DOCUMENT

GSM-G-CPL.002

DOCUMENT TITLE

AERODYNAMICS 1

CHAPTER 2 – AEROFOILS

Version 1.0

September 2012

CONTENTS ....PAGE

I

PRESSURE, VELOCITY AND LIFT

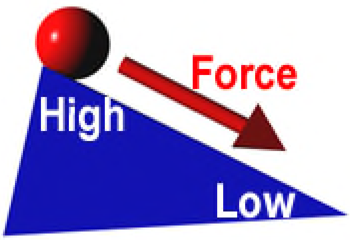
Introduction

Unlike a rocket, which makes use of power developed by the engines to fly, an aeroplane is designed to create LIFT. This lift unlike the rocket is developed by the aeroplane wing, much the same as a bird develops lift from its wings.

Therefore we can say that the wing is the primary source of lift in the aeroplane. How is this achieved? The wing creates lift by making use of pressure differentials, between the upper surface of the wing, and the lower surface of the wing. It is this difference in pressure, which results in the formation of lift.

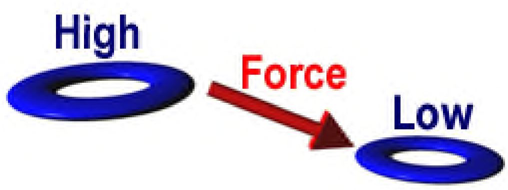
PRESSURE DIFFERENTIALS AND FORCE

If one where to take a ball and place it on top of a slope *(high pressure)*, and let it go, it would roll *(force)* down toward the lower side *(lower pressure)*. The resultant force would thus be toward the lower side *(lower pressure)*.



The same can be said for the high and low pressures in the study of Meteorology, where air moves from a high pressure area toward a low pressure area, thus creating a force *(wind)* in the direction of the low pressure area.

From what has been said, it seems that a force, in whatever format seems to move from an area of higher pressure to an area of lower pressure. This too is true for the force of lift. Lift is a force, which is created from the difference of pressure around a surface, in our case the wing.



It has been determined that pressure difference causes a force in the direction of the lower area of pressure, but how is such a difference created with regard to the aeroplane? The answer is quite simple, **the design of the wing**. Any surface designed to create a pressure difference will result in the formation of a force in the direction of the lower pressure.

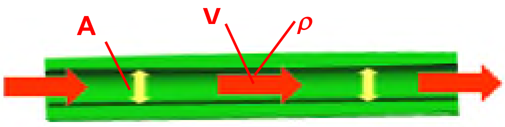
l

AIR FLOW THROUGH A TUBE

Before the creation of pressure differences is discussed, we should look at the behaviour of a moving parcel of air. In order to better describe the behaviour and properties, we will make use of a tube with a known diameter.

EQUATION OF CONTINUITY

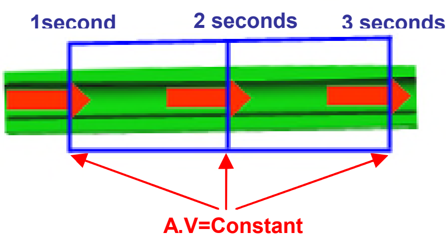
Firstly, the law of conservation of mass states that ***"mass cannot be created or destroyed"***. Meaning that if X amount of fluid or air is passed through a tube, the same amount of fluid must exit the tube (X), *i.e. what goes in must come out.*



Secondly*, Diameter of the tube (**A**),* **x** *Velocity of the air parcel (**V**)* **x** *density of the air (ρ) = Constant*

Density of the air (ρ) - The density of air moving below mach 0.4 is considered to be insignificant and is ignored for the purposes of this discussion.

We therefore use ***A.V = Constant***



This constant is the air mass flow per unit time. In other words if the tube is perfectly cylindrical *(diameter remains the same, i.e. **A** does not change),* then **V** must also remain the same in order to keep the constant value. Therefore the velocity at which the air enters the tube is the same velocity at which it exists the tube.

Because **A.V = Constant**, an increase in **A** *(diameter of the Tube)* would mean a decrease in **V** *(Velocity)* in order to maintain the **Constant** value, and vice versa.

BERNOULLI'S THEOREM

Bernoulli, a Swiss physicist discovered the pressure differential of subsonic flow. The following process explains how this was derived at:

A gas in steady motion has the following energies:

- ***Potential Energy***
- ***Heat Energy***
- ***Pressure Energy and***
- ***Kinetic Energy***

Bernoulli further stated that in an ideal fluid including air (one which has no friction and cannot be compressed), the sum of these energies is constant.

Potential Energy + Heat Energy + Pressure Energy + Kinetic Energy = Constant

Furthermore, at low speed (below Mach 0.4), potential and Heat Energy are insignificant, there is no heat or work transferred. This leaves us with the following:

Pressure Energy (p) + Kinetic Energy ($\frac{1}{2}\rho V^2$) = Constant

p = Static Pressure
ρ = Density
V = Velocity

Therefore as velocity increases, pressure decreases, and as velocity decreases pressure increases.

<u>What we know</u>

We know from the Equation of Continuity that:

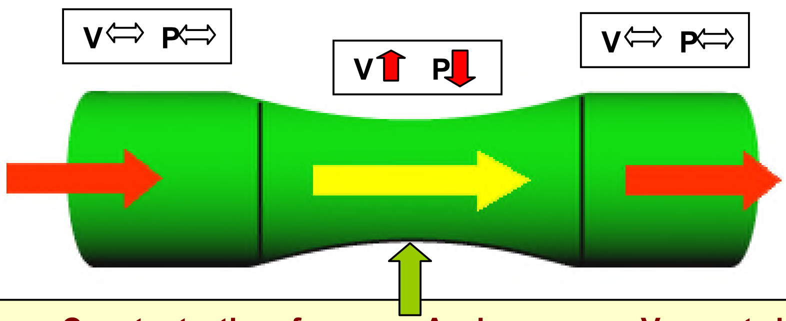
Air Mass Flow is a constant, (therefore what goes in must come out).
A .V = Constant. (If A is decreased then V is increased and vice versa)

We know from Bernoulli that:

p + ½ ρV^2 = Constant (If V is increased, then p is decreased and vice versa)

If we now take what we know, and pass air through a Venturi which is a cylinder with two concaves, it will become apparent how lift is derived.

A Venturi



A.V = Constant, therefore as A decreases, V must increase. Furthermore, according to Bernoulli, p + ½ ρV^2 = Constant, and therefore as V increases, p decreases.

We therefore have a relatively lower air pressure inside the Venturi at the concave.

The wing in subsonic aircraft is designed such that the distance along the top of the wing from A to B is longer than the distance from A to B along the bottom of the wing. This is a result of the curvature of the wing.

l

Applied to a Wing

This means that the airflow above the wing must travel faster than the airflow below the wing, in that B is reached by both at the same time. Because of the increase in the speed of the airflow, the pressure on the top of the wing decreases, resulting in a relatively lower pressure on the top, than is found at the bottom of the wing.

This pressure differential creates a force from the higher to the lower pressure. This force is called Lift!

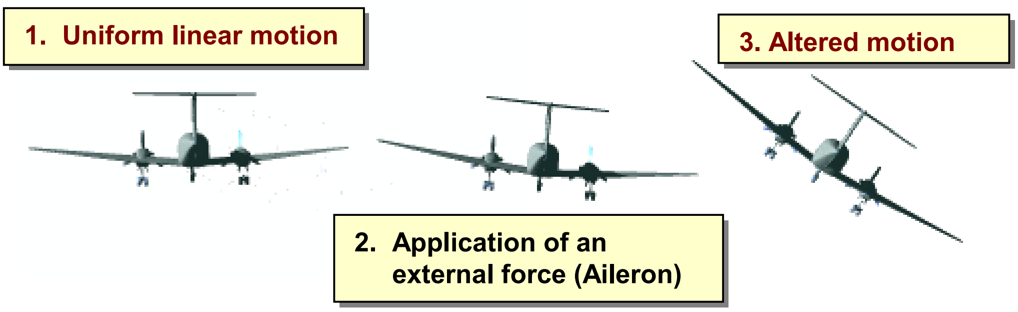
NEWTON'S LAWS OF MOTION

INTRODUCTION

Aerodynamics as a science is not excluded from the laws of nature, or of science. In this regard Newton's laws of motion are very relevant in the flight of an aircraft. By understanding the relationship between aircraft movements and these laws, we are able to apply these simple principles to everyday situations.

NEWTON'S FIRST LAW

A body will remain in a state of rest, or uniform linear motion, unless acted upon by an external, unbalanced force.



NEWTON'S SECOND LAW

When an external unbalanced force acts on a body, it produces an acceleration of that body in the direction of the force. This acceleration is directly proportional to the magnitude of the force and inversely proportional to the mass of the body. (F = ma).

If the rudder is deflected to the left, the angle of attack of the vertical stabiliser is altered. This change will result in a lifting force being created to the right, which results in a yawing moment toward the left wing tip.

The greater the rudder deflection the greater the angle of attack and therefore the force that produces the resultant yawing moment.

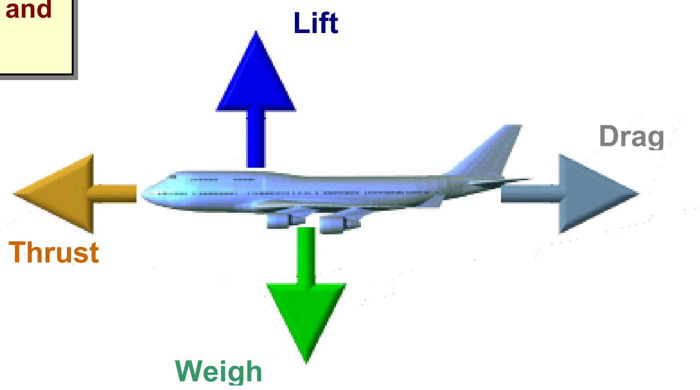
I

NEWTON'S THIRD LAW

For every action there is an equal, but opposite reaction.

While in level flight, the **weight** force is opposed by the **lift** force (equal but opposite). If this were not true, the aircraft would either climb or descend. Likewise, if the **thrust** and **drag** forces were not equal in opposite directions, the aircraft would accelerate or decelerate.

An aircraft in level flight, has four forces acting upon it, they are Lift, Weight, Thrust and Drag.



AIRFLOW AROUND AEROFOILS

AIRFLOW

When we speak of the flow of air around an aerofoil, we are referring to the path that air follows over a surface, and whether or not the flow follows the shape of the object, or breaks away. The following types of airflow are recognised:

- Steady Streamline Flow
- Unsteady Flow
- Two-dimensional Flow
- Three-dimensional Flow

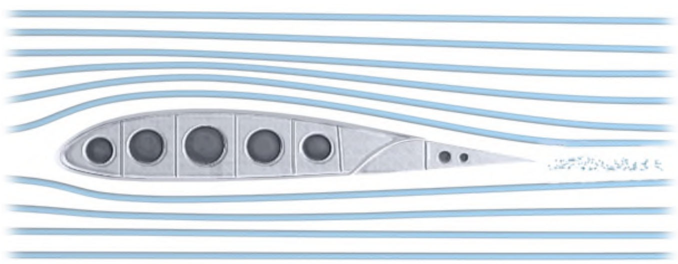
STEADY STREAMLINE FLOW

With steady streamline flow, the flow parameters (speed, direction, and pressure) may vary from point to point in the flow. These parameters however remain constant with respect to time.

This flow can be represented by streamlines and it is the type of flow that is hoped will be found over various components of the aircraft. Steady streamline flow may be divided into two types:

1. Classical Linear Flow
2. Leading Edge Vortex Flow

CLASSICAL LINEAR FLOW

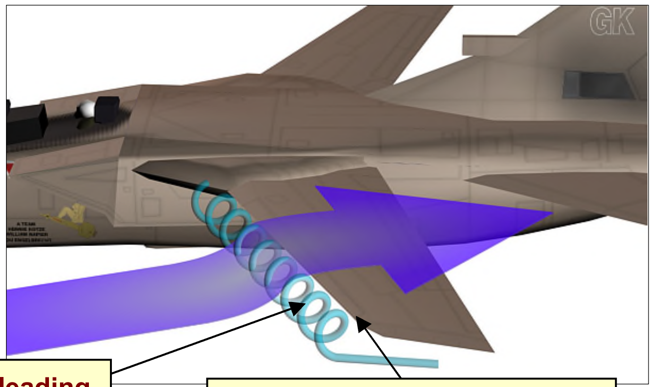


This is the flow found over a conventional aerofoil at low incidence. The streamlines all more or less follow the contours of the body and there is no separation of flow from the surface.

I

LEADING EDGE VORTEX FLOW

Leading edge vortex flow falls between classical linear flow and turbulent flow. It can be seen as controlled turbulent flow which is used to provide useful lift.



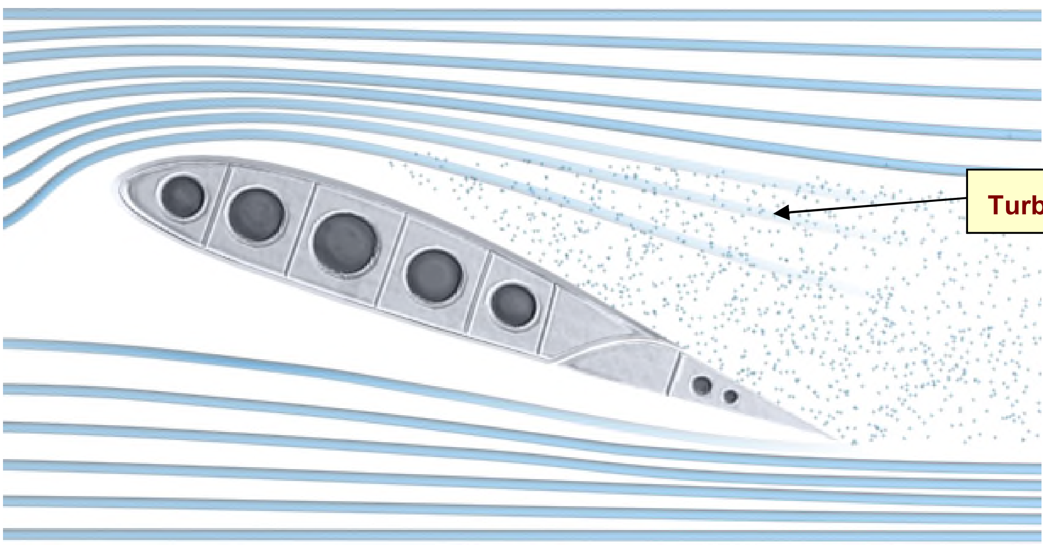
This type of flow is usually found on a wing designed for high speed, at high angle of incidence (angle of attack).

The wing producing this airflow, as a high speed wing, will have a sharp leading edge, and the vortex flow is the result of the airflow breaking away from the leading edge, and causing a vortex in this "hollow" area

UNSTEADY FLOW

Unsteady flow is airflow which is turbulent, and cannot be displayed using airflow lines as is the case with steady streamline flow.

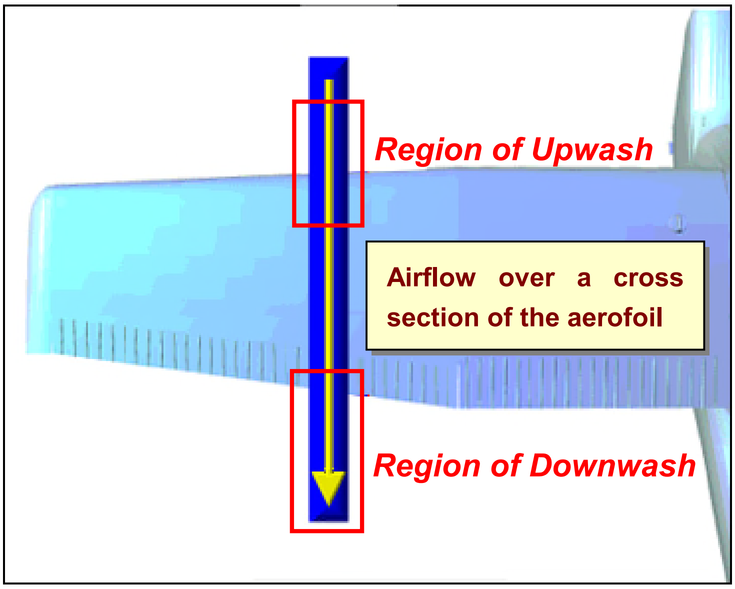
This type of flow generally does not produce any lift, and should this type of flow be dominant over the surface of the wing, the wing will no longer produce lift, and will stall. This type of airflow is seen when the wing is at a high angle of attack.

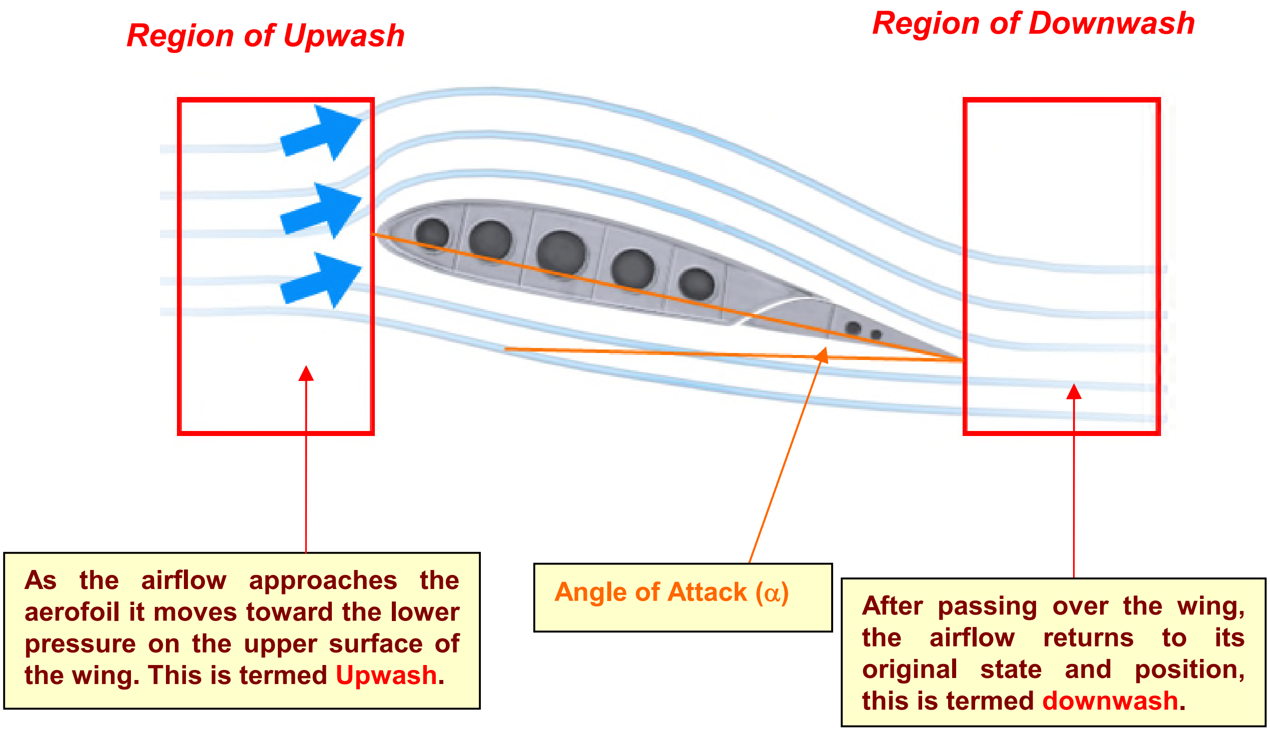


TWO DIMENSIONAL AIRFLOW

When looking at 2-Dimensional airflow, we are only concerned at the airflow over the wing in one plane only.

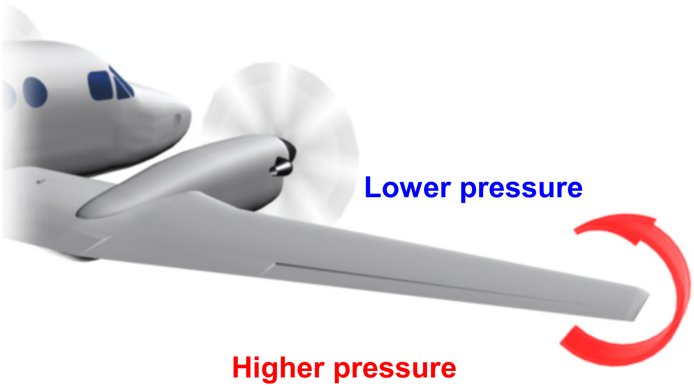
This means that we are only looking airflow over a cross-section of the aerofoil, and that the Relative airflow is restricted to movement in that cross section.





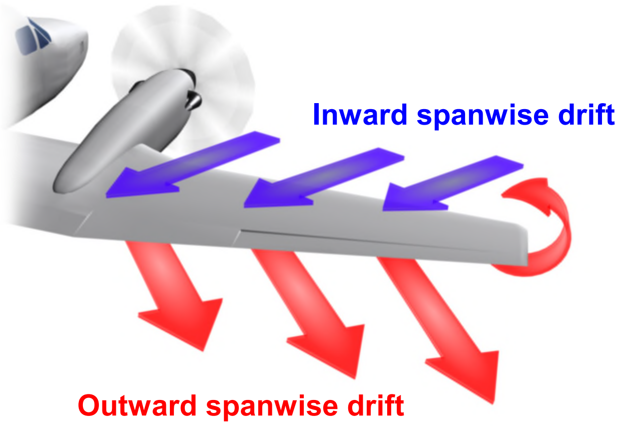
In reality however, airflow on an aerofoil cannot be defined in a 2-dimensional plane, because an aerofoil is exposed to more airflow than that of a cross-section. Because of this we are required to look at airflow in a 3-dimensional arena.

THREE DIMENSIONAL AIRFLOW



We know that in order for an aerofoil to create lift, that a pressure differential must be created with a relatively lower pressure being required on the upper surface of the wing, than on the lower surface.

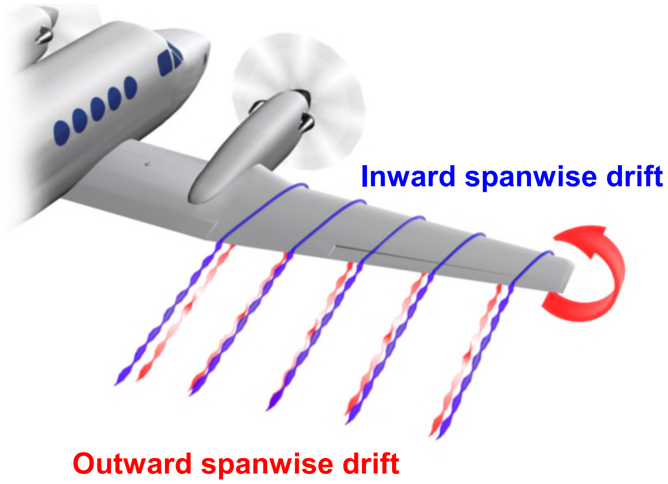
This pressure differential creates a tendancy for air below the wing (higher pressure area) to migrate toward the lower pressure on the upper surface. Air therefore tends to “spill” over at the wing tip.



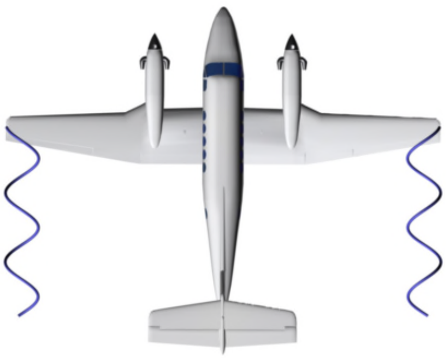
This results in airflow on the underside of the wing, moving toward the tip “Outward spanwise movement”

While the the airflow on the upper surface moves away from the tip toward the fuselage “Inward spanwise movement”.

This intensity of transverse flow reduces on both surfaces toward the fuselage.



As the airflow from the upper and lower surfaces meet at the trailing edge, they form vortices, which are strongest at the wing tip.



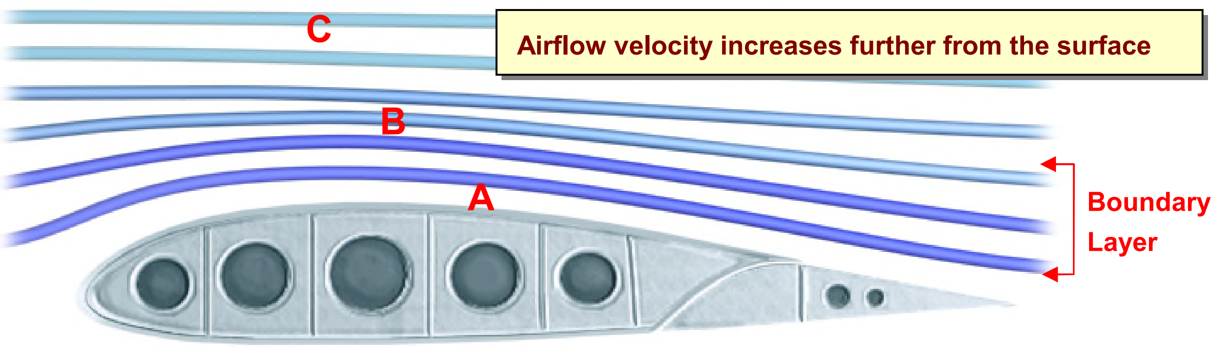
Thus 3-dimensional airflow takes into account not only a cross sectional airflow pattern, but also the movement of the air across the whole wing surface.

BOUNDARY LAYER THEORY

INTRODUCTION

Boundary layer theory plays an important role in both Lift and Drag. It is therefore important to understand the behavior of this layer when contemplating the forces acting on an aircraft in flight.

WHAT IS THE BOUNDARY LAYER?



Due to viscosity (***the internal friction of a fluid caused by molecular attraction which makes it resist its tendency to flow***.) the air particles flowing over a surface will encounter resistance and adhere or stick to the surface of the wing. Thus the particles closest to the surface will have a zero velocity relative to the surface **(A).**

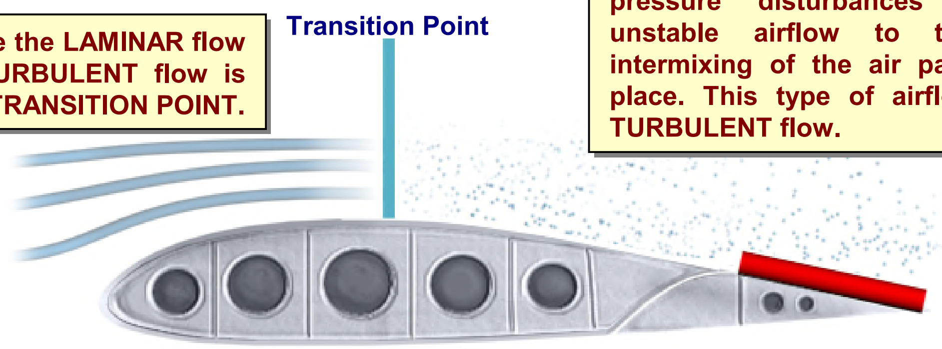
Particles slightly further away from the surface will be slowed down, but not brought to a stop **(B).** As the distance from the surface increases, so the velocity of the particles increase until they have the same velocity, pressure and temperature as that found in the Relative Airflow (Free stream velocity) **(C).**

The layer from the surface to the point where the velocity of the particles equals Relative Airflow is known as the ***BOUNDARY LAYER***. (The thickness of this layer varies from 1.8mm - 18mm.)

COMPOSITION OF THE BOUNDARY LAYER

As the airflow moves back from the leading edge, the boundary layer thickens and becomes unstable. Small pressure disturbances cause the unstable airflow to tumble, and intermixing of the air particles takes place. This type of airflow is called TURBULENT flow.

The area where the LAMINAR flow changes to TURBULENT flow is known as the TRANSITION POINT.



The beginning of airflow at the leading edge of a smooth surface produces a very thin layer of smooth airflow. This type of airflow is called LAMINAR airflow and is characterized by smooth regular streamlines. Fluid particles in this region do not intermingle.

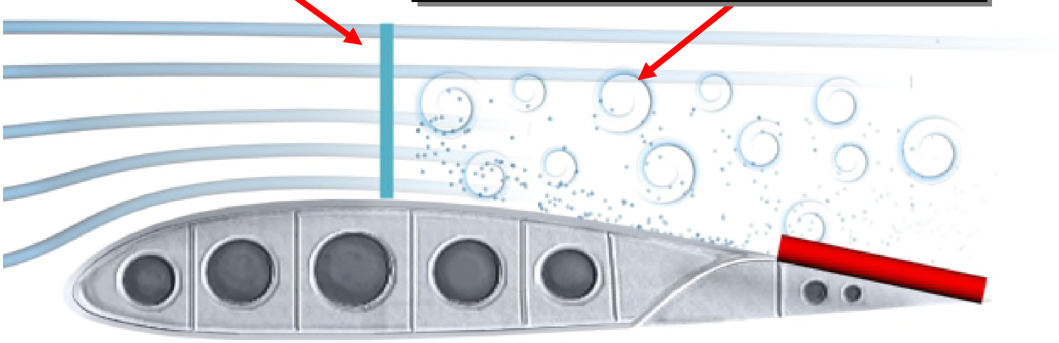
Below the TURBULENT layer exists a very thin layer where the random velocities are smoothed out. This layer is known as the LAMINAR SUB-LAYER.

THE TURBULENT ZONE OF THE BOUNDARY LAYER

Although it has been said that the airflow velocity at the surface of the wing is lower than that at the upper boundary of the boundry layer in the laminar flow, is the same true for the air flow in the turbulent flow?

From the transition point, the air flow in the boundary layer is turbulent, and there is a mixing of air particles.

This mixing of air particles, in the turbulent layer, means that those in the boundary layer take on the characteristics of those particles from the Relative Airflow particles incorperated into the turbulent area by the mixing.



Those Relative Air Particles incorperated into the turbulent boundary layer will tend to speed up this layer, as a result of their characteristics. This increase in speed of the turbulent boundary layer takes place as follows:

- **The air particles, (because of their low speed), nearer the surface will tend to increase in velocity relatively more than those in the upper areas of the layer. This increase in speed results in increased skin friction drag. *(As speed increases, drag increases.)***

The further forward the Transition point moves, the greater the area of the surface that is covered by turbulence. It is therefore important to delay the forward movement of the Transition Point for as long as possible.

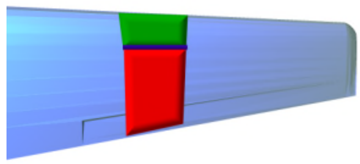
FACTORS AFFECTING THE POSITION OF THE TRANSITION POINT (TP)

The position of the transition point, is influenced by:

- ***Surface Condition***
- ***Speed and Size***
- ***Adverse Pressure Gradient***

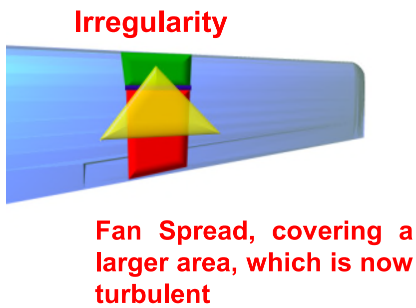
SURFACE CONDITION

Consider airflow in the Boundary layer over a smooth wing surface. It should look something like this graphic. The green represents Laminar flow and the red represents Turbulent flow.



However, the Boundary Layer is very sensitive to any irregularities on the surface. So much so, that any roughness that can be felt by hand, will cause the Boundary Layer to become Turbulent at that point.

The thickening of the Boundary Layer will spread out fanwise down-stream and the area of the wing covered by turbulent boundary layer will increase (yellow).

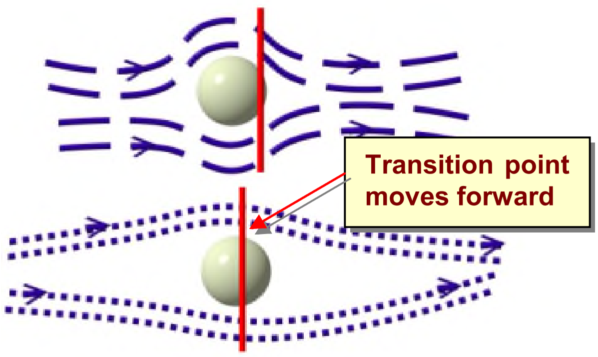


SPEED AND SIZE

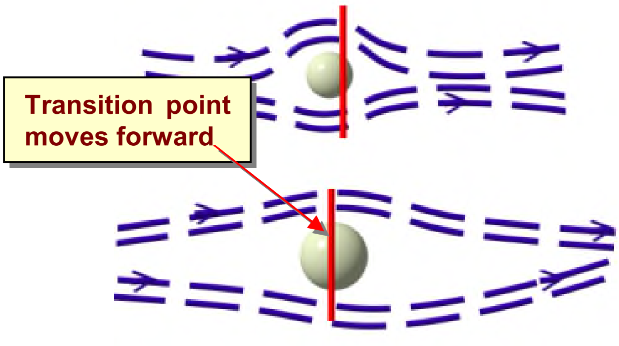
SPEED

When the velocity of the airflow over an object of given size is increased the Transition Point will move forward towards the leading edge.

This causes an increase in Surface Friction Drag because a greater part of the surface is covered by turbulent Boundary Layer.



SIZE



When a larger object is placed in airflow of a given velocity the Transition Point will move forward towards the leading edge.

This causes an increase in Surface Friction Drag because a greater part of the surface is covered by turbulent Boundary Layer.

ADVERSE PRESSURE GRADIENT

The equation of continuity states that **A(area) X V(velocity) = constant**.

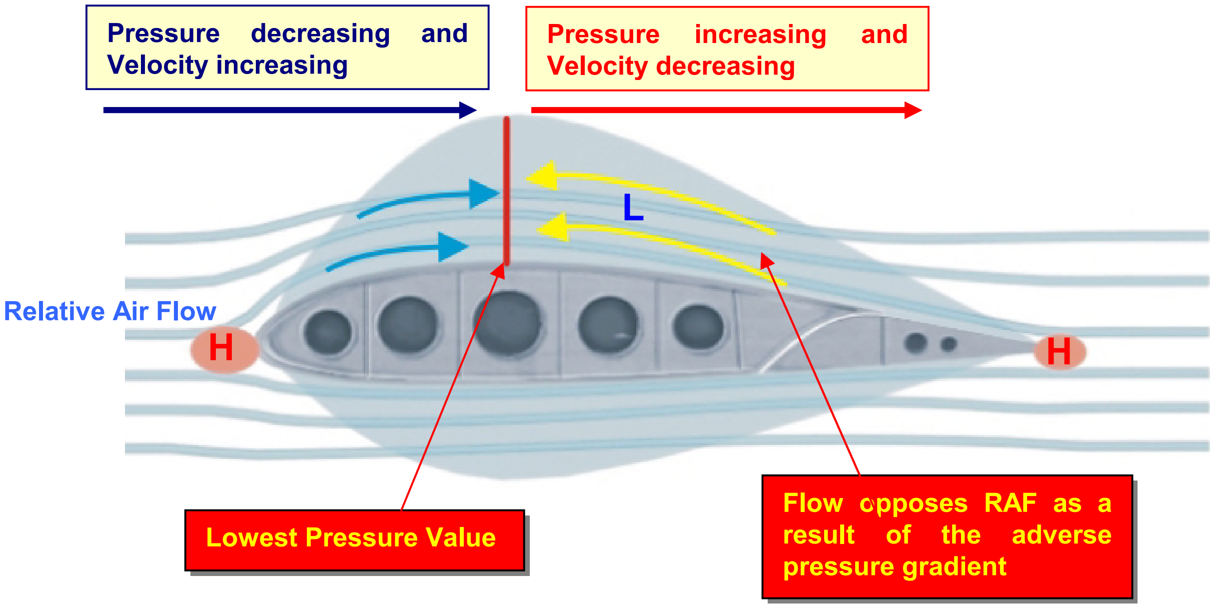
Bernoulli states that **p(pressure) + ½ ρV^2 (velocity) = Constant**

Therefore, as the area increases, velocity decreases, and while velocity decreases pressure must increase in order to maintain constant values in these equations.

If we look at the pressure distribution around an aerofoil, it is apparent that there is a point reached at which the pressure value is at its lowest *(this is usually at the point of maximum thickness)*.

Ahead of and behind this point the pressure values will be relatively higher. The transition point is usually at the point of maximum low pressure.

This pressure differential means that from the leading edge to this point, the flow will tend to move toward the point in the direction of the airflow. Beyond this point however, the flow will still tend to move toward it, but will tend to move against the relative flow, as a result of the adverse pressure gradient.

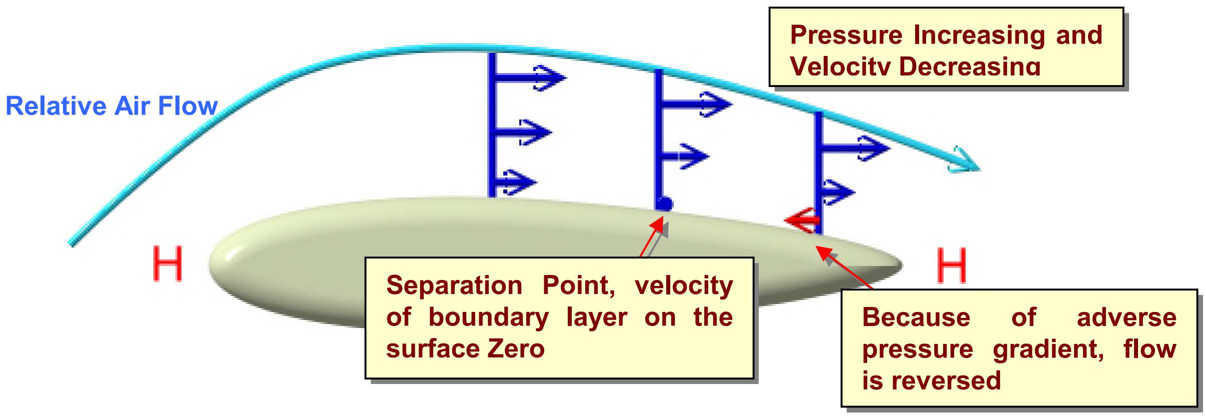


FLOW REVERSAL AND SEPARATION POINT

As the air within the boundary layer moves over the wing surface, it is exposed to surface friction. This surface friction reduces the velocity of the airflow (and also its kinetic energy).

The surface friction, together with the effects of the adverse pressure gradient ***(on the curved surface)*** eventually have the result that a portion of the boundary layer stops moving altogether or stagnating.

This air is now under the influence of the adverse pressure gradient, and moves toward the area of lower pressure. This flow is termed ***reversed flow (Flow Reversal).***



This flow reversal, occurs behind the ***Separation Point***, toward the trailing edge of the wing. Because of the stagnation, and flow reversal, this region is characterised by eddies.

This stagnation and reversal of the air flow, has the consequence that the boundary layer is separated from the surface, lift is destroyed, and drag becomes excessive.

PRESSURE DISTRIBUTION

Introduction

The picture above depicts a strange phenomenon on the top surface of this aircraft's wing. The explanation for this lies in the fact that the atmospheric conditions over the wing differ in certain areas from the conditions of the surrounding air. This change in the condition of the air is fundamental to the flight of heavier-than-air craft.

From **Bernoulli's Theorem** and the equation of continuity, it can be deducted that lift is produced by the creation of a pressure differential around the wing. However how this pressure is distributed around the wing is an important question, especially when the aerofoil changes its position relative to the air flow over it.

Bernoulli's Theorem:

In steady streamline flow of an ideal fluid the sum of the energies is a constant.

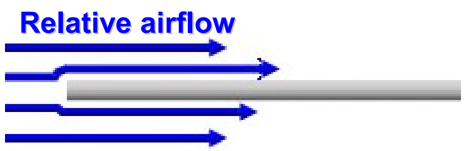
Thus an increase in velocity causes a decrease in pressure and vice versa.

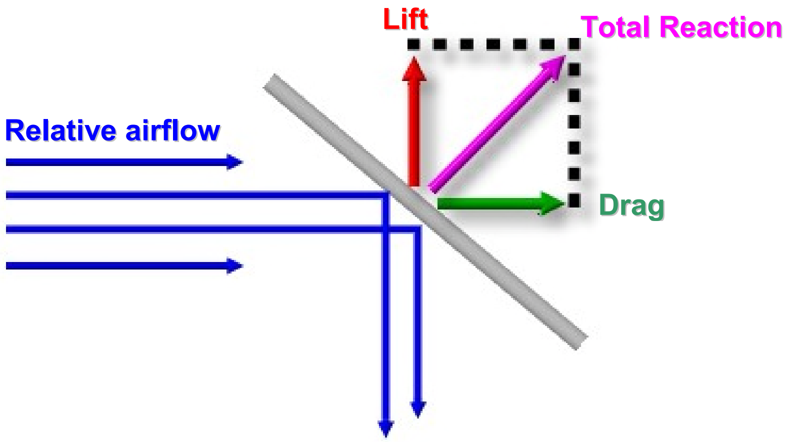
The pressure differential can only be created or exist, if there is a movement of air over the aerofoil ***(whether the wing moves through the air, or the air moves over the wing)***.

FLAT PLATE THEORY

Before looking at the pressure distribution around an aerofoil, it is useful to look at what happens when a flat plate is placed into airflow.

A flat plate placed in the airflow in this manner will have little, if any effect on the relative airflow.





However, if the plate is tilted against the relative airflow (RAF), the airflow is disrupted. This will result in a force acting perpendicular to the plate, which is called the **total reaction**. This force is comprised of a **lift force element** ***(acting perpendicular to the RAF),*** and a **drag force element** ***(acting tangential to the RAF).***

The wing of an aircraft is specifically designed to produce lift and therefore the airflow and pressure changes around it are of the utmost importance.

MEASURING PRESSURE AROUND AN AEROFOIL

Bernoulli's Theorem and the Equation of Continuity stated that when airflow accelerates over a curved surface the value of pressure will decrease.

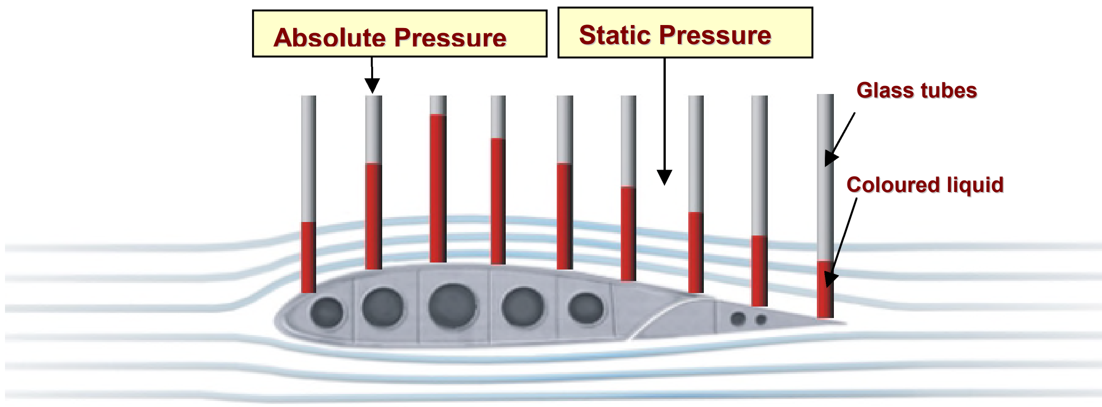
UPPER AND LOWER SURFACE OF THE AEROFOIL

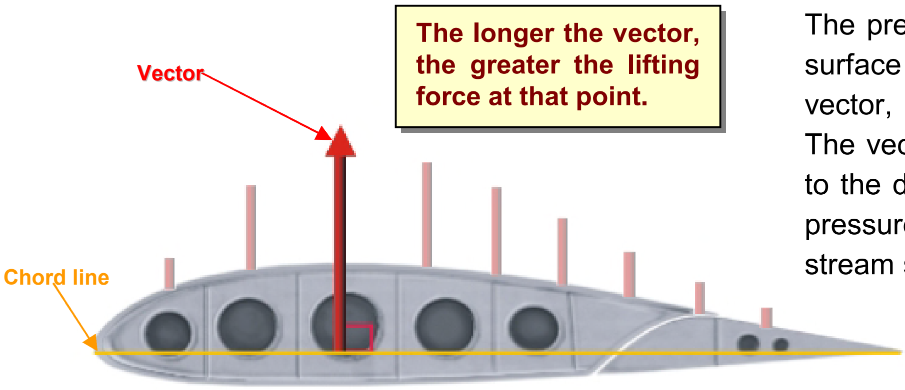
To measure the pressure distribution around an aerofoil, an instrument called a **manometer** is used.

This instrument consists of glass tubes filled with a coloured liquid, and connected to small holes in the aerofoil surface.

As air flows over the aerofoil, the variations in pressure are indicated by the differing levels of fluid in the tubes. These measurements are in absolute pressure.

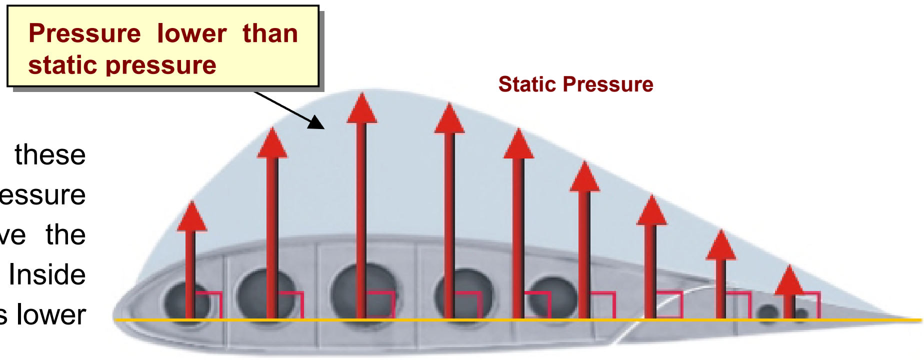
By comparing the difference in the absolute pressure and the static pressure the lifting effort produced by the aerofoil at each point can be seen. Thus the displaced fluid represents the lifting force of the aerofoil at that point.

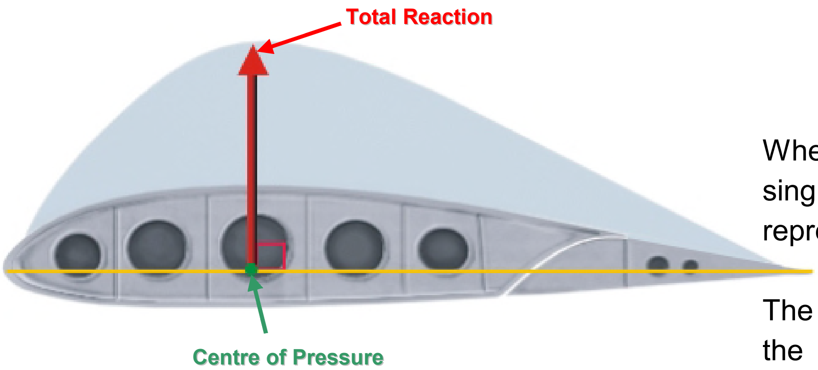




The pressure at a point on a aerofoil's surface may thus be represented by a vector, perpendicular to the chord line. The vector's length will be proportional to the difference between the absolute pressure at that point and the free stream static pressure.

By joining the ends of these vectors, a certain pressure pattern is indicated above the surface of the aerofoil. Inside this pattern the pressure is lower than the static pressure

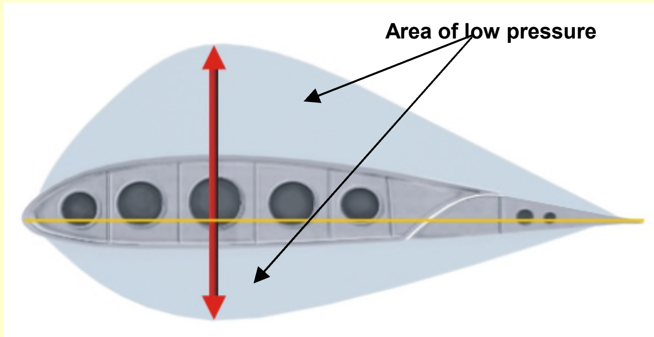




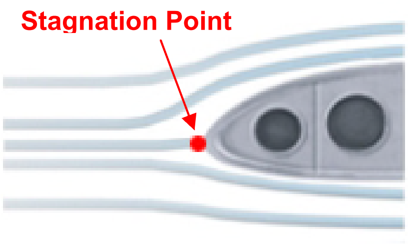
When all the vectors are combined, a single aerodynamic force is created representing the ***Total Reaction***.

The point on the chord line through which the TR acts is called the ***Centre of Pressure (CP)***. As the TR moves, so too does the CP.

Due to the curvature of the underside of the aerofoil, the air pressure will also decrease as the airflow accelerates. Because the curvature is less than the top surface the decrease in pressure will be less.

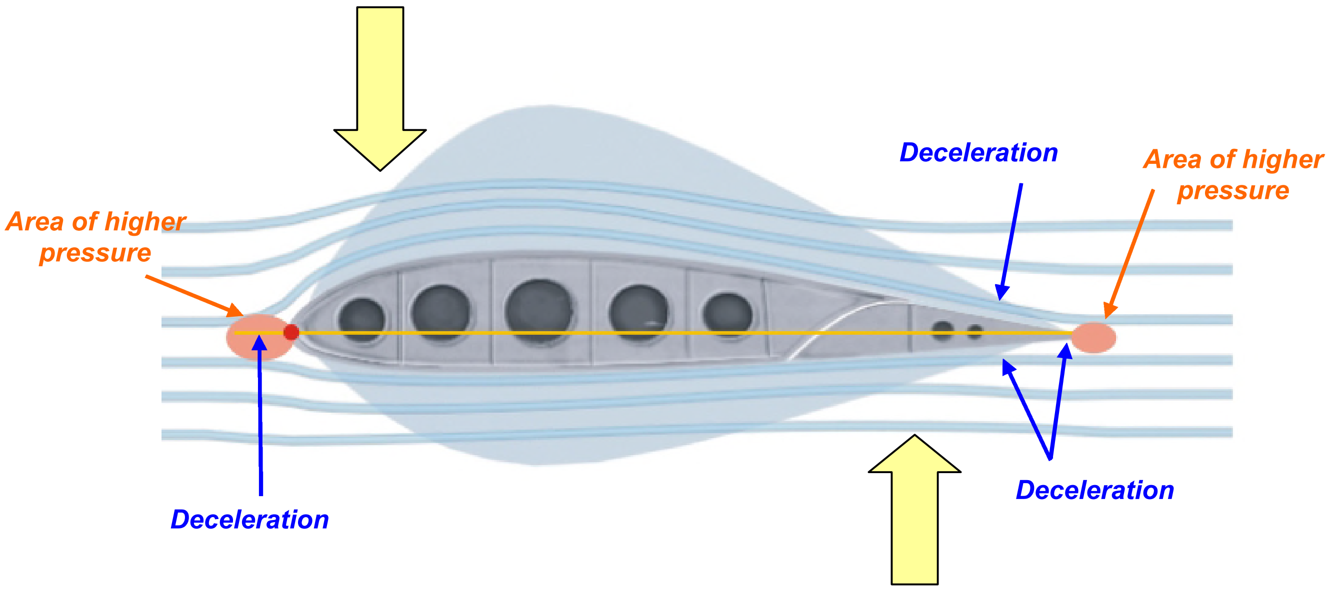


PRESSURE DISTRIBUTION AT THE LEADING AND TRAILING EDGE



The airflow approaching the wing is initially decelerated because the wing is actually an obstruction. Most of the air passes either over or under the wing, but some of the air is brought to a complete rest as it impacts the leading edge at 90°. This point is called the Stagnation point.

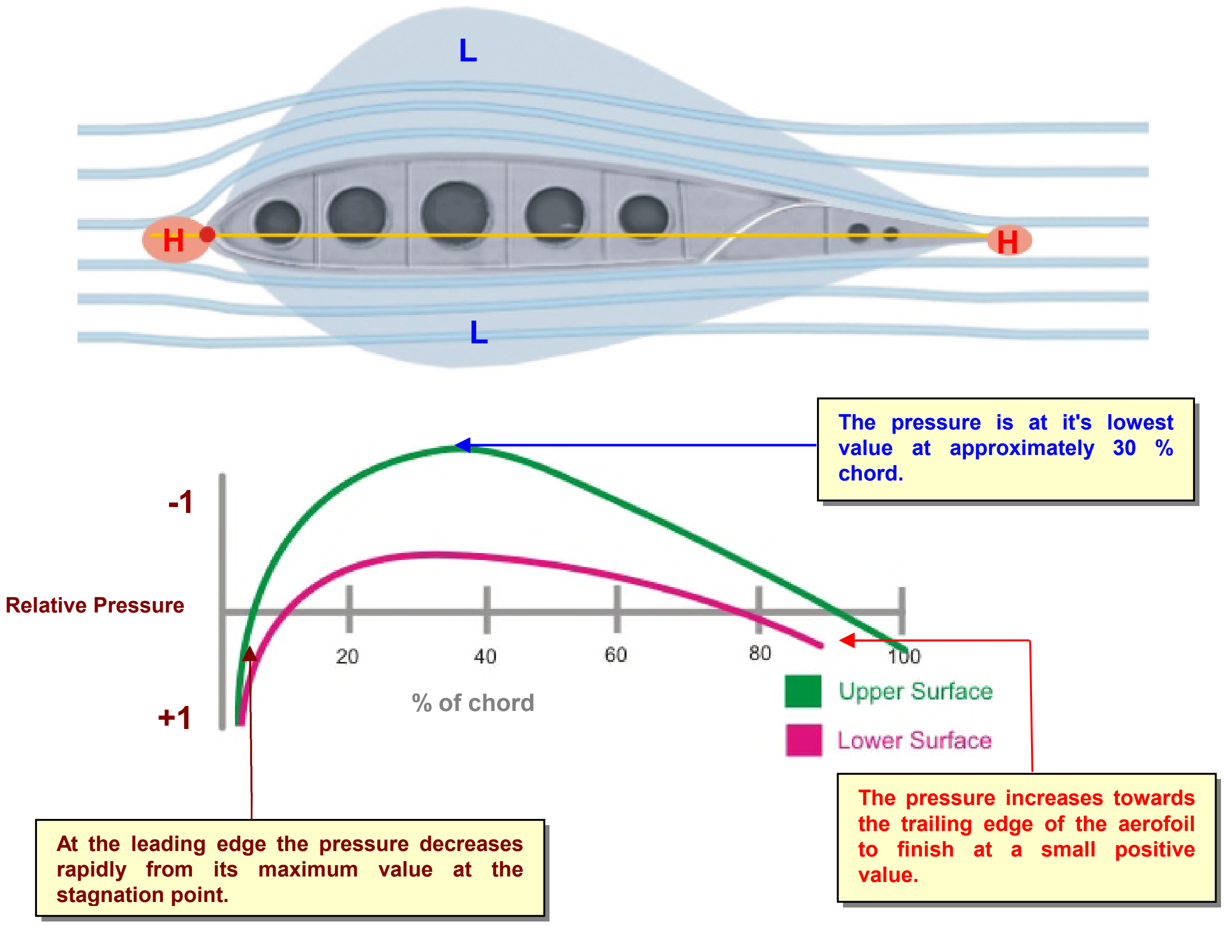
Bernoulli states that as velocity decreases, pressure increases, (***p* + ½ ρV² = Constant**), and therefore because the air at the leading edge is slowed down, it follows that there will be an area of higher pressure at the leading edge of the wing around the stagnation point.



With the airflow decelerating to the same velocity as the free stream at the trailing edge of the wing, a local area of higher pressure is also formed behind the aerofoil.

HIGH- AND LOW-PRESSURE GRAPH REPRESENTATIONS

Graphs are a popular method of representing pressure distribution over the aerofoil. These graphs will be drawn for an aerofoil at a ***fixed angle of attack***, (in this instance 0°). Note the convention of ***plotting negative values upwards to relate to lift in a natural sense***.



CHANGES IN DISTRIBUTION, AS A RESULT OF CHANGES IN ANGLE OF ATTACK (AOA)

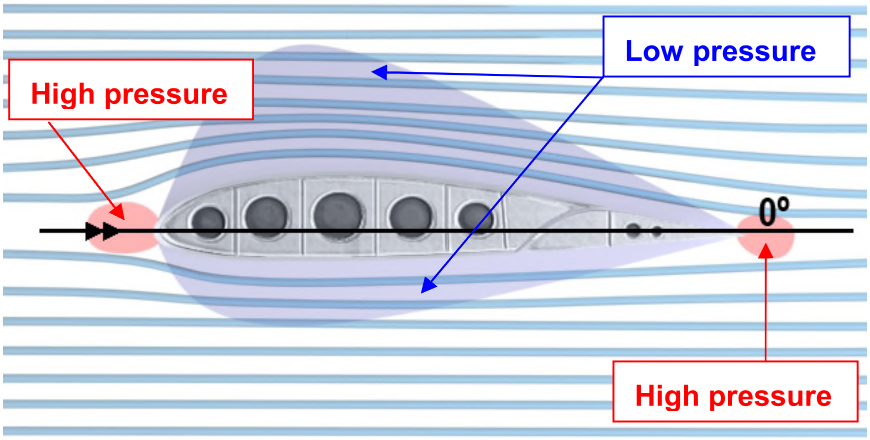
Because flying is such a dynamic environment, it goes to say that the changes of the airflow pattern and pressure distribution around the wing will not be a static but a dynamic and changing process.

One of the main factors affecting the pressure distribution around an aerofoil is the angle of attack. A normal range of angle of attack will be from 0 degrees to +15 degrees.

Initially, the aerofoil will be considered at four specific angles of attack (4 diagrams).

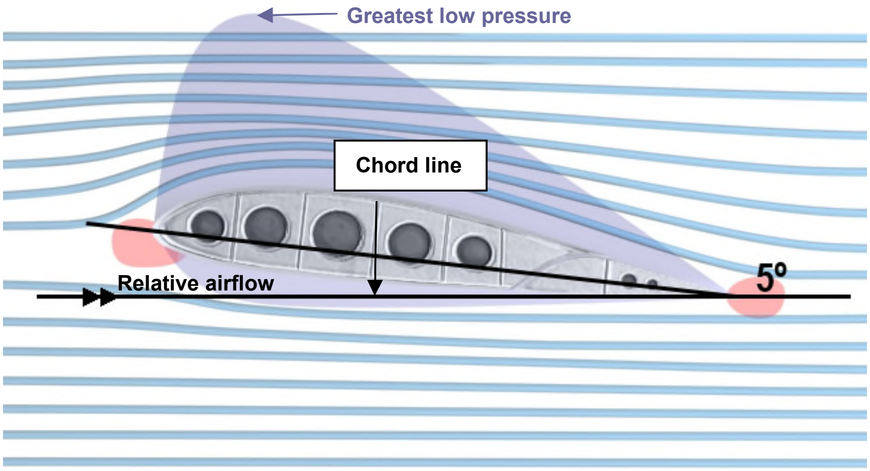
I

0° Angle of Attack



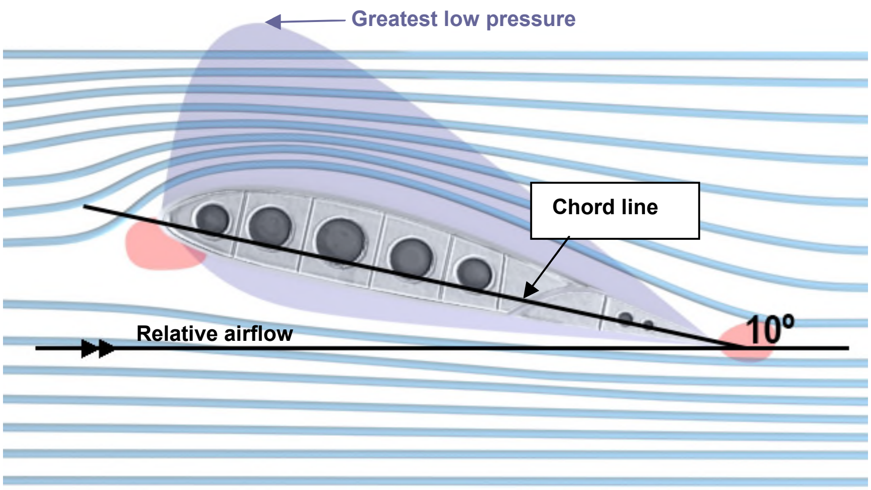
Due to the increased camber of the upper surface of the aerofoil, the low pressure on top of the aerofoil will be more intense than that of the lower surface.

5° Angle of Attack



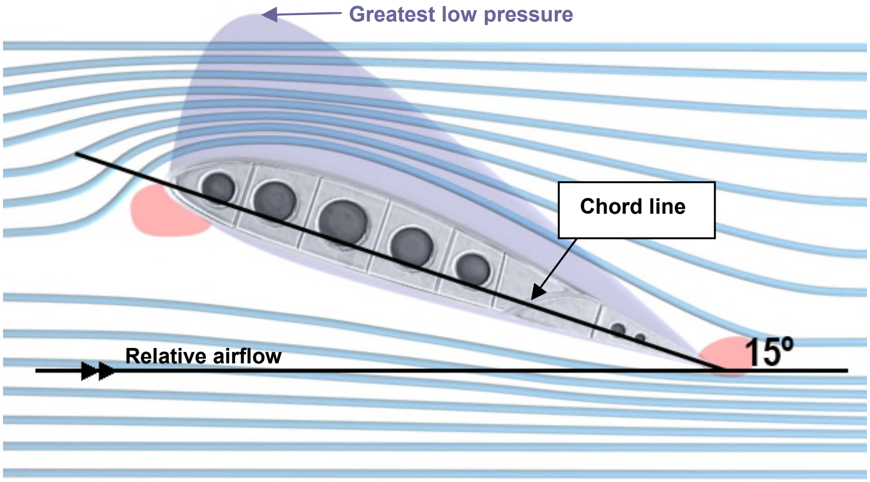
With an increase in angle of attack, the distance the airflow over the top of the wing has to travel increases. Thus the airflow has to increase in speed with the corresponding greater decrease in pressure. Underneath the aerofoil the distance the airflow has to travel decreases thus causing less of an increase in speed.

10° Angle of Attack



With the aerofoil at +10 degrees angle of attack, the same process as previously described takes place, but just to a greater measure. The high-pressure area at the trailing edge of the aerofoil undergoes a small movement throughout the range of angles of attack.

15° Angle of Attack



At approximately +15 degrees angle of attack the low-pressure area on top of the aerofoil is at it's greatest with the area underneath the aerofoil virtually gone. The high-pressure area ahead of the aerofoil has moved to the underside of the aerofoil.

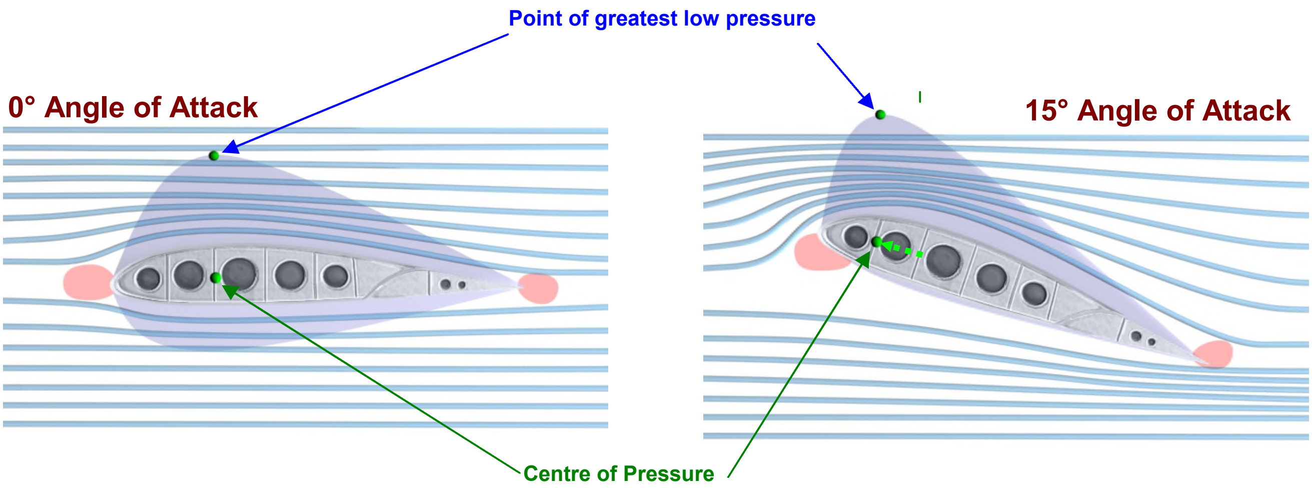
Summary

As the angle of attack of the aerofoil changes the following becomes apparent:

- The low-pressure area above the aerofoil grows in intensity and its maximum point moves forward.
- The intensity of the low-pressure area underneath the aerofoil decreases in intensity.
- The high-pressure area ahead of the aerofoil moves from its position directly ahead of the aerofoil to a position underneath the leading edge of the aerofoil.
- The high-pressure area at the trailing edge of the aerofoil undergoes minimal positional and size changes.
- The airflow ahead of the aerofoil is curved upwards towards the aerofoil and behind the aerofoil there is a downward component in the airflow.

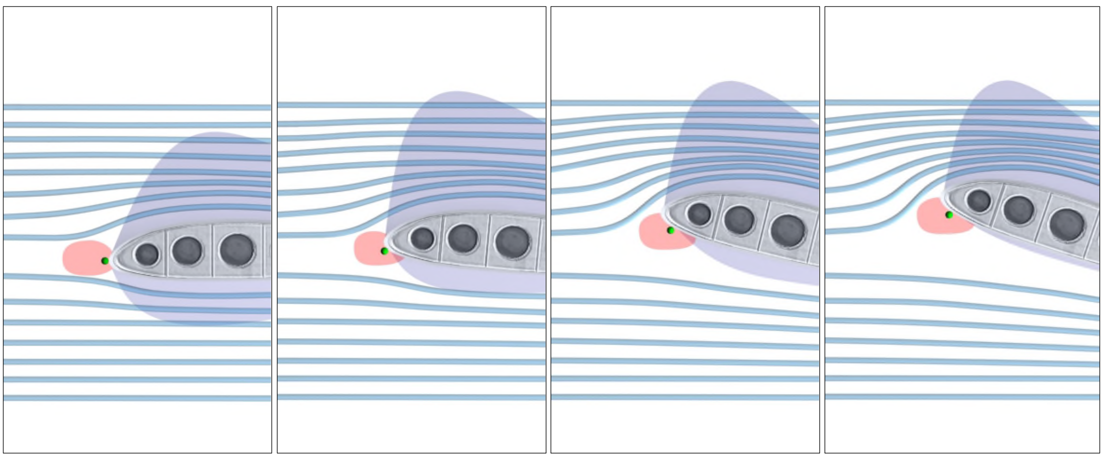
CENTRE OF PRESSURE (CP) MOVEMENT

As the point of the greatest low pressure above the aerofoil moves forward, the CP also moves forward because the Total Reaction can be said to act through the CP to point of the greatest low pressure. Thus as the point of the greatest low pressure moves forward, the CP will also move forward.



STAGNATION POINT MOVEMENT

The high-pressure area ahead of the aerofoil moved from its position directly ahead of the aerofoil to underneath the leading edge of the aerofoil. The stagnation point being the centre of this area it will mean that the stagnation point will follow the same movement.

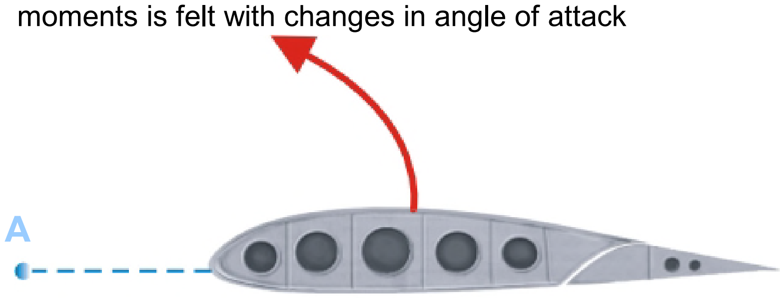


0° AoA 5° AoA 10° AoA 15° AoA

AERODYNAMIC CENTRE

DEFINITION

Aerodynamic Centre is the point on the aerofoil chord line about which no change in pitching moments is felt with changes in angle of attack



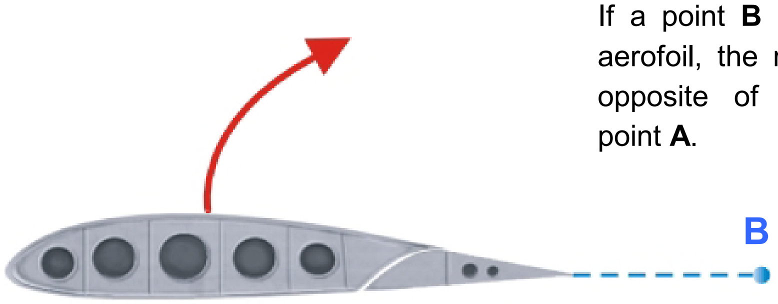
An arbitrary point (**A**) is chosen ahead of the aerofoil.

If the angle of attack of the aerofoil should increase, the lifting force of the aerofoil will increase as well and thereby cause an anti-clockwise turning **moment** around point **A**. The result of this movement is a decrease in the angle of attack of the aerofoil.

Moment:

The resultant when a force is applied around a point causing a turning motion.

If a point **B** is chosen behind the aerofoil, the movement will be the opposite of that experienced at point **A**.



Therefore, if the angle of attack should increase, there will be a clockwise turning moment around point **B**, causing a further increase in the angle of attack of the aerofoil.

Because the turning moment, experienced at **A**, is the opposite of that experienced at **B**, it follows that there is a point between **A** and B, where these two moments exactly oppose each other. This point, where the moment is constant, is called the **Aerodynamic Centre (AC)** of the aerofoil and is a fixed point at, or very close to the 25% chord point.