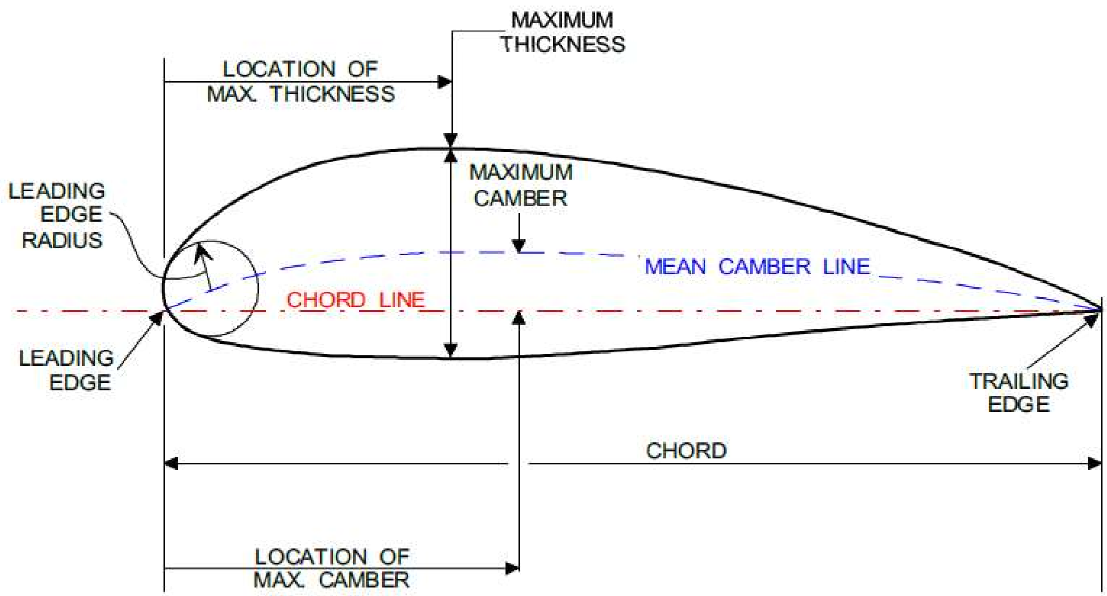
III. LIFT

1) Aerofoil & Definitions

Aerofoil: Surface that creates more LIFT than DRAG at a low Angle of Attack



Chordline: Straight line between the furthest points of the leading edge (LE) and the trailing edge (TE)

Chord: Distance of the chordline

Mean Camber Line: Line between the furthest points of the LE and the TE, equidistant of the upper surface and the lower surface, connecting all the aerofoil radius.

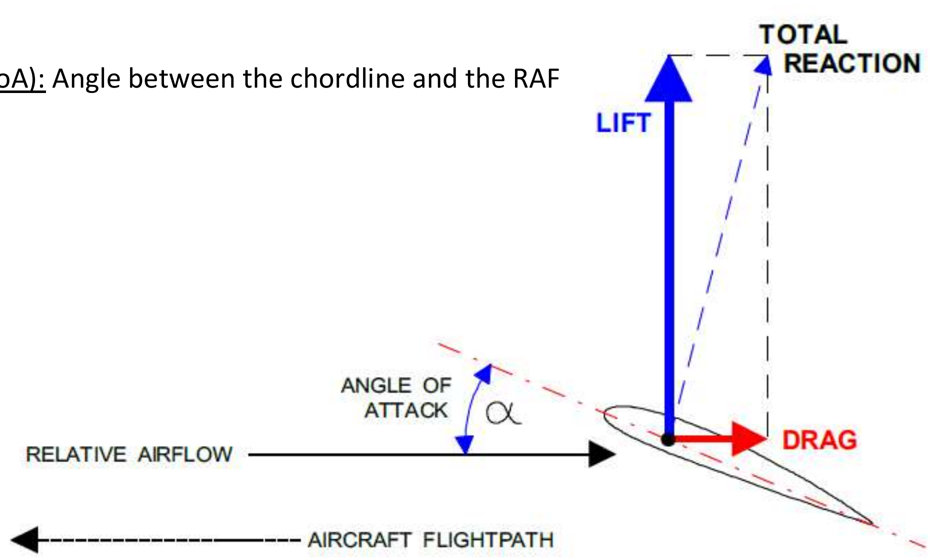
Maximum Camber: Largest distance between the Mean Camber Line and the Chordline

Maximum Thickness: Largest aerofoil radius

Relative Airflow (RAF): Relative wind opposite to the movement and parallel to the direction of travel

Angle of Incidence: Angle between the chordline and the longitudinal axis of the aircraft (horizontal plan)

Angle of Attack (AoA): Angle between the chordline and the RAF

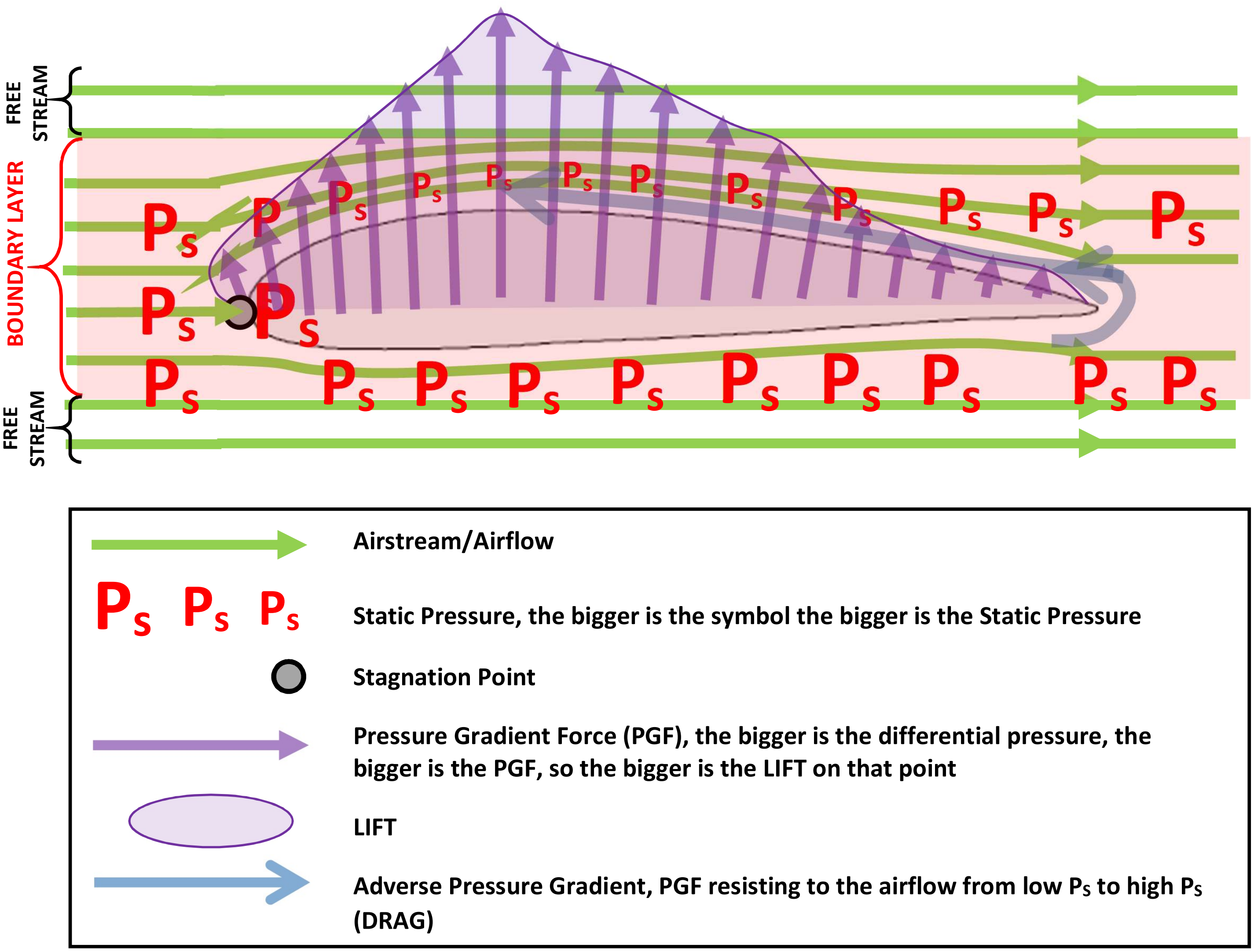


2) Boundary Layer – 2D airflow

<u>Boundary Layer</u>: Thin layer of air around the aerofoil, the layer affected by the aerofoil into the airstream.

Notice the airflow is deviating to flow around the aerofoil, however further away from the aerofoil, the airflow is flowing straight and no disturbed by the aerofoil, this part is called the **free stream** and the beginnings if the free stream mark the **boundary layer limits**.

On the drawing, the boundary layer looks think, but this is an exaggeration so the details could be studies, in real the boundary layer is very thin and studied at the microscopic scale.



<u>Flow motion</u>

When the airflow arrives at the aerofoil at the leading edge, it will be accelerated upward because of the area is reducing, this upward motion is called **UPWASH**. Then when it leaves the aerofoil at the trailing edge it will decelerate downward due to the increasing area, this downward motion is called **DOWNWASH**. The airflow that hits the front of the aerofoil will be stopped due to the net obstruction and its velocity (V) will drop to zero. This point is called the **STAGNATION POINT**. At the stagnation point, V=0

Pressure distribution

At the stagnation point, since the dynamic pressure is dropped to zero, the static pressure at the point will increase and reach its maximum value (total pressure).

Above the aerofoil the airflow will accelerate and so its static pressure will also drop, the more the area is being reduced, the more it will accelerate and the more the static pressure will drop. The static pressure will reach its minimum value when the area is the smallest and then, when the area starts to increase again, the airflow will decelerate and the static pressure will increase again until it reaches the ambient static pressure when the airflow leaves the aerofoil.

Below the aerofoil, the airflow velocity is not significantly change since the area is not significantly modified, the static pressure will remain almost the same as the outside static pressure and so relatively high compared to the static pressure above the aerofoil.

Pressure Gradient Force (PGF) / Lift Force

Remember, the PGF is the force that will tend to equalize the static pressure by moving the airflow from a high static pressure area to low static pressure area, and the magnitude of the PGF will be stronger when the differential pressure is higher.

Since the static pressure lower on the upper surface of the aerofoil than the lower surface, the PGF will exist and will be acting through the aerofoil from the lower surface to the upper surface. Obviously there won't be any upward motion of air since the aerofoil is acting as a physical barrier. The PGF will only **LIFT** up the aerofoil and so now, since this force will **LIFT** the aerofoil, we call this force the **LIFT**, and it's this force that will act against the aircraft's WEIGHT in flight.

Since the differential pressure is not the same along the aerofoil, the LIFT will be stronger when the differential pressure is higher (maximum thickness). Actually the entire aerofoil section is generating LIFT but at different magnitude across different points.

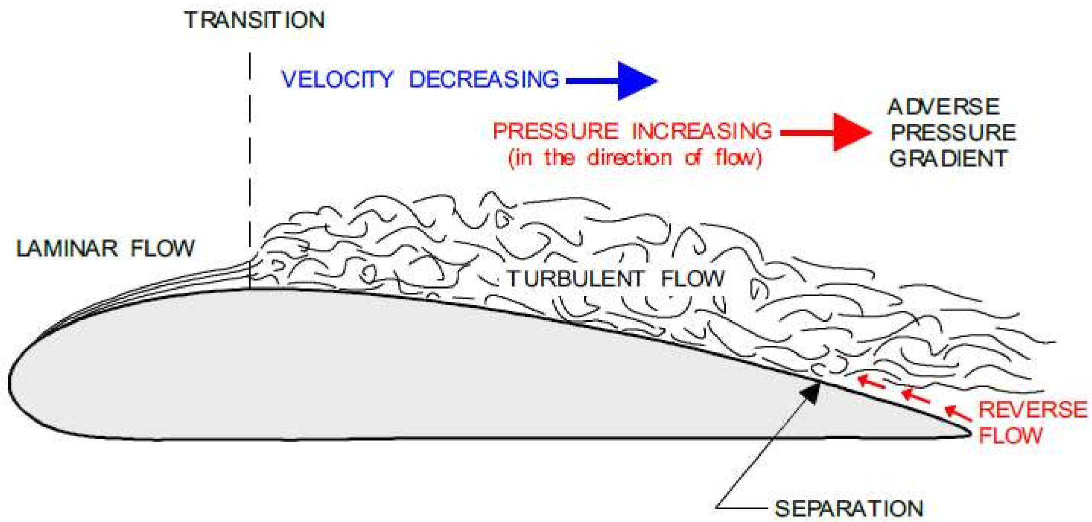
Adverse Pressure Gradient

On the upper surface from the leading edge to the trailing edge, the area will decrease then increase again, so the airflow flows from a high pressure to low pressure when the area decreases, but then it flows from low pressure to high pressure when the area increases, this phenomena is called **Adverse Pressure Gradient**.

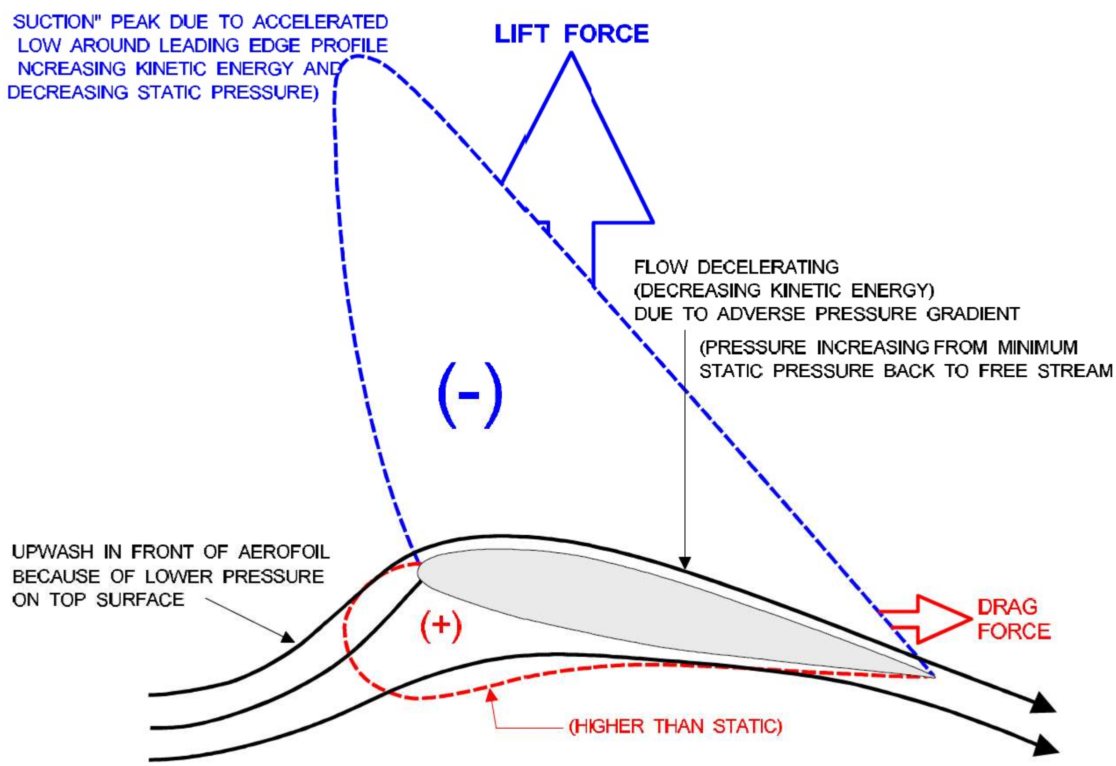
A differential pressure is felt from the trailing edge to the area above the aerofoil where the pressure is lower, and there the PGF will act in the opposite direction of the airflow and will resist to it. The PGF will actually start to act and resist from the trailing edge lower surface where the static pressure is higher than the lower surface. This resistance to the airflow is known as **DRAG** and it will be covered later.

This resistance will make the airflow to lose its kinetic energy (dynamic pressure) and so **the static pressure will increase**, which will reduce the differential pressure between the lower and upper surface on those points where the resistance is felt, and the LIFT is reduced for those points.

The airflow's properties will also be affected. From the leading edge to the trailing edge, when the airflow travels from high pressure (leading edge) to low pressure, the motion is normal and the airflow will be **laminar**, and attached the aerofoil surface. Then, when it flows from low pressure to high pressure (trailing edge), the resistance will make it loose its kinetic energy and so the airflow won't be able to remain laminar and becomes **turbulent**. The point where the static pressure starts to rise and where the resistance starts to be felt is called the **transition point**. After at a given point, the kinetic energy of the airflow is so reduced that is won't be able to remain attached to the aerofoil and will separate from it, at point called **separation point**.

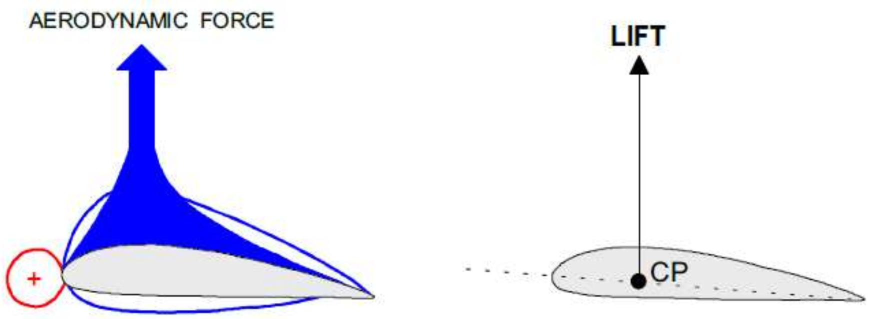


Now we know the pressure distribution around the aerofoil and the LIFT magnitude at different point. When the airflow is turbulent the LIFT is significantly reduced.



LIFT (L): Upward force perpendicular to the RAF generated by an aerofoil due to differential pressure. In flight, LIFT acts against the WEIGHT.

When the LIFT force is represented, it is drawn at the Centre of Pressure (CP)



Centre of Pressure (CP): Point where the TOTAL LIFT is acting. Since many LIFTs are generated at different points of the aerofoil and at different magnitudes, the result will be the same if the total LIFT is applied through point. In other words, it's the point where the LIFT is focused or the point of equilibrium of the TOTAL LIFT, and it depends on pressure distribution along the aerofoil.

Increasing the Angle of Attack (AoA)

- **Coefficient of Lift (C_L)**

When the AoA in increased, on one hand the cross section area above the aerofoil is further reduced which accelerate more the airflow and lower more the static pressure, and on the other hand the cross section area below the aerofoil is increased which increase the static pressure. So now the differential pressure is even higher and the aerofoil has a higher capability to create LIFT.

This LIFT capability is represented by a number (index) called the **Coefficient of Lift (C_L)**. So when the AoA increases, C_L increases. When the AoA is decreased, the opposite is true. (see graph below)

- **Stagnation Point**

When the AoA in increased by a rotation (pitch) of the aerofoil, the airflow will be obstructed at the point behind the leading edge and on the lower surface. So the stagnation point will move afterward on the lower surface. When the AoA is decreased, the opposite is true.

- **Transition Point and Separation Point**

When the AoA in increased, the cross section area is further reduced above the aerofoil and toward the leading edge, and then will increase more sudden toward the trailing edge. This means that the static pressure is initially more reduced, but then increase more sudden. This means, when the cross section area increases, the differential pressure will be higher and the Adverse Pressure Gradient will be stronger, therefore there will be more resistance to the airflow, which will be become turbulent earlier and so separate earlier.

When the AoA is increased, the transition point and the separation point will move forward (or occur earlier). When the AoA is decreased, the opposite is true.

- **Centre of Pressure (CP)**

When the AoA is increased, since the airflow will become turbulent earlier and separate earlier because of the stronger Adverse Pressure Gradient, so there will more points toward the trailing edge generating less or zero LIFT. So the majority of the LIFT will be concentrated toward the leading edge, which means that the CP will be more forward.

When the AoA is increased, the CP moves forward. When the AoA is decreased, the opposite is true.

<u>Increasing further the Angle of Attack (AoA)</u>

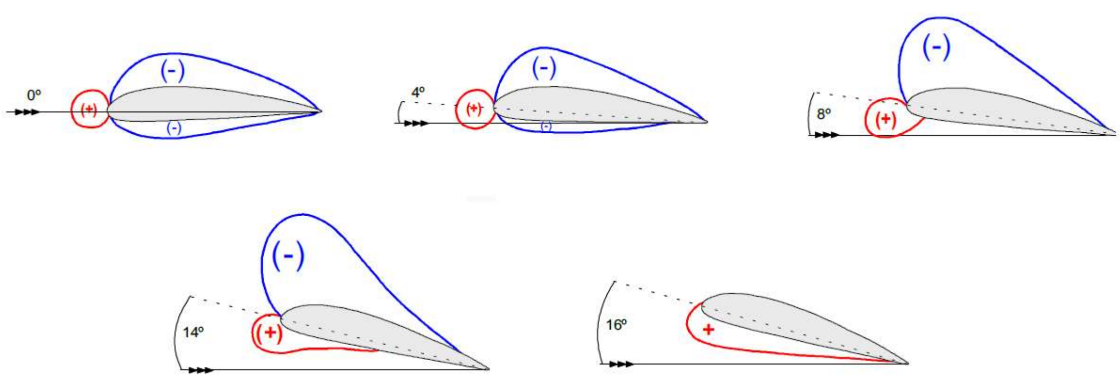
When the AoA is further increase, the three points (transition point, the separation point and the CP) move further forward and the C_L increases more for the reasons explained.

However at the given AoA, the three point will be extremely close the each other, the airflow will be turbulent and separate just after passing the CP. Increasing further the AoA (≈16°) will make the airflow totally turbulent and separated from the aerofoil. The LIFT will be decrease everywhere along the aerofoil and now the aerofoil will generate less LIFT, means that the Coefficient of Lift (C_L) decreases.

So, continuously increasing the AoA, C_L will first increase but then exceeding a given AoA it will decrease. That AoA is called the **Critical Angle of Attack (AoA_{CRIT})**, and at the AoA_{CRIT}, C_L reaches its maximum value known as the **Maximum Coefficient of Lift (C_{Lmax})**.

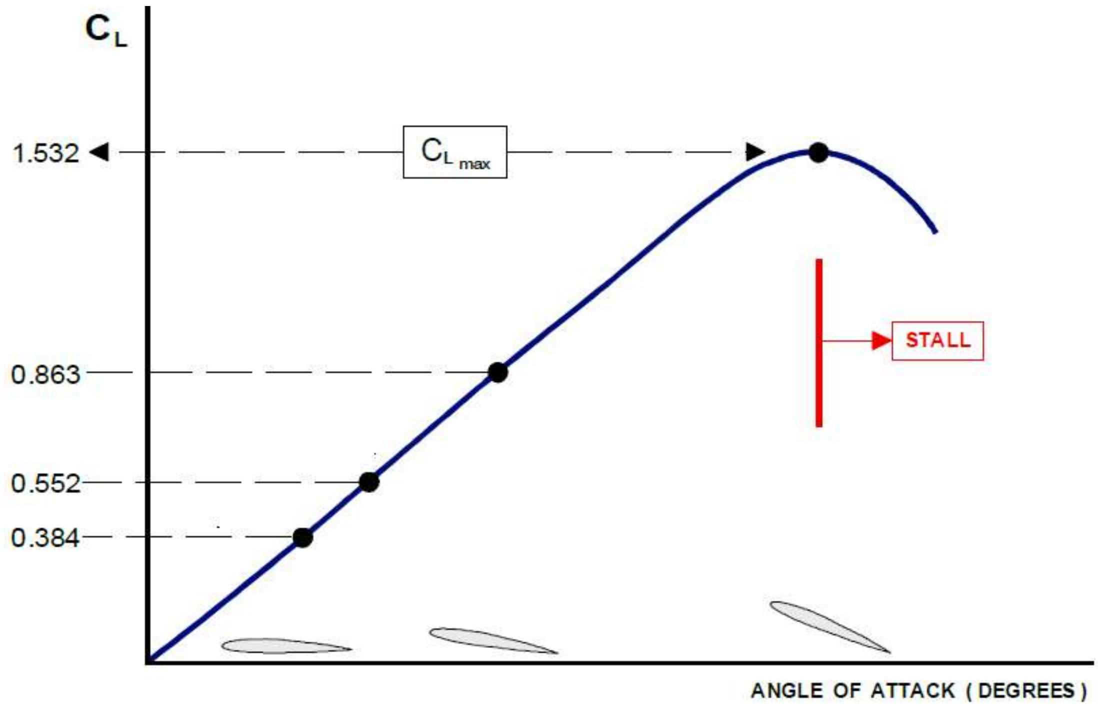
When C_L decreases when exceeding the AoA_{CRIT}, this phenomena is called STALL (which will be covered later), because the LIFT decreases and the aerofoil literally starts to stall (fall).

Concerning the CP, the majority of the LIFT is generated toward the leading edge and the CP moved forward when the AoA increased. However, when exceeding AoA_{CRIT}, the LIFT will decrease everywhere, so no more LIFT is focused near the leading edge and so the CP will move afterward.



Lift Curve

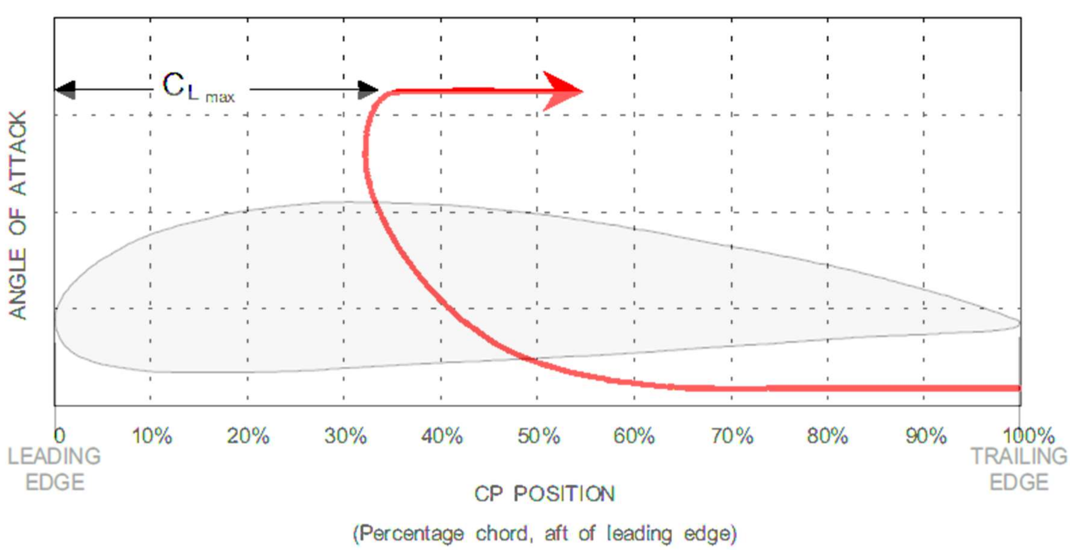
It has been seen that the C_L increases with increasing the AoA, until the AoA_{CRIT} where C_L reaches its maximum value C_{Lmax}, and exceeding the AoA_{CRIT} will result in a decrease of C_L



Typical Lift Curve

Centre of Pressure movement

It has been seen that the CP pressure moves forward when the AoA in increased because the LIFT will be mostly focused toward the leading edge, however when exceeding the AoA_{CRIT}, there will be less LIFT focused toward the leading edge and so the CP will move afterward.

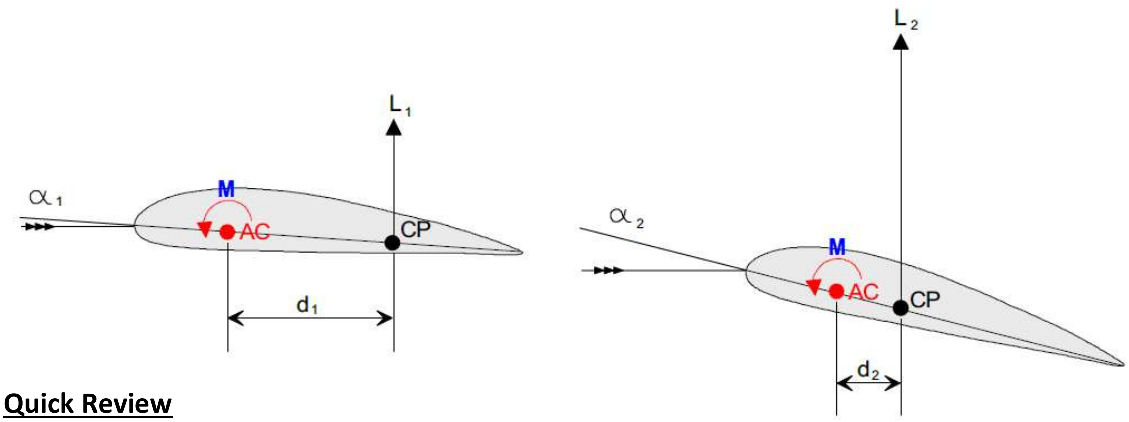


Aerodynamic Centre (AC): This is the point where the pitching moment of the aerofoil remains constant.

A rotation is caused by a rotational force called MOMENT, the MOMENT is the product of the amount of force applied and the arm (distance from the point of rotation) where the force is applied.

As the AoA increase, the CP moves forward and so the arm decreases, resulting in the same rotation pitch. From that point where the arm is measured, this how the AC is defined.

AC is found at 25% of the aerofoil chordline (length measured from the leading edge to the trailing edge) usually in front of the CP in subsonic incompressible airflow (M<0,4)



Quick Review

- ➢ **Increasing/decreasing the AoA to/from the AoA$_{CRIT}$:**

- C_L increases/decrease until reaching CL_{MAX} at the AoA$_{CRIT}$
- Stagnation Point moved below the lower surface to the rear/forward to the leading edge
- Transition point and separation point move forward/afterward
- CP move forward/afterward

- ➢ **Increasing AoA beyond the AoA$_{CRIT}$:**

- C_L decreases
- Stagnation Point moved below the lower surface to the rear
- CP move afterward

3) Lift Equation

$$L = ½\rho V^2 .\ S.\ C_L$$

$½\rho V^2$: The Dynamic Pressure (often written **Q**), it is simply the kinetic energy of the air, the Q depends on the airspeed and on the density (ρ). When the density is higher, the amount of molecules will be higher and so the airflow will have a higher kinetic energy or Q, so the differential pressure will be higher. As well, when the airspeed increase, the static pressure will be more reduced above the aerofoil and the differential pressure will be higher.

S: The wings area. On the drawing, the LIFT has been described only at the aerofoil, which is one section of the wing. Remember the wing is an infinite number of aerofoil (wingspan) and also the LIFT is generated from different points along the aerofoil (chord). The wing area is simply **S=wingspan x chord**. The wider is the wing area and the higher is the LIFT.

C_L: The Coefficient of Lift. The Coefficient of Lift depends on the AoA only (in an airflow <M0,4) and of the type of aerofoil (covered later). The higher the AoA, the higher is the C_L and higher the LIFT, however the C_L is limited, C_L is reached when the AoA_{CRIT} is attained.

<u>If the speed is double, V → 2V</u>

$$L = ½\rho V^2\ S\ C_L \rightarrow ½\rho(2V)^2\ S\ C_L$$

$$½\rho(2V)^2\ S\ C_L = ½\rho\ 4\ (V)^2\ S\ C_L$$

When V is doubled, L increase 4 times, therefore to maintain a constant lift, one parameter has to be 4 times less

$$4L = ½\rho\ 4\ (V)^2\ S\ C_L \rightarrow L = ½\rho\ 4\ (V)^2\ S\ ¼C_L$$

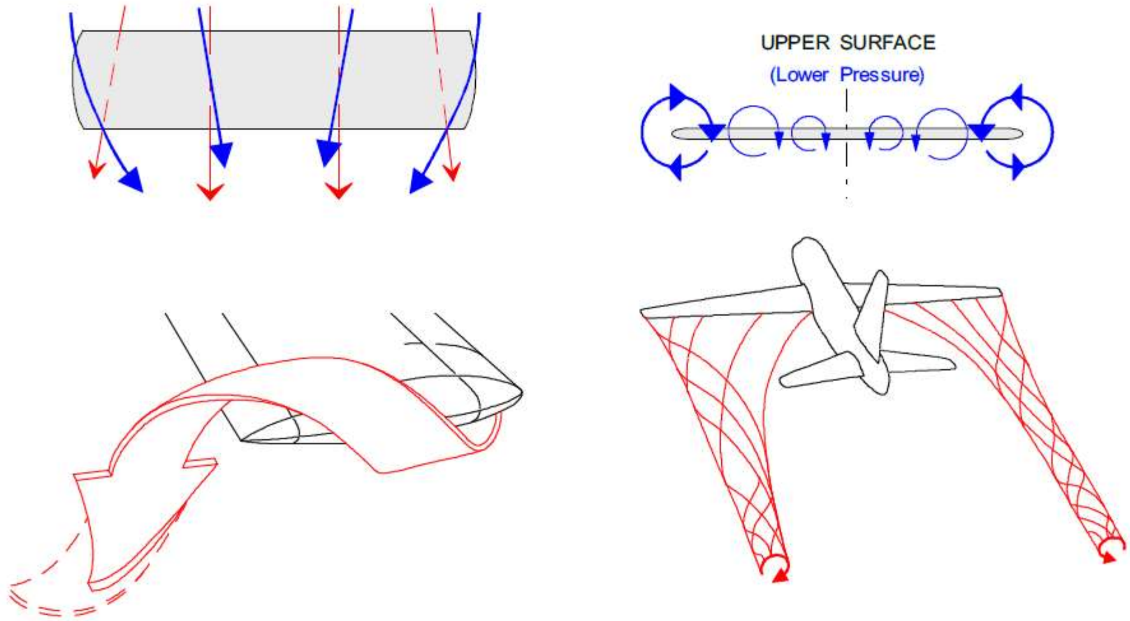
So, if the speed is doubled, AoA has to be decreased in order to have C_L 4 times less. The opposite is also true, if the speed is halved, C_L must be 4 times greater to maintain the same amount of LIFT.

To maintain the same LIFT, C_L is inversely proportional by the square of the speed change factor

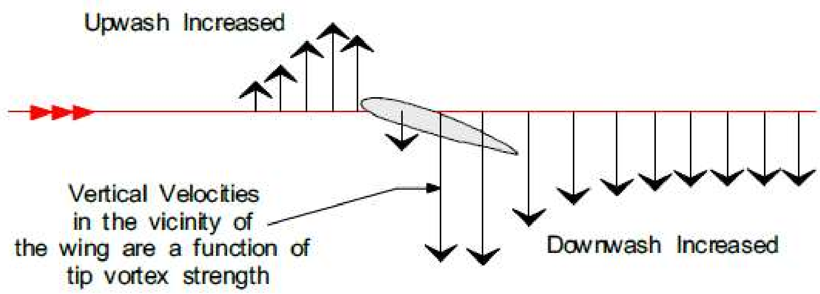
Therefore, at higher speed, AoA is reduced, and at a slower speed, AoA is increased, however when the AoA_{CRIT} is reached, a further reduction of the speed couldn't not be compensated by increasing the AoA, because when exceeding the AoA_{CRIT}, the aircraft will stall, that speed is called the **Stall Speed (V_S)** (covered more in details later)**.** The aircraft cannot fly below V_S.

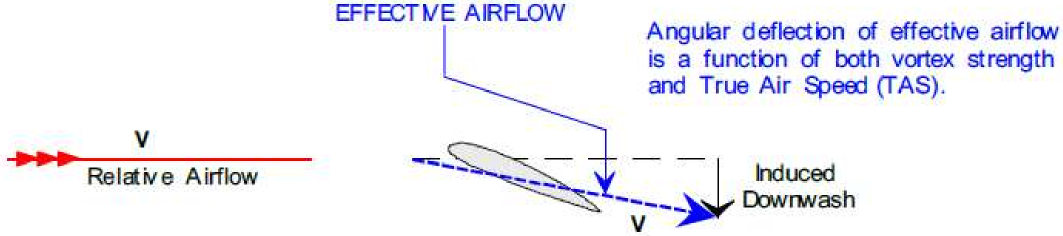
4) Boundary Layer – 3D airflow

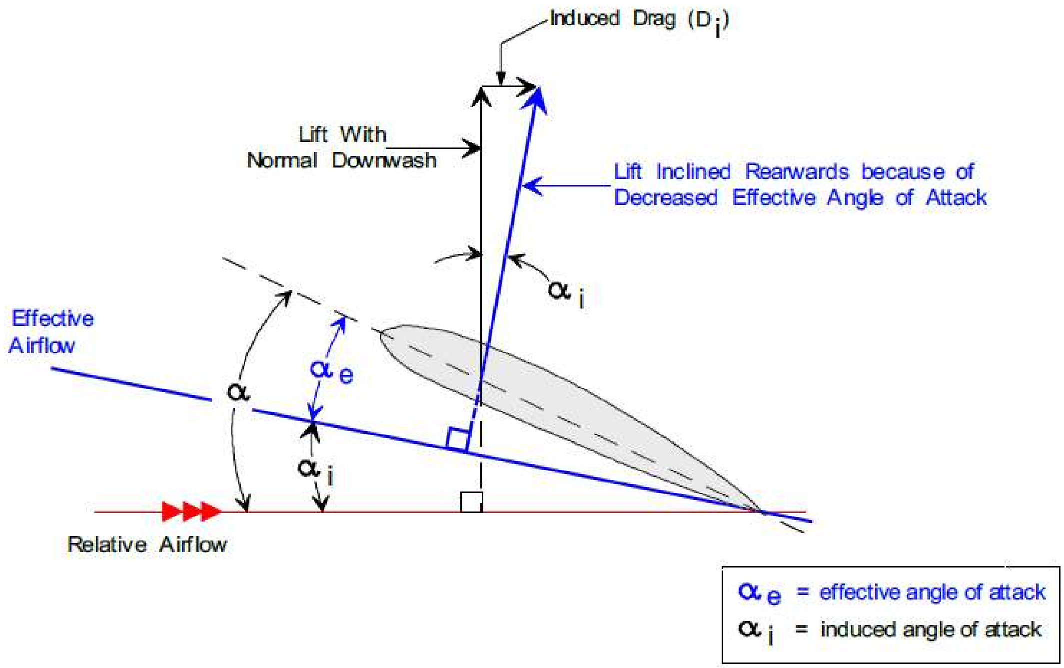
Due to differential pressure between the lower surface and the upper, a spanwise flow will exist flowing from the wing root toward the wing tip on the lower surface, rotate around the wing tip to continue toward the wing root on the upper surface.



The rotation around the wing tip will generate a vortex that will amplify/increase the upwash and the downwash, causing the effective airflow to deviate upward, leading to decrease in the effective AoA (AoA_{EFF}) and increase in the induced AoA (AoA_i), resulting in a decrease of the LIFT, and an increase of a rearward force known as Induced Drag (D_i)



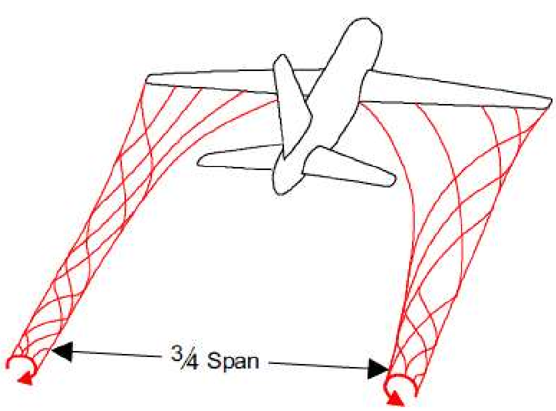


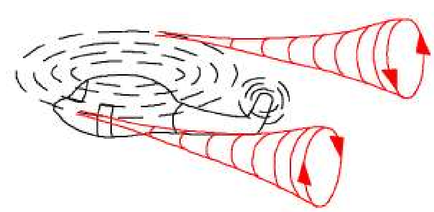


At slower/faster speed, in order to maintain a constant LIFT, the AoA must be increased/reduced, resulting in more/less spanwise flow due to the increased/reduced differential pressure between the lower surface and the upper surface, making more/less wing tip vortices, causing more/less deviation of the effective RAF, leading to a further decrease/increase of the AoA_{EFF} and increase/decrease in the AoA_i, resulting in a decrease/increase of the LIFT, and an increase/decrease of the Induced Drag.

Wing Tips Vortices

The wing tips vortices will generates turbulences behind the aircraft, known as WAKE TURBULENCES





The amount of WAKE TURBULENCES will depend on the aircraft TAS,

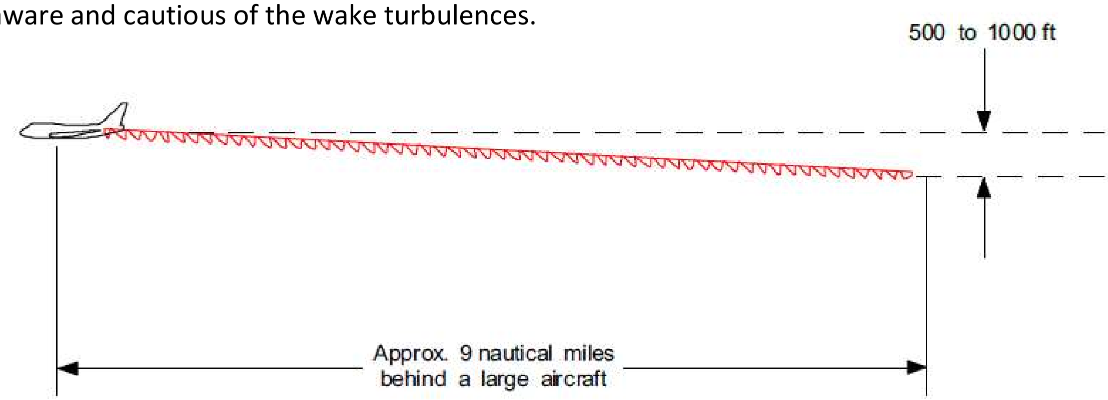
- Slower TAS, result in higher AoA, so more wing tips vortices and so more wake turbulences
- Faster TAS, results in less AoA, so less wing tips vortices and so less wake turbulences

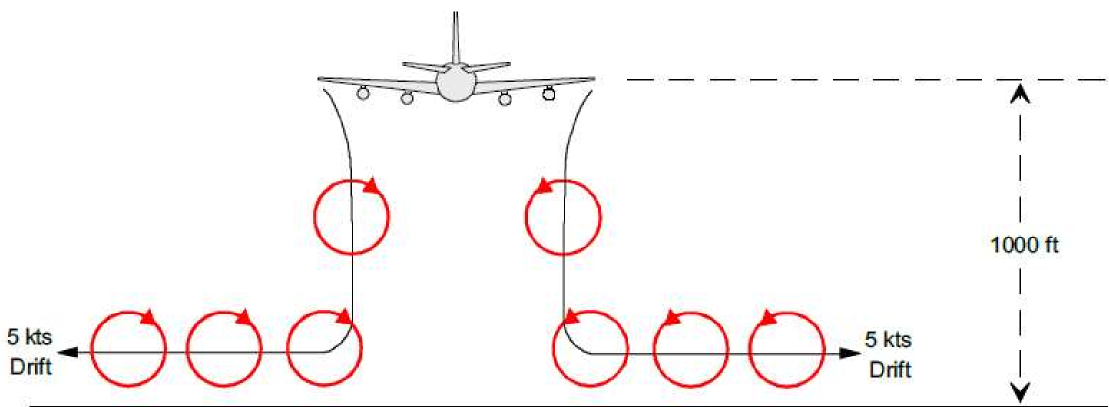
And it will also depend on the aircraft weight

- Heavier aircraft, result in higher AoA, so more wing tips vortices and so more wake turbulences
- Lighter aircraft, results in less AoA, so less wing tips vortices and so less wake turbulences

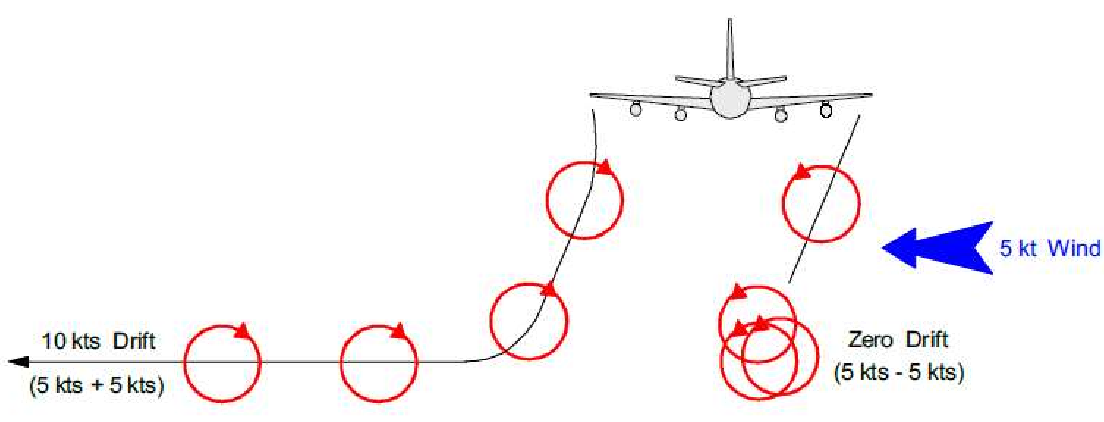
Flying into wake turbulences, results in dangerous flight characteristics, and could lead to loss of control.

Usually ATC will provide separation between the aircrafts accordingly, and the pilots must be aware and cautious of the wake turbulences.



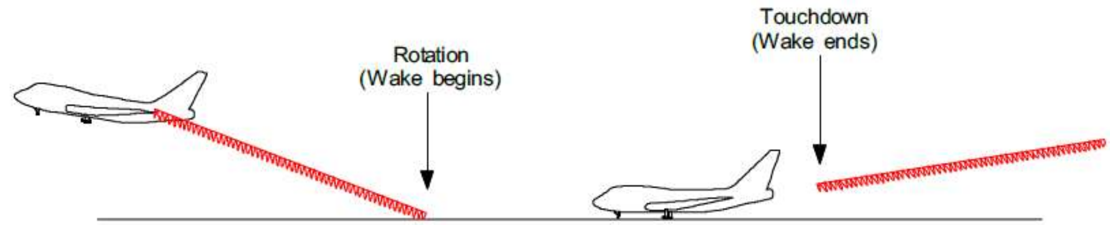


STILL AIR - (viewed from the rear)



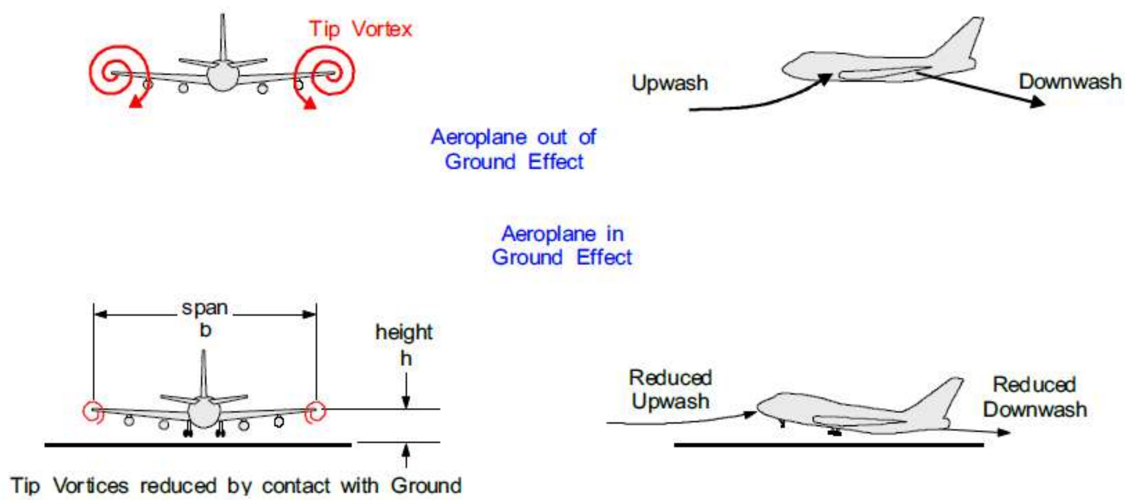
5 kt CROSSWIND - (Viewed from the rear)

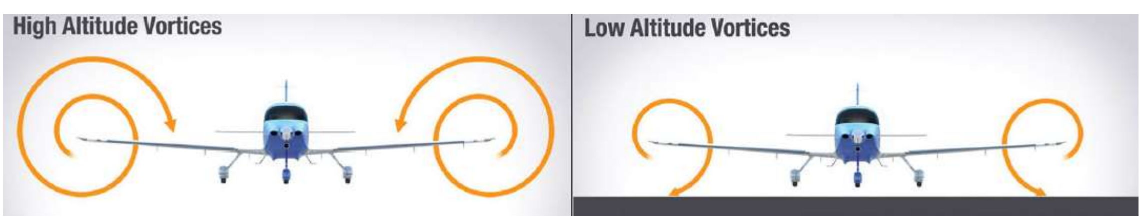
Wake turbulences will start from the take-off when aircraft rotates to leave the ground until the landing when the aircraft touches down.



5) Ground Effect

Near the ground, the vortices will be restricted to flow from the lower surface to the upper surface





Entering ground effect

- cause less wingtip vortices
- so decrease in upwash and downwash
- resulting in increase of the effective AoA
- and decrease of induced AoA
- Increase in LIFT
- Decrease in induced drag

Leaving ground effect

- cause more wingtip vortices
- so increase in upwash and downwash
- resulting in decrease of the effective AoA
- and increase of induced AoA
- Decrease in LIFT
- Increase in induced drag

The ground effect start from a height equivalent to half of the wingspan.