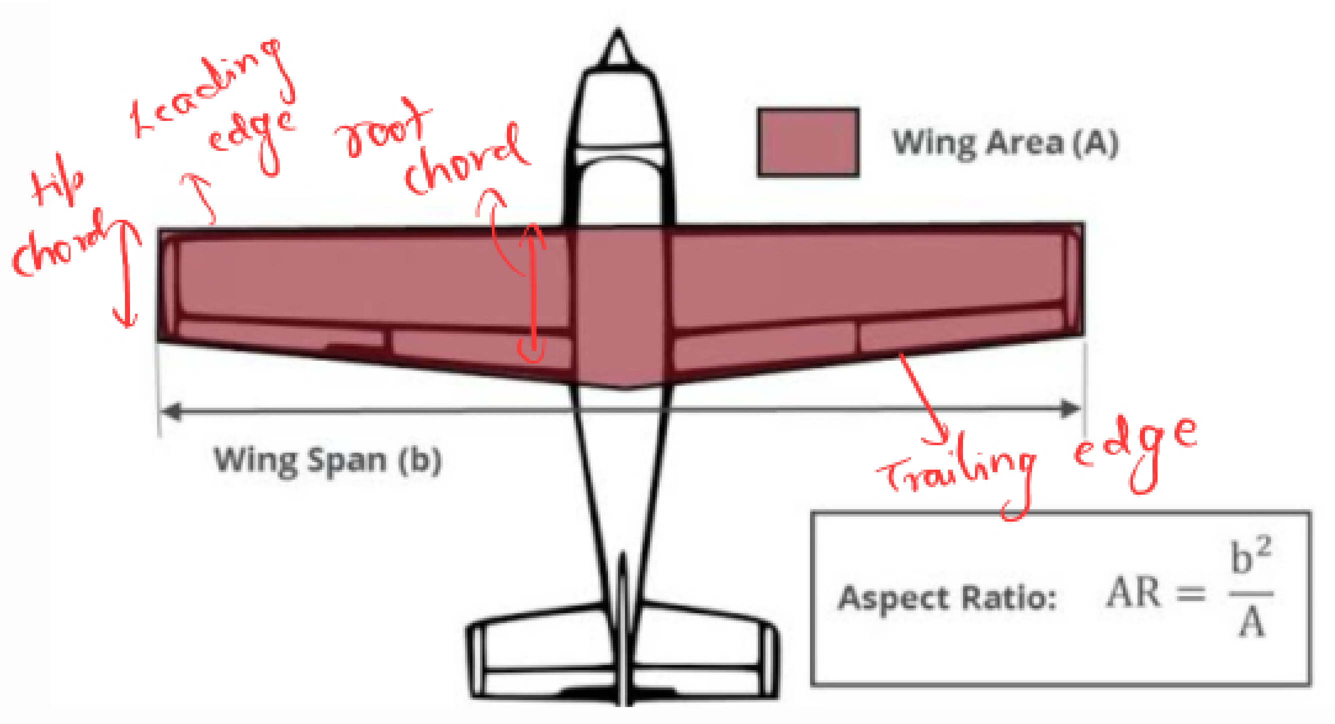


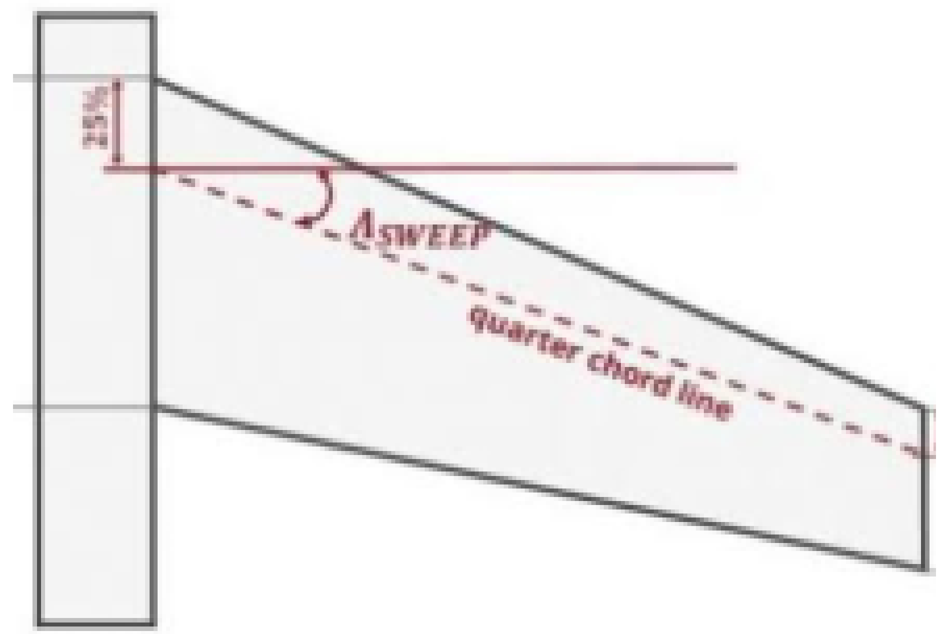


Airfoil terminology

- Airfoil ---The cross-sectional shape of the wing is called an airfoil
- Chord—the length of the chord line from leading edge to trailing edge; it is the characteristic longitudinal dimension of the airfoil section.
- Chord line—a straight line intersecting leading and trailing edges of the airfoil.
- Mean camber line—a line drawn halfway between the upper and lower surfaces of the airfoil.The shape of the mean camber is important for determining aerodynamic characteristics of an airfoil section.
- Camber: The maximum distance between the chord line and camber line.
- Thickness:it is the distance between upper and lower surface of an airfoil
- Leading edge—the front edge of an airfoil.
- Trailing edge—the rearmost edge of an airfoil.
- Angle of attack (AOA)—the angle measured between the resultant relative wind and chord line.
- Center of pressure—the point along the chord line of an airfoil through which all aerodynamic forces are considered to act

Wing terminology





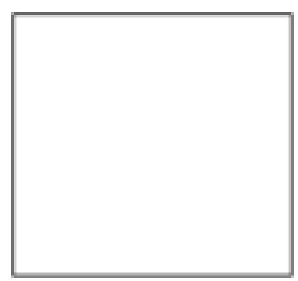
- **Wing tips :**The ends of the wing are called the wing tips,
- **Wing span** :The distance from one wing tip to the other is called the span.
- **Wing planform:**The shape of the wing, when viewed from above looking down onto the wing, is called a planform.
- **The wing area** is the projected area of the planform and is bounded by the leading and trailing edges and the wing tips.
- **The total surface area** includes both upper and lower surfaces. The wing area is a projected area and is almost half of the total surface area
- **The aspect ratio** (AR) of a wing is defined to be the square of the span (b)divided by the wing area (A). Aspect ratio is a measure of how long and slender a wing is from tip to tip
- **Taper Ratio** :It is defined as the ratio between the tip chord (Ct) to the root chord (Cr).
- **Sweep angle** :The angle between a constant percentage chord line along the semispan of the wing and the lateral axis perpendicular to the aircraft centerline (y-axis) is called leading edge sweep (□LE).

a. AR = 26.7

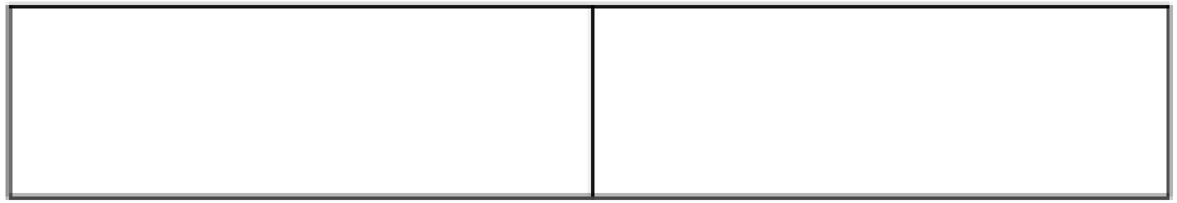
b. AR = 15

c. AR = 6.67

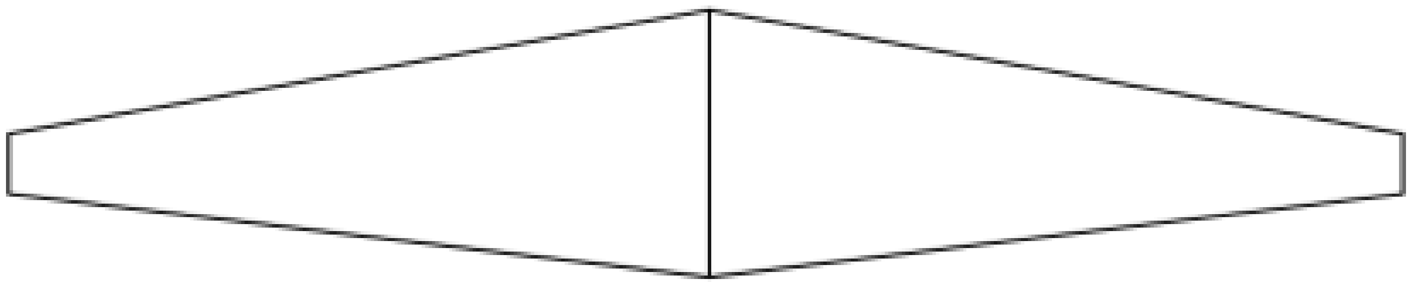
d. AR = 3.75



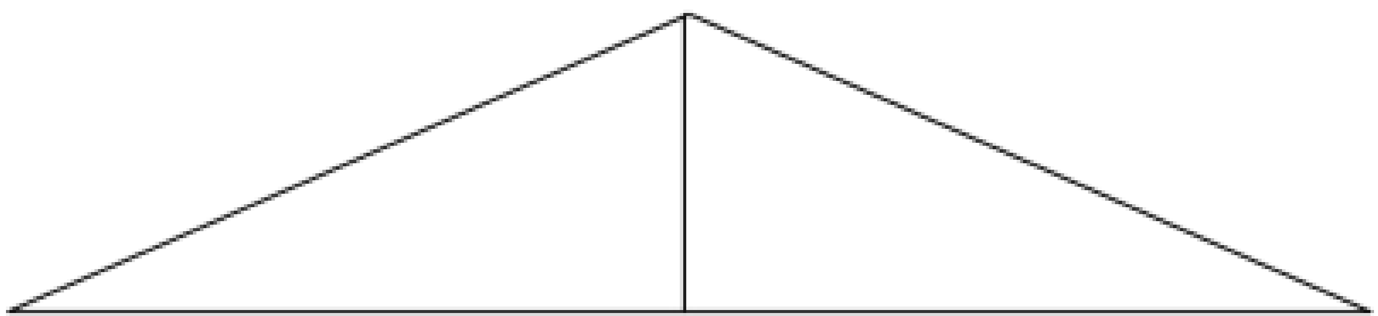
e. AR = 1



a. Rectangle (λ =1)



b. Trapezoid $0 < \lambda < 1$ (straight tapered)



c. Triangle (delta) $\lambda = 0$

Lift

- Lift is a force that is produced by the dynamic effect of the air acting on the airfoil, and acts perpendicular to the flight path through the center of lift (CL) and perpendicular to the lateral axis.
- In level flight, lift opposes the downward force of weight.
- As the AOA increases, lift increases (all other factors being equal).
- Lift depends on the density of the air, the square of the velocity, the air's viscosity and compressibility, the surface area over which the air flows, the shape of the body, and the body's inclination to the flow

Lift Formula

$$F_L = \frac{1}{2} \rho v^2 C_l A$$

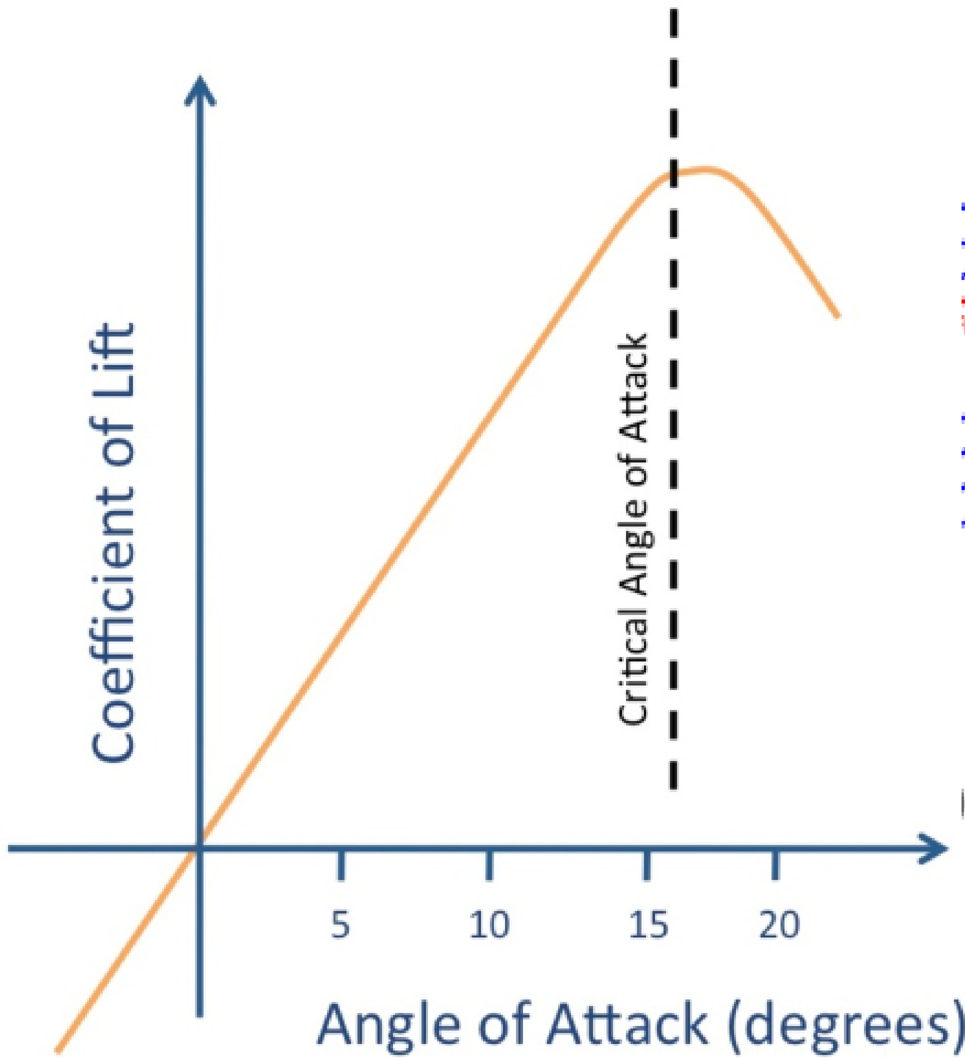
- F_L = Force of lift
- ρ = Density of air
- v = Velocity
- A = Total area of wings
- C_l = Coefficient of lift

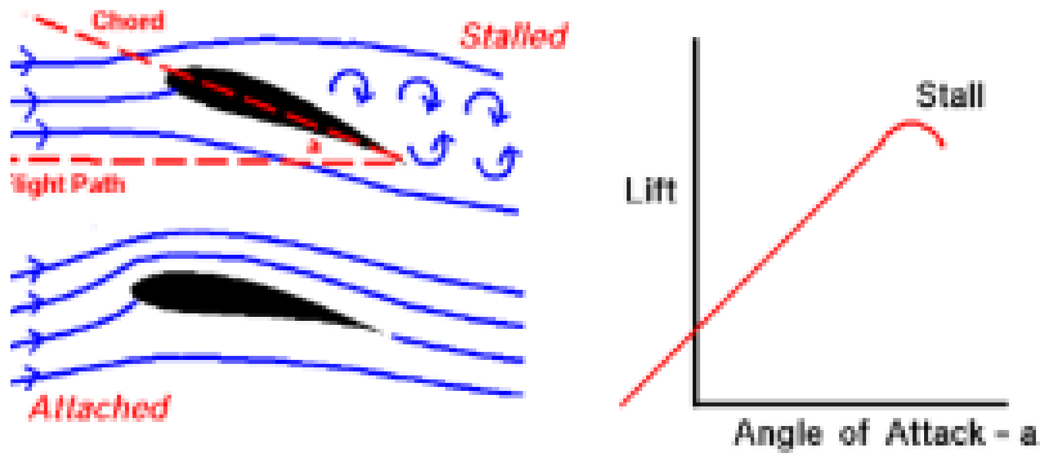
Lift coefficient

$$Cl = \frac{L}{\rho V^2 A / 2}$$

- The lift coefficient is a number that engineers use to model all of the complex dependencies of shape, inclination, and some flow conditions on lift.
- The lift coefficient then expresses the ratio of the lift force to the force produced by the dynamic pressure times the area.
- Engineers usually determine the value of the lift coefficient by using models in a wind tunnel. Within the tunnel we can set the velocity, density, and area of the model and measure the lift produced. Through division, we arrive at a value for the lift coefficient.

Cl vs AOA





For small angles, lift is related to angle.

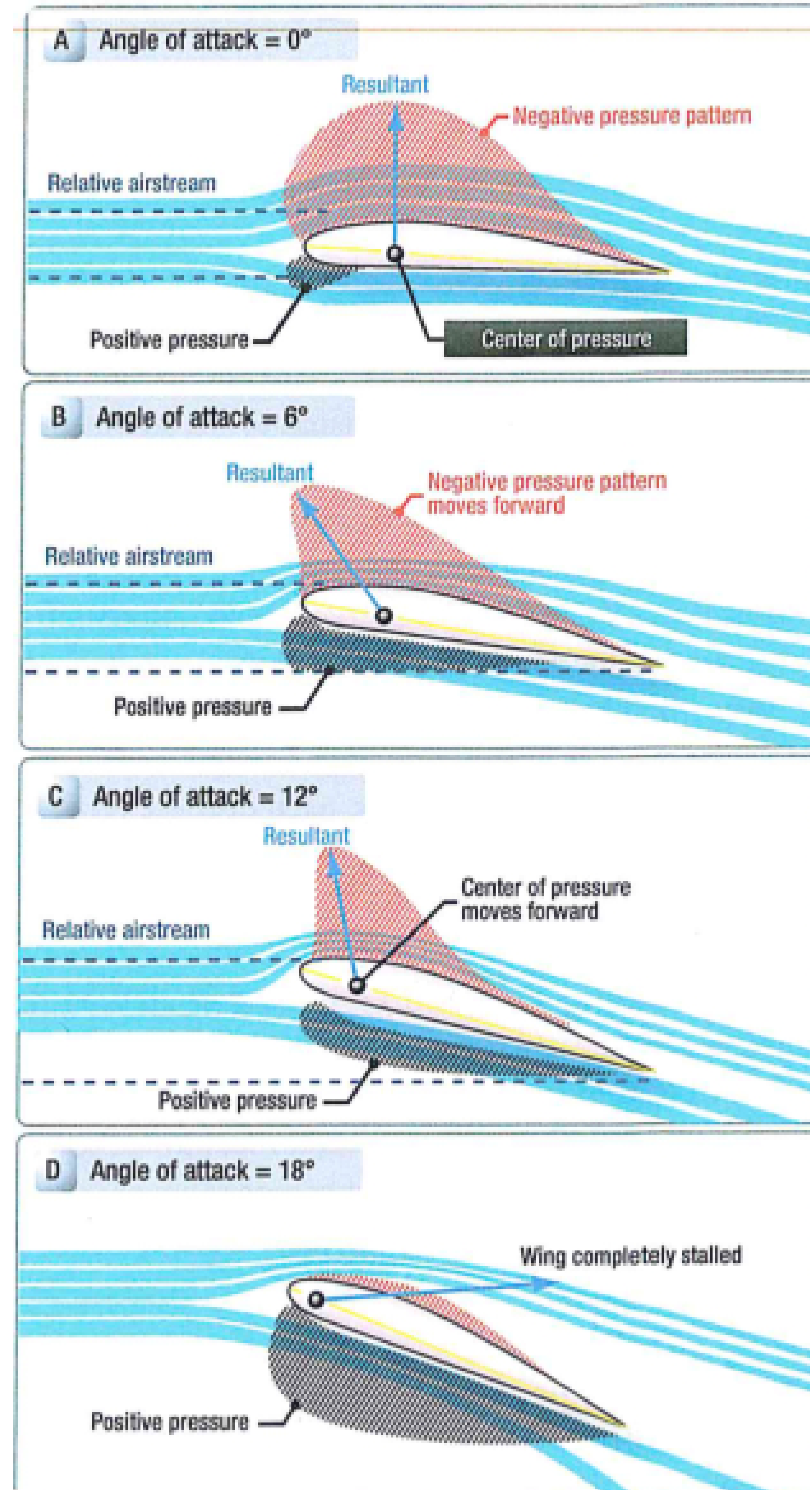
Greater Angle = Greater Lift

For larger angles, the lift relation is complex.

Included in Lift Coefficient

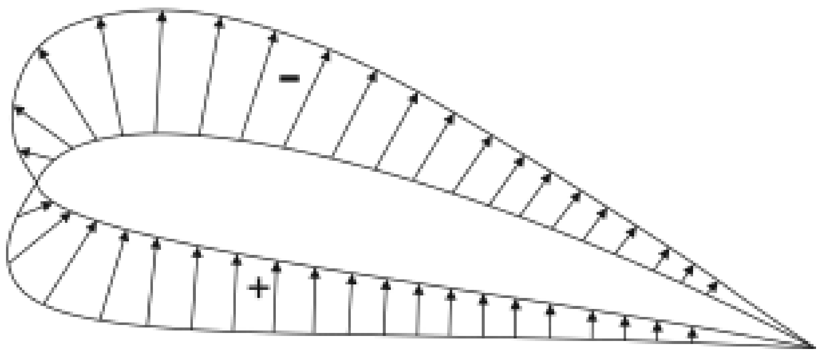
Stall

When the AOA is increased gradually toward a positive AOA, the lift component increases rapidly up to a certain point and then suddenly begins to drop off. During this action the drag component increases slowly at first, then rapidly as lift begins to drop off. When the AOA increases to the angle of maximum lift, the *burble point* is reached. This is known as the *critical angle*. When the critical angle is reached, the air ceases to flow smoothly over the top surface of the airfoil and begins to burble or eddy. This means that air breaks away from the upper camber line of the wing. What was formerly the area of decreased pressure is now filled by this burbling air. When this occurs, the amount of lift drops and drag becomes excessive. The force of gravity exerts itself, and the nose of the aircraft drops. This is a *stall*. Thus, the burble point is the stalling angle.

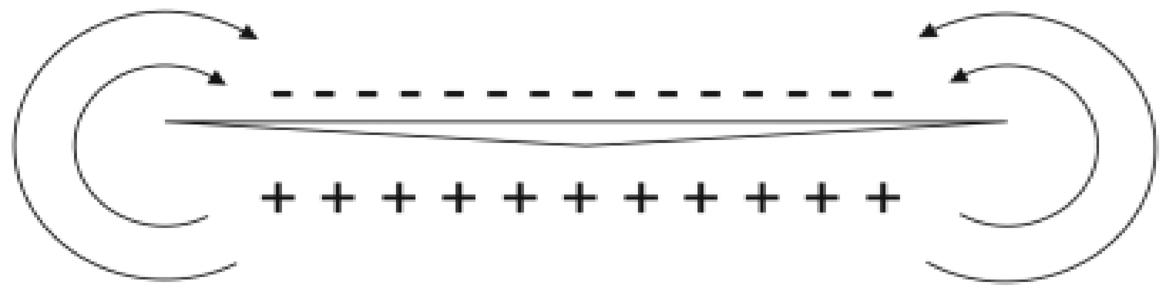


- Upwash means the upward movement of air just before the leading edge of the wing. A corresponding downwash occurs at the trailing edge

Pressure distribution over airfoil and wing



Over airfoil

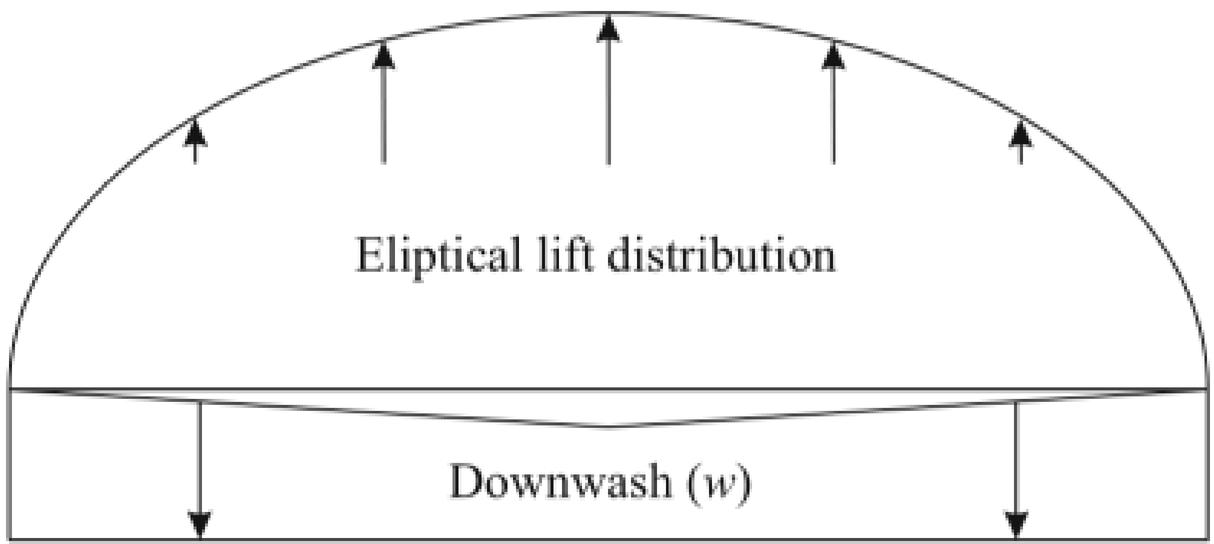


Spanwise

- It is apparent that a wing would have positive pressure on its underside and negative (in a relative sense) pressure on the top. This is shown in Figure as plus signs on the bottom and minus signs on the top as viewed from the front or leading edge of the wing.

Elliptical lift distribution

- An elliptic lift distribution causes the downwash across the span to be a constant. As a result the induced drag is a minimum when compared to a planar wing of equal span, total lift and velocity



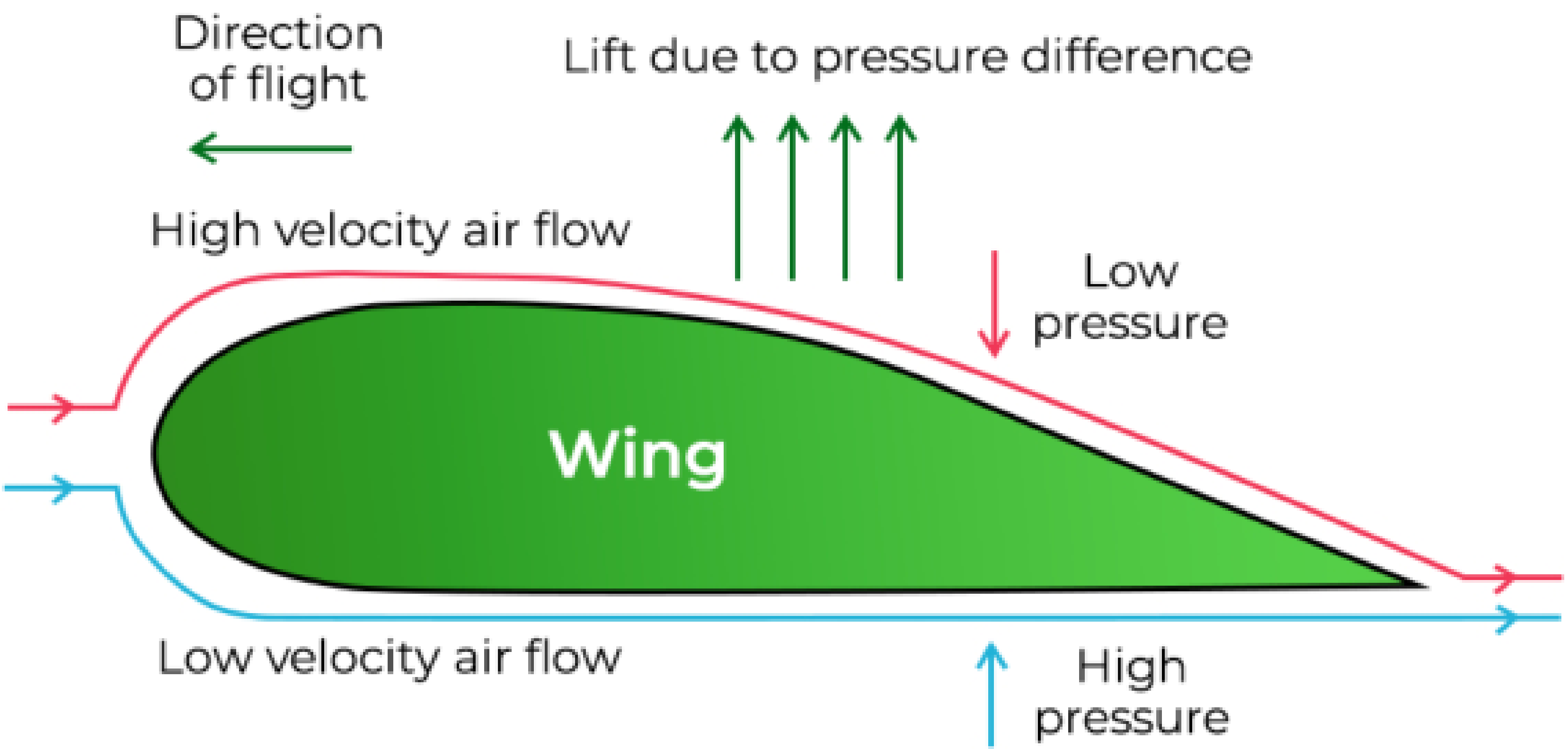
Mechanism of lift generation

Bernoulli's Principle

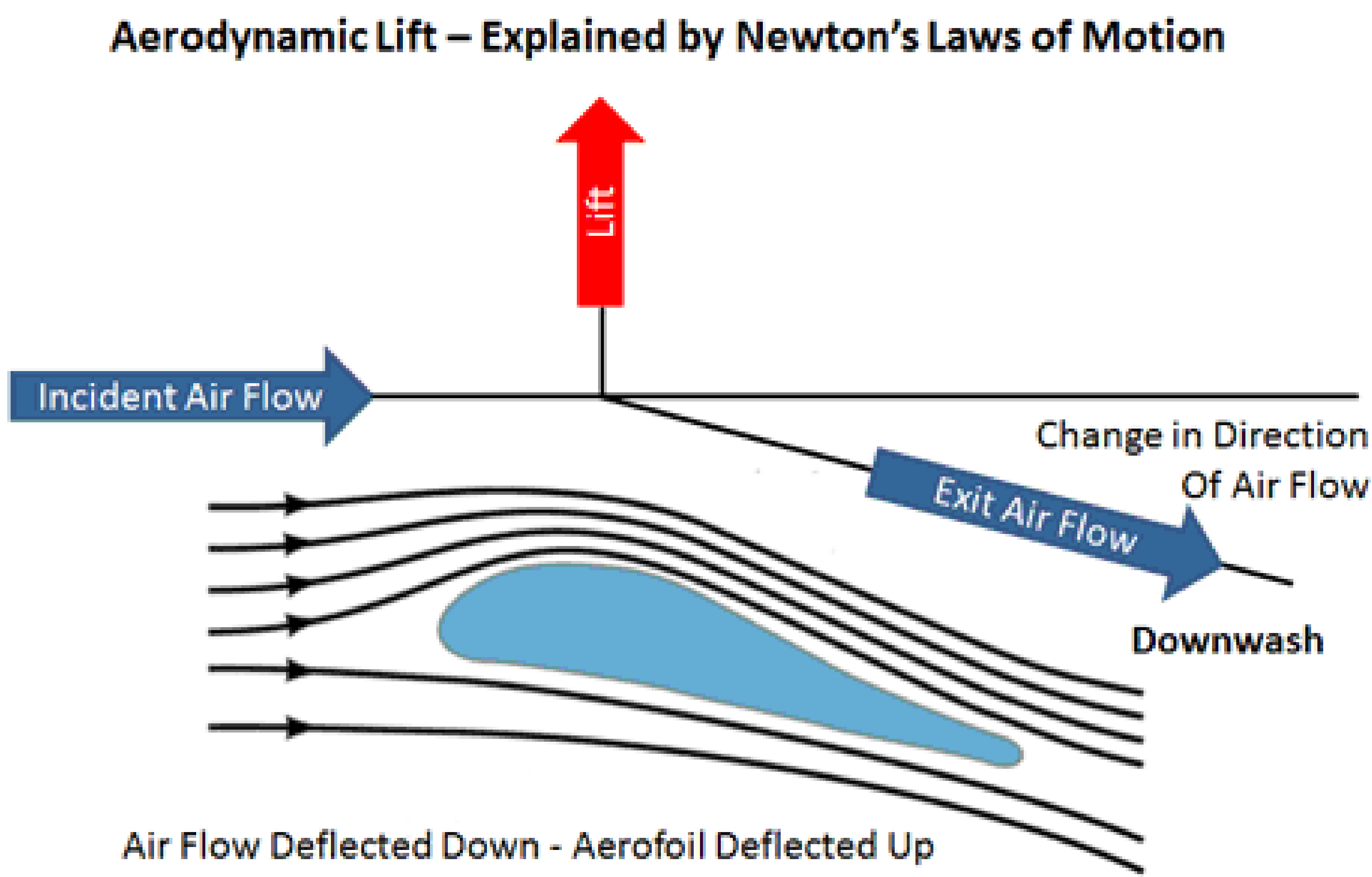
- Bernoulli's Principle provides the relationship between the pressure (P) and velocity of the fluid flowing.
- Bernoulli's Principle says that when a fluid is flowing horizontally, the points where the speed is higher exhibit low pressure, while the points where the speed is lower exhibit high pressure.
- Bernoulli's theorem governs the operation of airplanes. The plane's wings have a certain form. When the plane is moving, the air flows past it at a high rate, despite the plane's low surface wig. There is a variation in the flow of air above and below the wings due to Bernoulli's principle. As a result of the flow of air on the wing's up surface, this concept causes a change in pressure

Bernoulli's Principle Example

Lift of an Aircraft



Newton's principle



Lift occurs when a moving flow of air is turned by a solid object.
The flow is turned in one direction, and the lift is generated in the opposite direction, according to Newton's Third Law of action and reaction.
For an aircraft wing, both the upper and lower surfaces contribute to the flow turning or the downwash.

Drag

- Drag is the force that resists movement of an aircraft through the air.
- There are two basic types: parasite drag and induced drag.
- **Parasite Drag**:As the term parasite implies, it is the drag that is not associated with the production of lift. This includes the displacement of the air by the aircraft, turbulence generated in the airstream, or a hindrance of air moving over the surface of the aircraft and airfoil.
- There are three types of parasite drag: form drag, interference drag, and skin friction.
- **Form drag:**it is the portion of parasite drag generated by the aircraft due to its shape and airflow around it.
- **Interference Drag**:Interference drag comes from the intersection of airstreams that creates eddy currents, turbulence, or restricts smooth airflow.
- **Skin friction drag:** It is the aerodynamic resistance due to the contact of moving air with the surface of an aircraft

Induced drag: The second basic type of drag is induced drag.It is the drag caused due to generation of lift.

Wave drag: The drag caused due to formation of shock waves when an aircraft is travelling faster than the speed of sound.

Drag formula

$$F_D = \frac{1}{2} \rho v^2 C_D A$$

where

F_D is the **drag force**,

ρ is the density of the fluid,[11]

v is the speed of the object relative to the fluid,

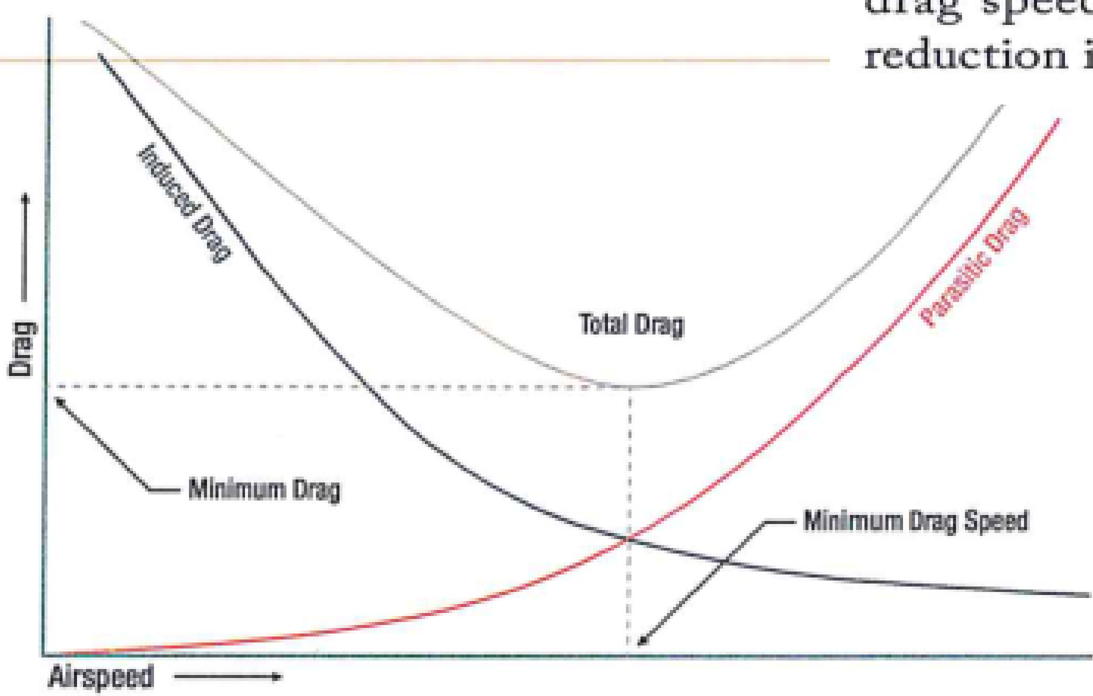
A is the cross sectional area, and

C_D is the drag coefficient – a dimensionless number.

Drag vs airspeed

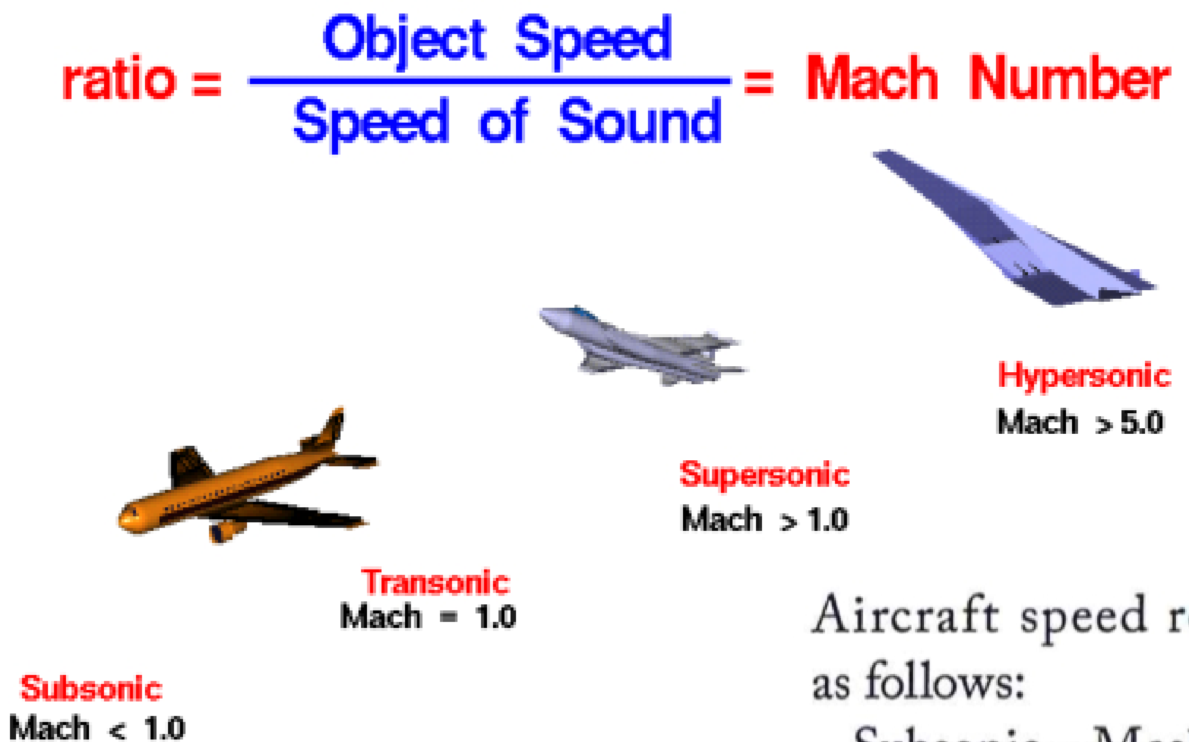
Parasitic Drag increases with the square of the airspeed, while induced drag, being a function of lift, is greatest when maximum lift is being developed, usually at low speeds. ***Figure 2–21*** shows the relationship of parasitic drag and induced drag to each other and to total drag.

There is an airspeed at which drag is minimum, and in theory, this is the maximum range speed. However, flight at this speed is unstable because a small decrease in speed results in an increase in drag, and a further fall in speed. In practice, for stable flight, maximum range is achieved at a speed a little above the minimum drag speed where a small speed decrease results in a reduction in drag.



Speed ranges

- Mach number:The ratio of the speed of the aircraft to the speed of sound



Aircraft speed regimes are defined approximately as follows:

Subsonic—Mach numbers below 0.75
Transonic—Mach numbers from 0.75 to 1.20
Supersonic—Mach numbers from 1.20 to 5.00
Hypersonic—Mach numbers above 5.00

Reynolds Number (Re)

- *Viscosity:* resistance of a liquid to change of form.
- *Inertia:* resistance of an object (body) to a change in its state of motion.
- These two forces together influences an organism's ability to move in water and how water flows.
- The ratio of inertial force to viscous force is Re of an object.

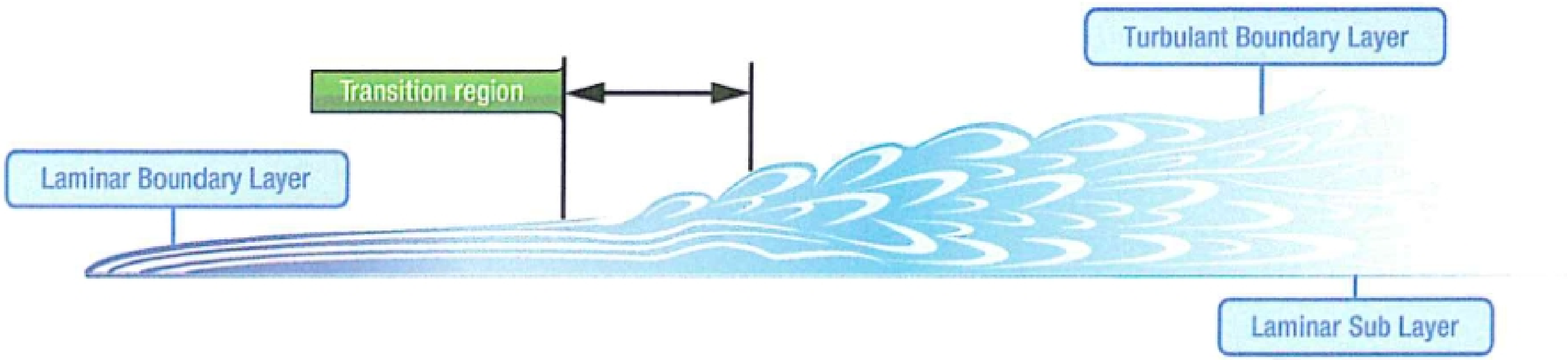
$$\frac{F_i}{F_v} = \frac{\rho S U^2}{\left(\frac{\mu S U}{l}\right)} = \frac{\rho\, U\, l}{\mu}$$

- U = velocity of object relative to the fluid; l = object length; S = surface area; μ = dynamic viscosity; p = object density

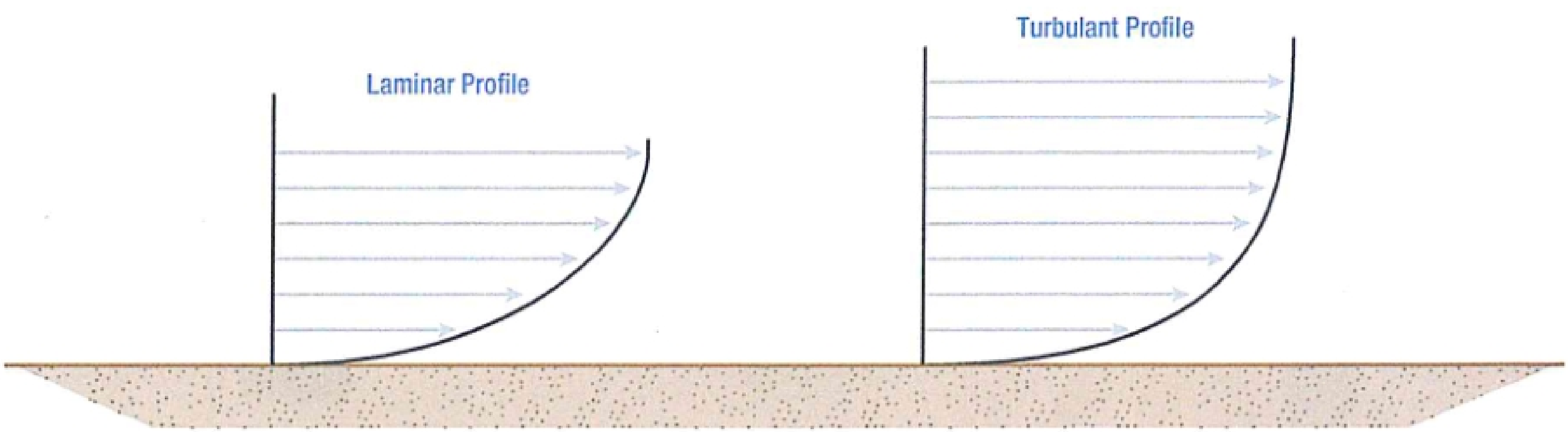
- The Reynolds number is an important indicator of whether the boundary layer is in a laminar or turbulent condition. Laminar flow creates considerably less drag than turbulent but nevertheless causes difficulties with small surfaces as we shall learn later. Typical Reynolds numbers are:

General Aviation Aircraft	5,000,000
Small UAVs	400,000
A Seagull	100,000
A Gliding Butterfly	7,000

BOUNDARY LAYER



Comparison of Velocity Profiles for Laminar and Turbulant Boundary Layers

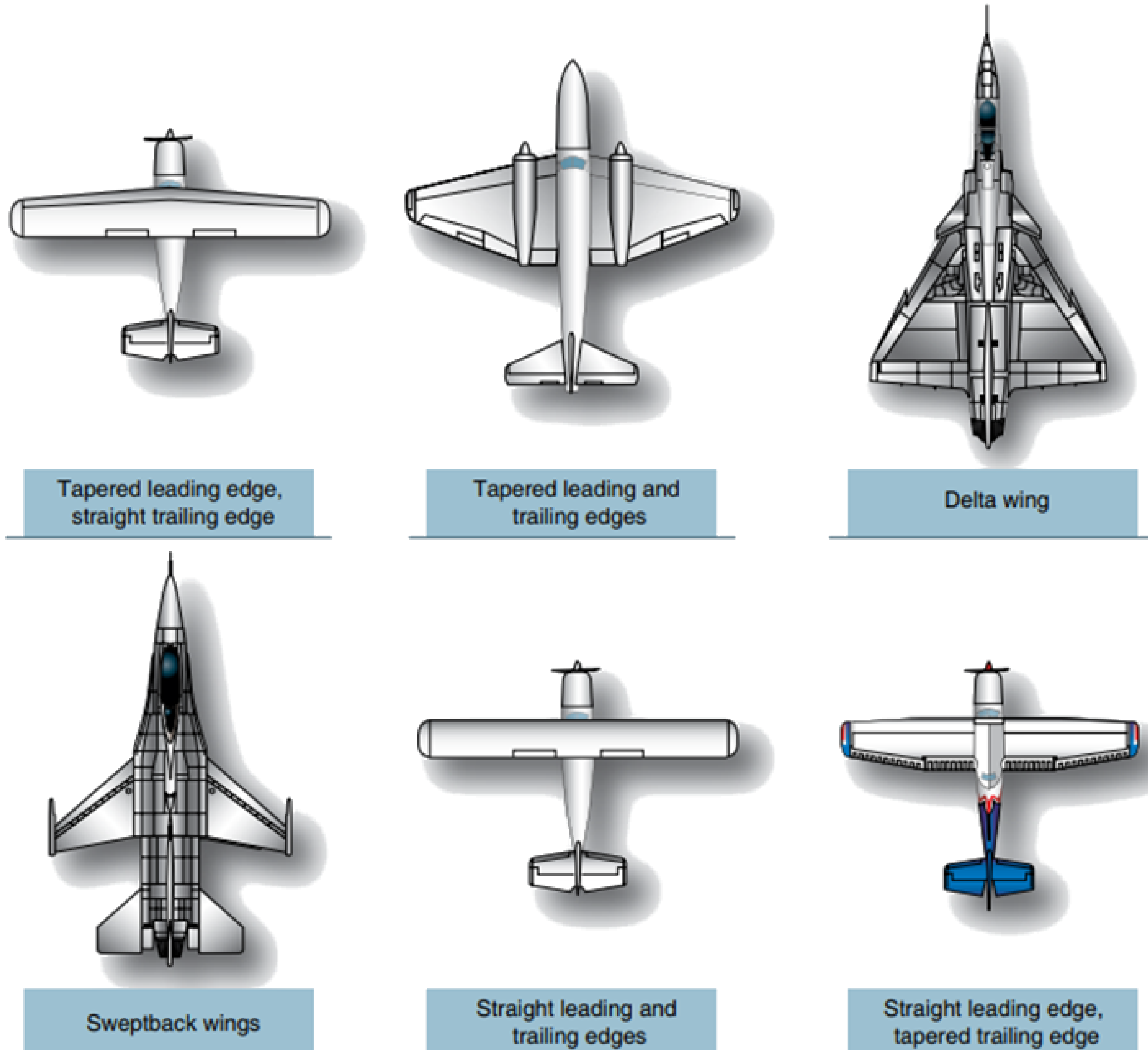


- Low Thickness
- Low Velocities Next to Surface
- Gradual Velocity Change
- Low Skin Friction

- GreaterThickness
- Higher Velocities Next to Surface
- SharpVelocity Change
- Higher Skin Friction

S.no	Laminar Flow	Turbulent Flow
1.	It is a fluid flow in which the fluid layers move parallel to each other and do not cross each other.	It is a fluid flow in which the fluid layers cross each other and do not move parallel to each other.
2.	The laminar flow generally occurs in the fluid flowing with low velocity.	The turbulent flow occurs when the fluid flows with high velocity.
3.	Laminar flow occurs in the small diameter pipes in which fluid flows with low velocity.	Turbulent flow occurs in large diameter pipes in which fluid flows with high velocity.
4.	The fluid flow is laminar when the value of Reynolds number (Re) is less than 2000.	The fluid flow is turbulent when the value of Reynolds number is greater than 4000.
5.	Shear stress in laminar flow depends only on the viscosity of the fluid and independent of the density.	Shear stress in the turbulent flow depends upon the density of the fluid.
6.	The fluid flow is very orderly i.e. there is no mixing of adjacent layers of the fluid and they move parallel to each other and also with the walls of the pipe.	The fluid flow is not orderly i.e. there is mixing of adjacent layers of fluid with each other and they do not move parallel to each other and also with the walls of the pipe.

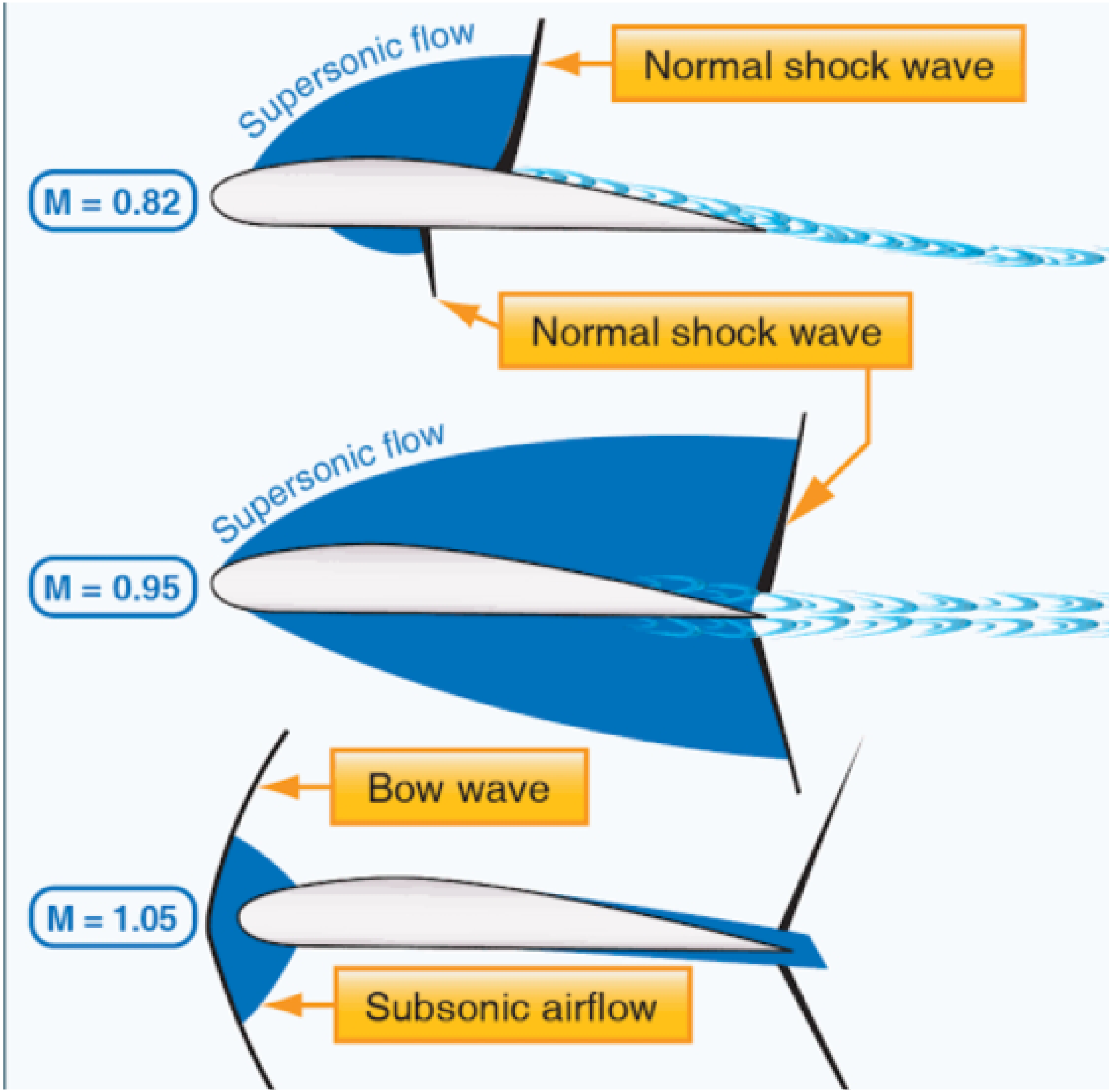
Wing planform shapes



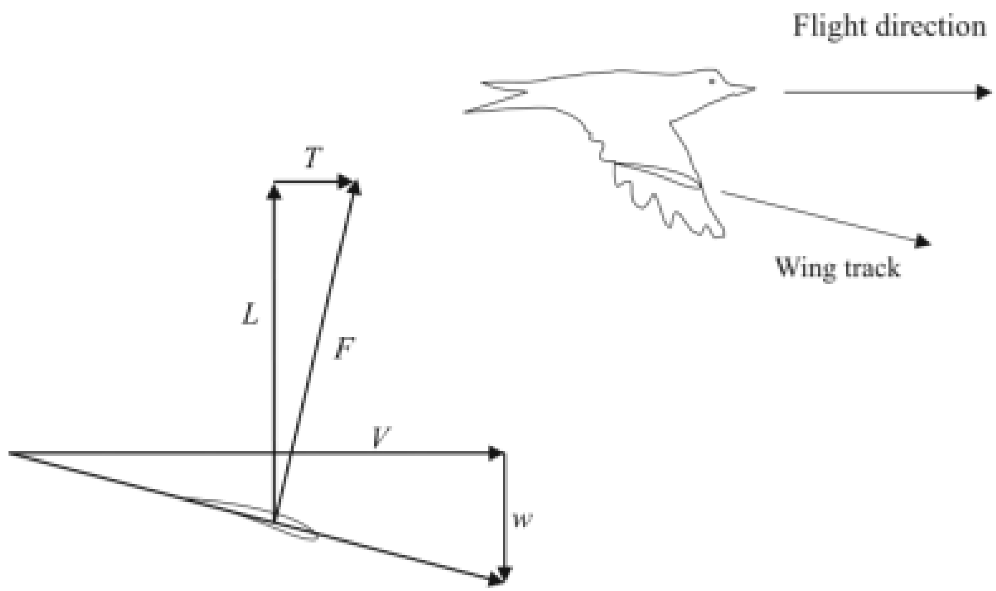
- **Rectangular Wing**: The rectangular wing is the simplest to manufacture. It is a non-tapered, straight wing that is mostly used in small aircrafts. This wing extends out from the aircraft's fuselage at right angles.One major disadvantage of a rectangular wing is that it isn't aerodynamically efficient.
- **Elliptical wing:** Elliptical wing is aerodynamically most efficient because elliptical spanwise lift distribution induces the lowest possible drag. However, the manufacturability of this aircraft wing is poor.
- **Tapered Wing:**The tapered wing was designed by modifying the rectangular wing. The chord of the wing is varied across the span for approximate elliptical lift distribution.While it isn't as efficient as the standard elliptical wing, it does offer a compromise between efficiency and manufacturability.
- **Delta Wing:**This low aspect ratio wing is used in supersonic aircrafts. The main advantage of a delta wing is that it is efficient in all regimes (supersonic, subsonic, and transonic). Moreover, this type of wing offers a large area for the shape thereby improving maneuverability and reducing wing loading.
- **Swept back wings:**Sweeping the wings makes the wing feel like it's flying slower. That, in turn, delays the onset of supersonic airflow over the wing - which delays wave drag.

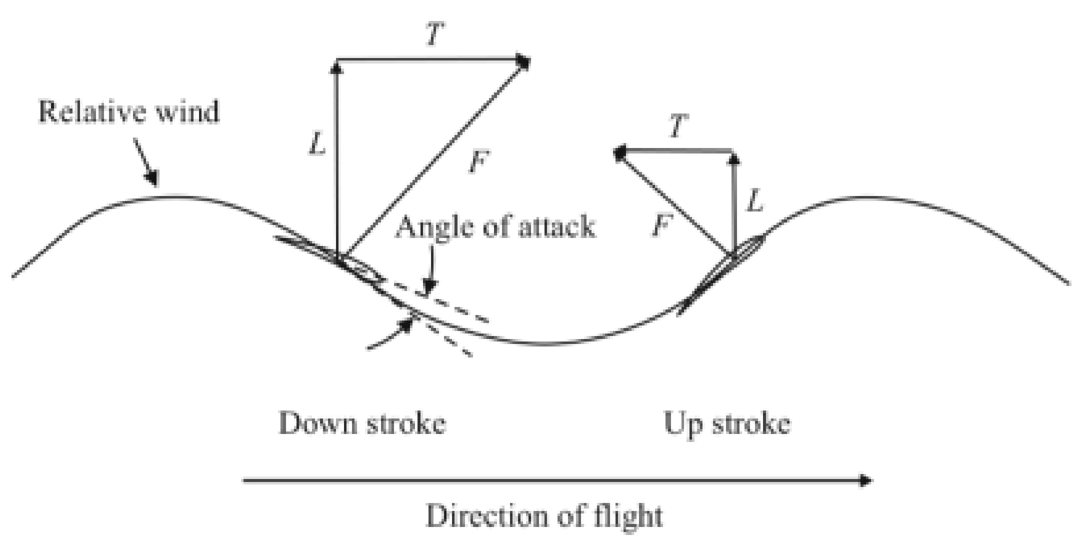
Shock Wave and critical mach number

- When an airplane travels less than the speed of sound, the air ahead of it actually begins to flow out of the way before the plane reaches it. The pressure waves created by the airplane passing through the air end up being smooth and gradual.
- But as an airplane reaches the speed of sound and catches up to its own pressure waves, the air ahead of it receives no warning of the plane's approach. The airplane plows through the air, creating a shock wave. As air flows through the shock wave, its pressure, density, and temperature all increase—sharply and abruptly.
- **Critical Mach number**: The critical Mach number (Mcr or M*) of an aircraft is the lowest Mach number at which the airflow over some point of the aircraft reaches the speed of sound, but does not exceed it.


Supersonic flow
Normal shock wave
M = 0.82
Normal shock wave
Supersonic flow
M = 0.95
Bow wave
M = 1.05
Subsonic airflow

Flapping Wings





- The flapping of the wings of birds is not a pure up and down or rowing backstroke as commonly thought. The wings of a flying bird move up and down as they are
- flapped, but they also move forward due to the bird's velocity through the air mass. Figure shows the resulting velocity and force triangles when the wing is moving downward. The net velocity of the wing through the air mass is the sum of the forward velocity of the bird's body (V) and the downward velocity of the wing, driven by the muscles of the bird (w), which varies over the length of the wing, being greatest at the wing tip. The resulting total velocity through the air mass is forward and down, which means that the relative wind over the wing is to the rear and up.
- The net aerodynamic force generated by that relative wind (F) is perpendicular to the relative wind and can be resolved into two components, lift (L) upward and thrust (T) forward.
- It is also possible for the bird to introduce a variable twist in the wing over its length, which could maintain the same angle of attack as w increases and the relative wind becomes tilted more upward near the tip. This twist can also be used to create an optimum angle of attack that varies over the length of the wing. This can be used to increase the thrust available from the wing tip.
- The bird can make the negative thrust during the up stroke even smaller by bending its wings during the up stroke.This largely eliminates the forces induced by the outer portions of the wings, which are the most important contributors to thrust, while preserving much of the lift produced near the wing roots