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# AERODYNAMICS 1

# CHAPTER 6 – AUGMENTING LIFT

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# AUGMENTING LIFT

## INTRODUCTION

Different planforms have been designed to be utilised in specific roles and are most efficient in specified speed ranges. However all aircraft need to be able to land and take-off safely and here it is of primary concern to reduce the minimum control speed as much as possible. In order to achieve this, the lift developed by aerofoils has to be augmented in certain areas.

## WING LOADING

The wing loading of an aircraft explains the ratio between the weight of an aircraft and its wing area, in other words the amount of weight that has to be carried by a given area of a wing.

The formula used to obtain this ratio, is:

$$\text{Wing Loading} = \frac{\text{Weight (W)}}{\text{Wing Area (S)}}$$

The two aircraft below have a marked difference in wing loading, which also represents the lift required in level flight per unit area of wing. The problem of getting more lift from a given wing has exercised many designers' ingenuity.

Although aerofoil designs have improved, the basic value of the lift coefficient for an aerofoil hasn't changed much during the last fifty years. Thus for aerofoils with a high wing loading (***but still an average lift coefficient)***, the speed at which it travels through the air has to increase proportionately in order to carry the extra weight imparted to it. This is shown below when the average cruising speeds of the two aircraft below are compared.

**36137lb**
**400sq.ft**

**90.34 lb/sq.ft**

**430kts → 90.34 lb/sq.ft**

**2409lb**
**159.5sq.ft**

**15.10 lb/sq.ft**

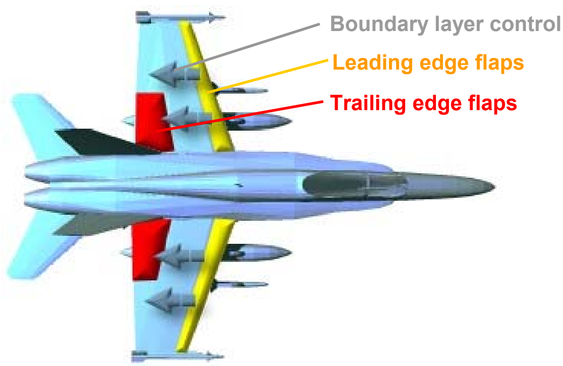
**104kts → 15.10 lb/sq.ft**

The wing loading of the aircraft below (2.14 lb/sq.ft) was of such a nature that its approach speed for landing could be lowered to 60-70 knots. In this case the lift produced was sufficient to compensate for the weight of the aircraft. This resulted in a speed from which a safe landing could be executed, taking the aircraft design and runway conditions of that time into consideration.

The aircraft with a high wing loading needs to fly at speeds in the region of 210 knots in order to develop sufficient lift to compensate for the increased wing loading. As the stalling speed can easily be more than ten times the stalling speed of the aircraft with the low wing loading, it can lead to higher touchdown- and take-off speeds that require longer runways. The alternative is to reduce the approach speed by augmenting the lift, which is produced at low speeds by the wing of such an aircraft. In the case of the McDonnell Douglas F/A 18 Hornet, the approach speed has been reduced to 134 knots.

## AUGMENTING LIFT

The devices that are used to augment lift must not affect the performance of a wing during normal flight. These devices have to be deployed when required and when not in use, they must retract to form a part of the wing. The main devices used to augment the **$C_{Lmax}$** are:



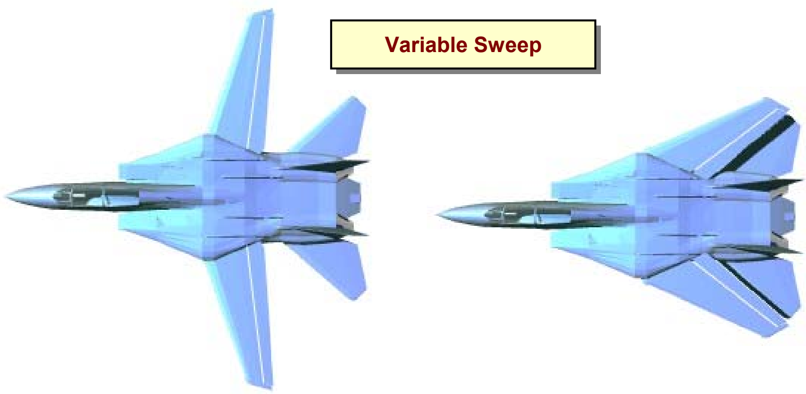

- **Slats** - either automatic or controlled by the pilot. Slots also fall into this classification.
- **Flaps** - these include leading edge, trailing edge and jet flaps.
- **Boundary layer control** (  ) - the use of either sucking or blowing of air over the wing to re-energize the boundary layer.

## CHORD LENGTH

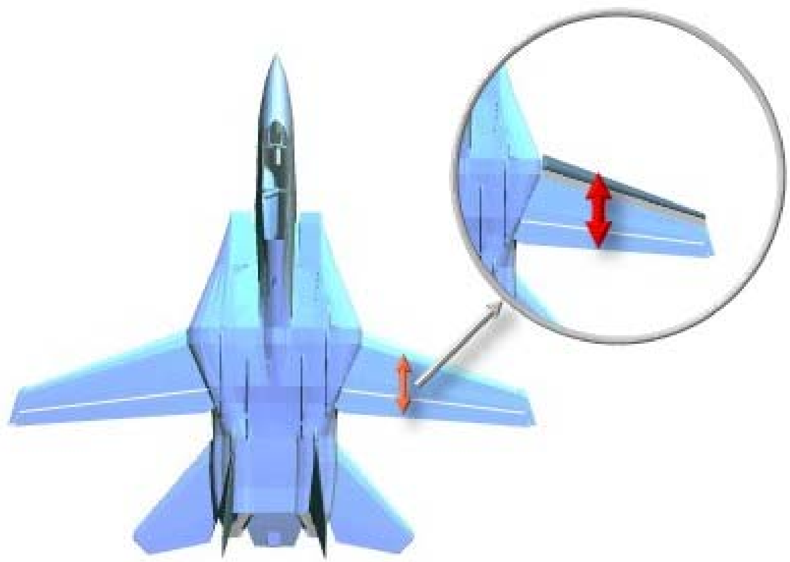
In the lift formula (**$L = C_L \frac{1}{2}\rho V^2 S$**), each element of the equation influences the value of lift. If the speed (**V**) and density (**ρ**) in the formula are kept at a constant value, both the coefficient of lift (**$C_L$**) and the wing area (**S**) can be altered in order to change the amount of lift developed. The coefficient of lift can be altered by changing the chord length, the chord line and camber. Changing the chord length or the wingspan can alter the wing area.

### CHANGING OF THE CHORD LENGTH

Altering the wing area has a direct influence on the lift produced by a wing. As seen in the graphics below, a pilot can use variable sweep to alter the wingspan in flight, which in turn changes the aspect ratio. Changing the wing area by increasing or reducing the chord length will produce the same effect as the Wing Area formula proves ***(Wing Area = Wing Span x Chord)***.




**Referring back to the previous statement and the formula for induced drag, as the Aspect Ratio of a wing increases for a given Angle of Attack, the coefficient of drag ($C_D$) will decrease accordingly.**



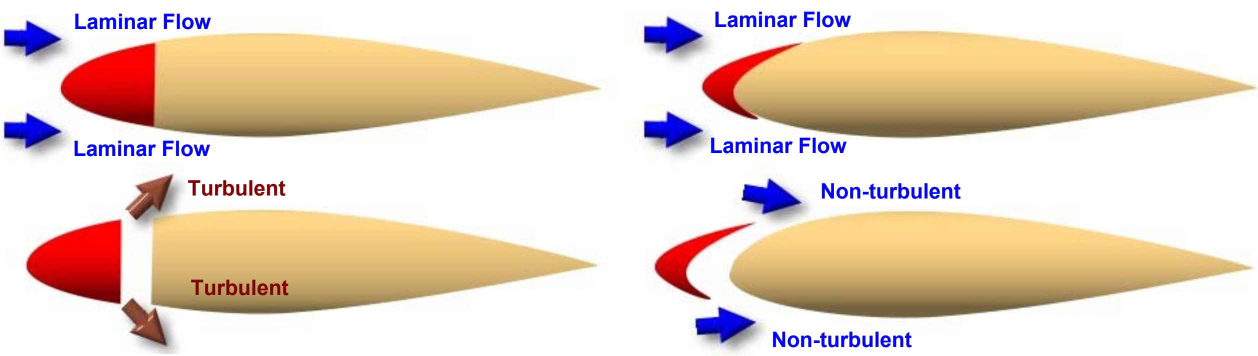
By increasing the chord length of the aircraft shown, the wing area is increased from 565 sq ft to 611.20 sq ft. The lengthening of the chord can be achieved by means of a device called a **Slat**.

## SLATS AND SLOTS

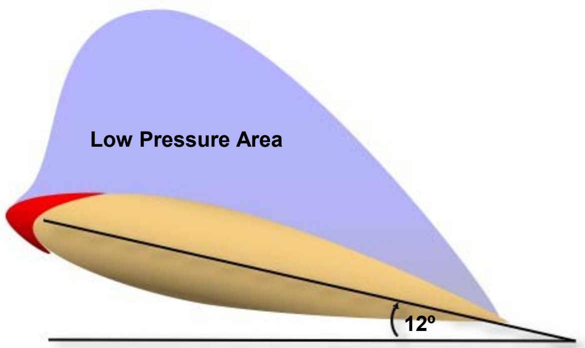
By increasing the chord length of a wing, the desired increase in C**Lmax** can be achieved, provided that the lengthening effect doesn't create any adverse pressure pat-terns or separation of the airflow over the wing.

If the whole front section of the wing is moved forward (**Wing A**), the flat surface of the leading edge of the wing (an obstruction in the airstream) as well as the sharp corners where the split is, will cause turbulent airflow with an accompanying decrease in C**Lmax**. It follows then that the slat has to be an aerofoil itself (**Wing B**) and the wing section behind it has to be designed to promote smooth airflow in the area behind the slat.

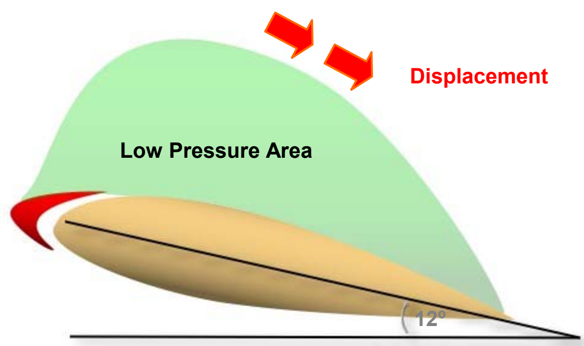
**WING A** **WING B**

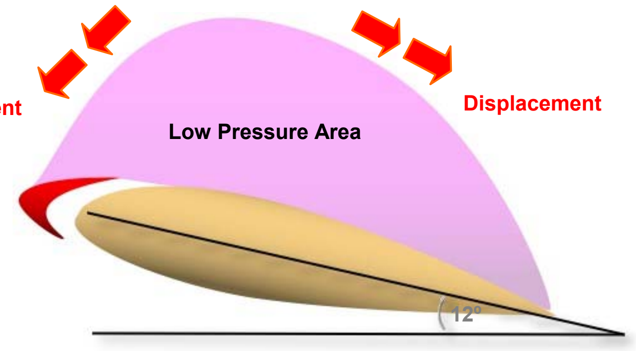



When a slat is operated at an angle of attack ***(eg 12°)*** where the wing is normally still in an "unstalled" situation ***(separation hasn't occurred yet)***, the slat will not cause the value of $C_L$ to increase or decrease, it merely alters the shape of the pressure pattern around the aerofoil as illustrated.




As the slat starts to deploy, the marked peak of the low-pressure area starts to disappear. The Pressure is redistributed ***(displaced)*** to an area where the low-pressure area is normally not as well developed.

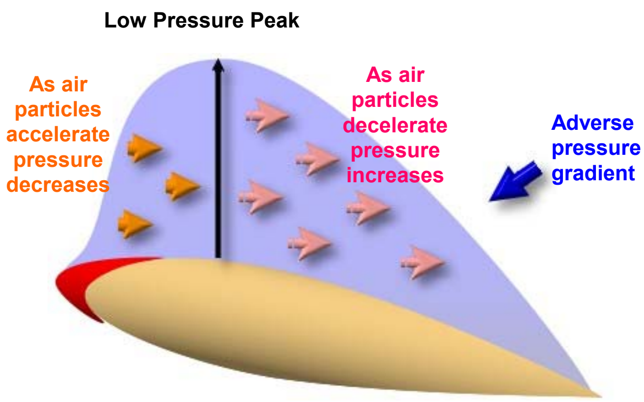





When the slat is deployed completely, the low-pressure pattern has an even spread over the wing which in turn causes changes in the boundary layer. ***(These changes will be dealt with later on in this lesson).***

**This is a dynamic process and the low-pressure pattern changes at the same rate at which the slat is moving.**

On an unslatted wing, it has been demonstrated that the low-pressure envelope above the wing has a marked peak in the area where the wing is at its thickest **(acceleration of airstream is the greatest and thus the pressure is the lowest in this area).**

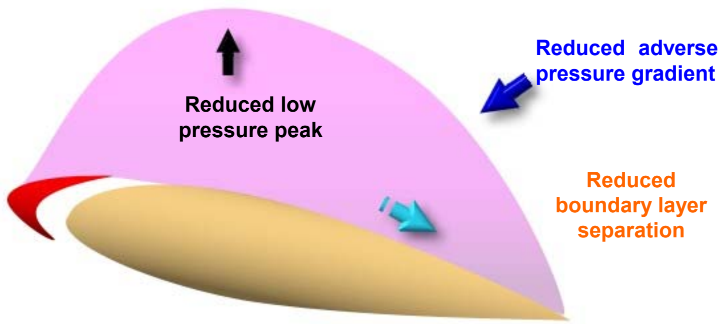



Referring to Bernoulli's Theorem and the Equation of Continuity, it follows then that the area behind the low-pressure peak will have a steep gradient as the airflow has to slow down ( ) again in order to reach the trailing edge of the wing at the same time as the air that went underneath the wing.

Refer back to the Lesson on the Boundary Layer. In that lesson it was explained that an adverse pressure gradient causes the air in the boundary layer to decelerate and to stagnate. At the separation point the air in the boundary layer actually starts to flow back towards the area where the low pressure is reaching its peak value. This situation hampers the wings capability do develop lift.

If the boundary layer starts to flow against the direction of the airflow, it will cause excessive turbulence and an accompanying breakdown in the low-pressure pattern. This can thus cause the wing to stall if the separation point moves too far forward or if the low-pressure pattern is reduced below a certain value.

When the slat is deployed, it has been shown that the low-pressure envelope takes on a more gradual pressure gradient. This flattening of the lift distribution envelope means that the adverse pressure gradient is not as strong or well developed as with the slat retracted.

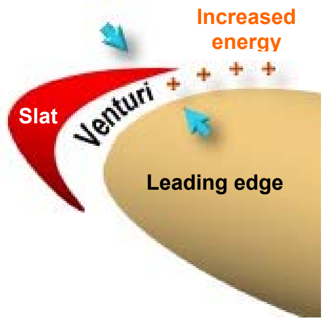



The flattening of the lift distribution envelope means that the boundary layer does not have to negotiate the steep adverse pressure gradient that exists behind the former suction peak. Therefore it retains much of its energy, thus enabling it to penetrate almost the full chord of the wing before separating.

An added bonus from a slat is that it increases the energy of the boundary layer through the venturi effect. Air that passes between the wing and the slat experiences an increase in velocity (increased kinetic energy) because of the venturi formed between the wing and the slat.

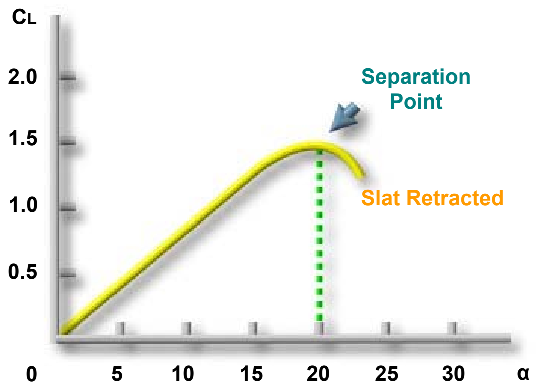
**Venturi:**

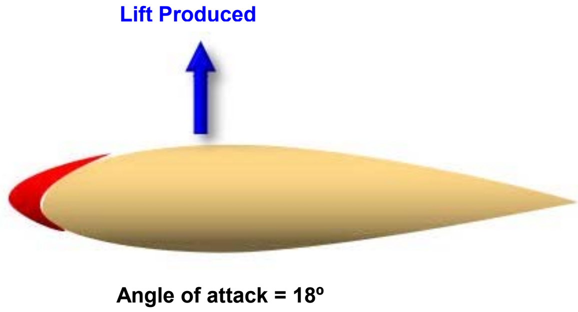
**A constricted area in an air passage that causes airflow to accelerate (increased kinetic energy) with an accompanying decrease in air pressure (pressure energy).**

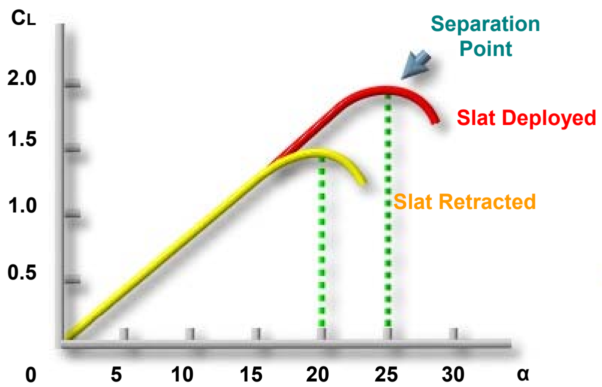


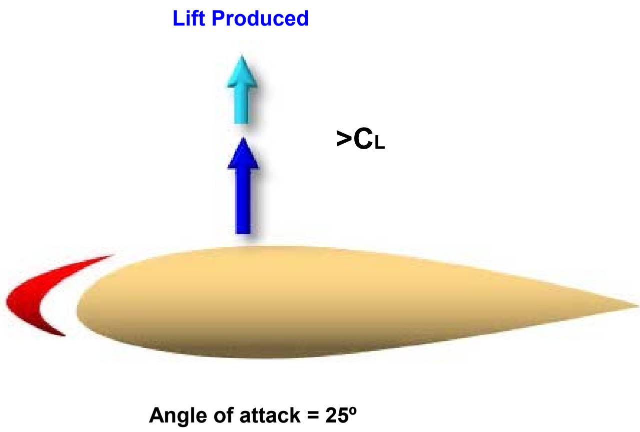

This increase in kinetic energy causes the boundary layer (++) to adhere to the wing for a longer distance before it separates due to the effects of the adverse pressure gradient, thus enabling the low-pressure area above the wing to attain higher values at higher angles of attack without the wing experiencing a stall.

If the lift coefficient and angle of attack of a slatted and an unslatted wing of the same basic dimensions are compared graphically, the following can be seen: when a small auxiliary aerofoil slat of highly cambered section is fixed to the leading edge of a wing along the complete span and adjusted so that a suitable slot is formed between the two, the $C_{Lmax}$ may be increased by as much as 70% and more. At the same time, the stalling angle can be increased by up to 10º.



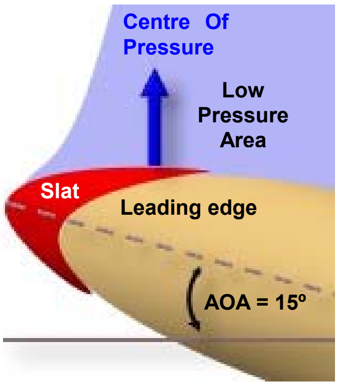



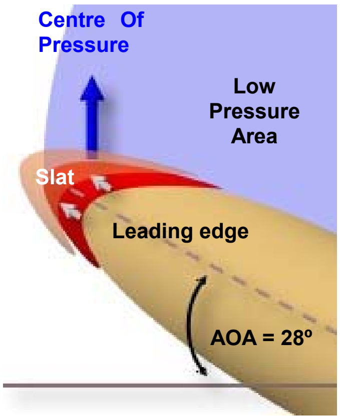

As was mentioned earlier, the use of a slat can delay the stall of this wing-planform considerably. The aircraft with a high wing loading needs to fly in the region of 210 kts in order to develop sufficient lift to compensate for the high wing loading.

By deploying a slat, the approach speed can be reduced to 134 kts. The exact amount of the reduction in stalling speed depends upon the length of the leading edge covered by the slat and the chord of the slat.

## AUTOMATIC SLATS




At an angle of attack of 15º, lift ***(the arrow represents the lift)*** acts perpendicular to the direction in which the slat deploys. Since the slat is only required at angles where the wing will require lift augmentation, the distribution of the low pressure at high angles of attack can be used to raise the slat clear of the wing, leaving a slot between the two surfaces when required.




At a high angle of attack the low-pressure area creeps well over the slat itself. In the design of an automatic slat, the designers determine the amount of suction or low pressure when the wing is still in an unstalled situation, but where the critical angle for that wing is being approached. The weight of the slat is then calculated to be such that the low pressure will automatically raise the slat when required.

## USES OF THE SLAT

**<u>Stalling Attitude</u>:**

**Remember that the CRITICAL ANGLE for a particular wing or aircraft will always remain the same, no matter what the conditions (speed, weight, altitude) or configuration (power, flaps, undercarriage). However, the nose attitude or angle relative to the horizon can differ under different circumstances.**

- Refer back to the lesson on Aspect Ratio. If a wing with a low aspect ratio is compared to a wing with high aspect ratio, the wing with the low aspect ratio will have the higher stalling attitude when measured relative to the horizon.

  Since the slat can increase the attitude at which a wing stalls, it stands to reason that a high performance aircraft with a low aspect ratio wing that can fly at a very high nose attitude when measured relative to the horizon, will have an even more exaggerated angle of attack with a slat deployed along its leading edge.

- The main purpose of slats on swept back wings, is to improve control at low speed by augmenting the $C_L$. Slats also alleviate tendencies towards wing tip stalling. However, slats produce high angles of attack at low speeds, which result in unacceptable landing attitudes and poor forward visibility. These tendencies can be reduced by using flaps in conjunction with the slats/slots to maintain acceptable attitudes and levels of forward visibility for the pilot during an approach.

Built-In Slots

Slots serve the same purpose as slats. They differ in design, in that suitably shaped slots are built into the wing just behind the leading edge of the wing. At high angles of attack, air from below the wing passes through the slots, thereby re-energizing the boundary layer that results in an increase in the $C_L$.

## STALLING WITH SLATS

As was mentioned earlier, the effect of the slat is to boost the extent of the low-pressure area over the wing. At angles of about 25º with slats, the area above the wing is considerably enlarged and a proportionally larger amount of lift is being developed. This force is increased up to 28º where after the pressure envelope collapses and the wing stalls. This sudden loss in lift can cause drastic changes in attitude of the aircraft. However, an uneven collapse of the pressure envelope results in a strong rolling moment.


**Stalling Angle (No slats deployed)** **Stalling Angle (Slats deployed)**

# TYPES OF FLAPS

## INTRODUCTION

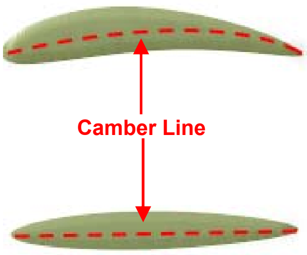
The ultimate purpose of all lift augmentation devices is to increase the value of $C_L$ and therefore lift.

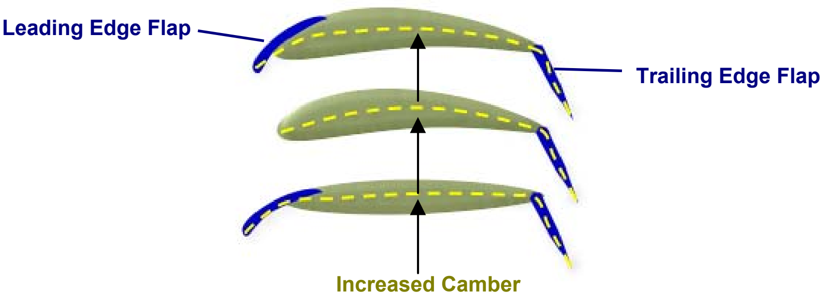
The curved camber line ***(The line joining the leading and trailing edges of an aerofoil equidistant from the upper and lower surfaces)*** of the top aerofoil is characteristic of a high lift aerofoil that produces large amounts of lift even at low speeds.

The camber line of the high-speed aerofoil is straight and is indicative of the high speeds required to produce large amounts of lift.

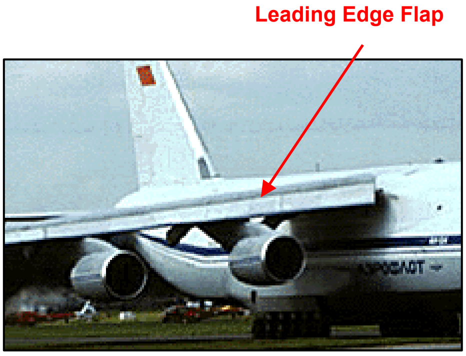
The greater the curve, ***(and therefore the mean camber)*** the greater the inherent lift capability of a wing.

An increase in camber causes an increase in lift. The purpose of flaps, whether they are situated on the leading or trailing edge on a symmetrical or cambered wing, is to increase the camber and in so doing; increase the $C_{Lmax}$ and lift.





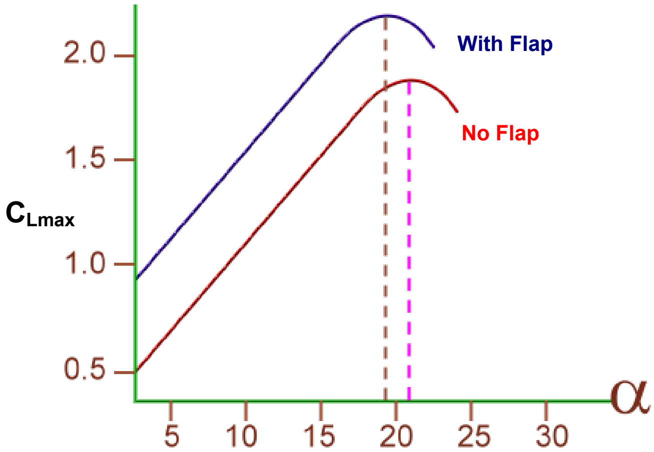


## ACTION OF FLAPS

Camber ***(and therefore Lift)*** is increased by deflecting the leading or trailing edge ***(or both)*** of the wing down.

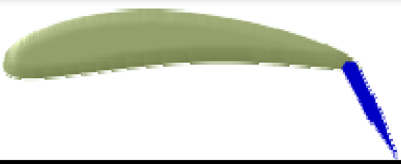
**Note : The curve of the mean camber line of a wing with both leading edge and trailing edge flaps down, is abrupt at the leading and trailing edges. Therefore the increase in lift is not as much as with a properly curved mean camber line.**


**The increase in camber (and therefore lift), means that the speed can be reduced.**

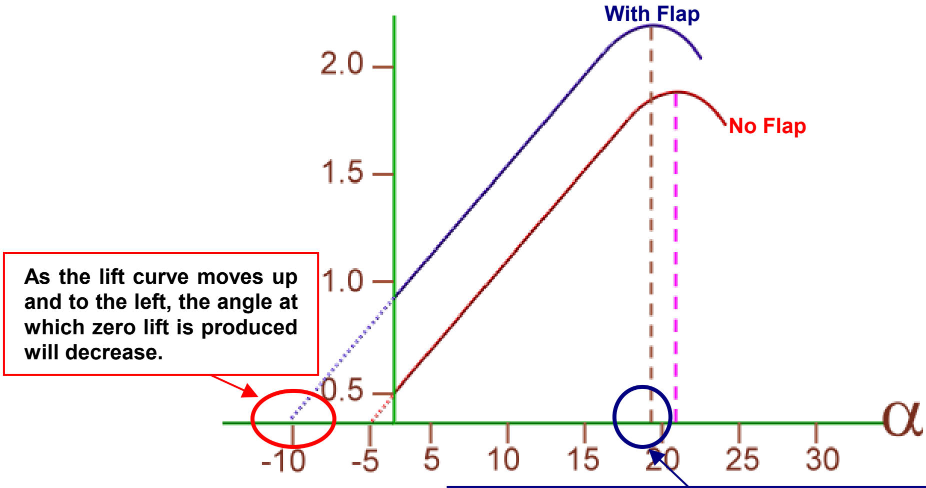



The graph shows the lift curve for a wing without flaps. With flaps down, the lift curve moves up and to the left; giving an indication of the increase in $C_{Lmax}$ at a smaller angle of attack.

**An aircraft with leading edge flaps. The leading edge flaps form an integral part of the leading edge of the wing and thus the change in camber occurs with the leading edge flaps in the down position.**



**The B727 is also equipped with powerful trailing edge flaps. As with the leading edge flaps, the trailing edge flaps form an integral part of the trailing edge of the wing and therefore a change in camber also occurs with the trailing edge flaps in the down position.**




**The stalling angle and the angle at which zero lift is produced is also reduced.**

**This means that the angle of attack at which the $C_{Lmax}$ is produced, is slightly less with trailing edge flaps than with the basic aerofoil eliminating the high angles of attack associated with slats.**

## TYPES OF FLAPS

Aircraft come in all shapes and sizes ***(from the small to the huge),*** with different take-off, approach and stalling speeds.

It is therefore logical that not all aircraft will make use of the same type of flap, but that designers will incorporate flaps that are best suited to the requirements of that specific aircraft.

The trailing edge flap comes in many variations. All increase the $C_{Lmax}$, but some are more efficient than others and increases in $C_{Lmax}$ vary from between ***50%*** to ***120%.*** The more efficient types of flap are usually more complicated and better suited to larger type aircraft.

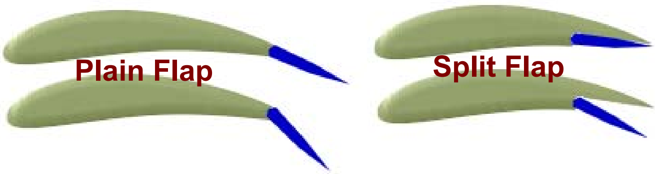
$$L = C_L \tfrac{1}{2}\rho V^2 S$$

The variable factors in the lift formula that affect lift are : **$C_L$ *(camber and α)*, $V^2$ *(Velocity)*** and **S *(Wing Area)*.** For the sake of simplicity, $V^2$ and α are kept constant. **Therefore, this leaves camber ($C_L$) and S *(wing area)*, which are design factors.**

## FLAPS THAT INCREASE $C_{LMAX}$ BY INCREASING CAMBER

The two most-simple forms of flaps are:

- **Plain Flaps, and**
- **Split Flaps**.




**Plain and Split flaps** form part of the wing trailing edge when not in use and can thus be made very strong while saving weight - a very critical consideration with fighter aircraft.

When lowered, the flaps cause an increase in camber at the trailing edge. On average Plain flaps increase the $C_{Lmax}$ by about ***50%*** while Split flaps increase $C_{Lmax}$ by about ***60%.***

### PLAIN FLAPS

Plain flaps are most commonly used by fighter aircraft, and some smaller commercial aircraft.

### SPLIT FLAPS

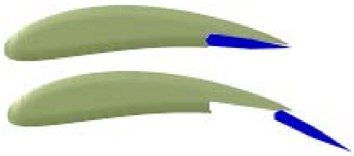
Split flaps are widely used by light commercial aircraft and some older fighter aircraft such as the Voodoo. The DC-3 and Harvard also make use of split flaps.

## FLAPS THAT INCREASE $C_{LMAX}$ BY INCREASING WING AREA (S)

### FOWLER FLAPS

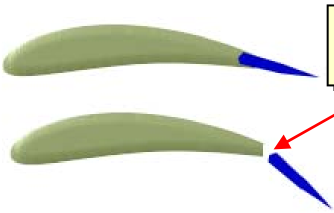
Where plain and split flaps increase $C_{Lmax}$ by increasing camber, Fowler flaps not only increase $C_{Lmax}$ by increasing the camber, but also increase the chord length thereby increasing the wing area and thus lift. ***(Span x Chord = Wing area.)*** Simple Fowler flaps increase $C_{Lmax}$ by as much as ***90%.***

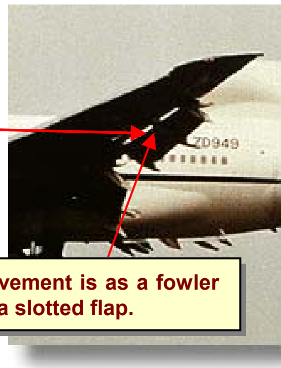




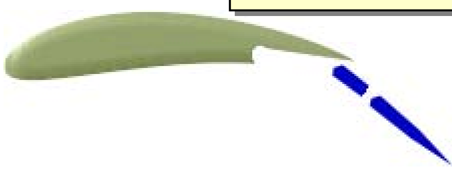
### SLOTTED FLAPS

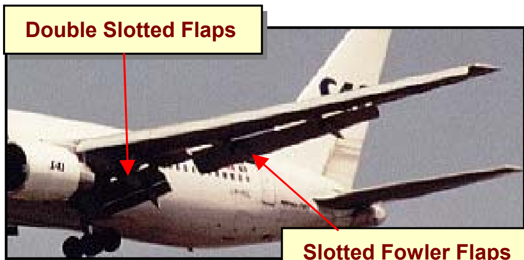
If air could be constrained to follow the deflected surface of the flap and not break away or stall, the effectiveness of flaps would be vastly increased. When Slotted flaps are lowered, gaps are left between two or more flap sections. These gaps function in the same way as leading edge slots. The air flowing through these gaps is accelerated by the venturi effect and therefore the boundary layer is re-energized and thus stays attached further down the next flap section. $C_{Lmax}$ increases are in the region of ***100%.***







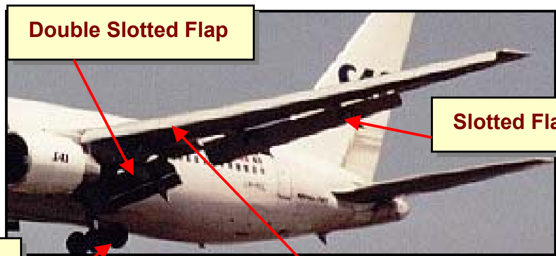

Most modern airliners combine different types of flap. This A-300 has ***Double Slotted Flaps*** on the inboard sections with ***Slotted Fowler Flaps*** on the outboard sections.

## LEADING EDGE FLAPS

The use of leading edge flaps is becoming more prevalent on large swept wing aircraft. Aircraft like the DC-10 use full span leading edge slats. Other large airliners such as the Boeing 707, 727 and 747 use leading edge flaps - otherwise known as Krueger flaps.

Leading Edge Flap

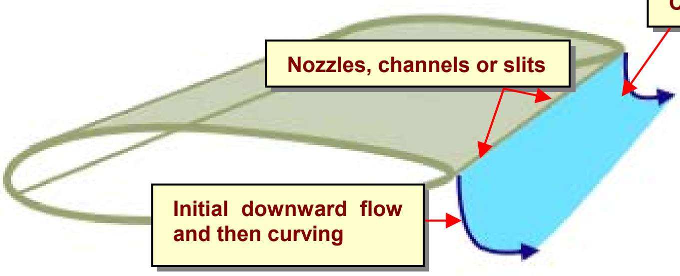
By using a combination of leading and trailing edge flaps, lift can be increased by as much as 120%.




The extent to which different types of flaps are combined to achieve the maximum possible lift increase is very apparent. In this case full span leading edge flaps (Krueger flaps) with slotted and double slotted trailing edge flaps.

## JET FLAPS

Jet flap makes use of a gas jet or efflux that is directed from the trailing edge via a channel or slits to form a high velocity ***(even supersonic)*** "curtain of air".




**This is an example of a very basic jet flap. Such jet flap schemes require that the efflux be ducted through the wing and are normally referred to as "internal flow" systems.**

The flow although initially directed downward from the slits curves ***(as a result of the free stream flow)*** to align with the flight path resulting in an increase in lift. ***(On a conventional airfoil, the local pressures on the top and bottom surfaces must return to ambient at the trailing edge. But for the jet-flap airfoil, the curvature results in higher pressure on the bottom of the high-momentum jet and lower pressure on its top and therefore an increase in up wash in the vicinity of the leading edge.)***

In effect, the jet adds to the chord of the airfoil, and it contains vorticity, which can affect the pressure distribution at the forward part of the airfoil. Part of the additional lift, of course, comes from the momentum in the downward-pointing jet.

The air forms an equally energized and highly stable boundary layer.

The effect of this type of jet flap is to reduce the stall speed by a considerable margin.

***(The Lockheed F-104 Starfighter had a tiny wing with a razor-sharp leading edge designed for good supersonic flight. As a consequence, its takeoff and landing characteristics would have been very poor were it not for the use of a jet flap.)***

The most common type of jet flaps are "external flow" systems where the efflux is directed over the wing or flaps. Where the efflux is combined with flaps, it is known as **"power-augmented high-lift devices"** or more commonly as **"blown flaps".**

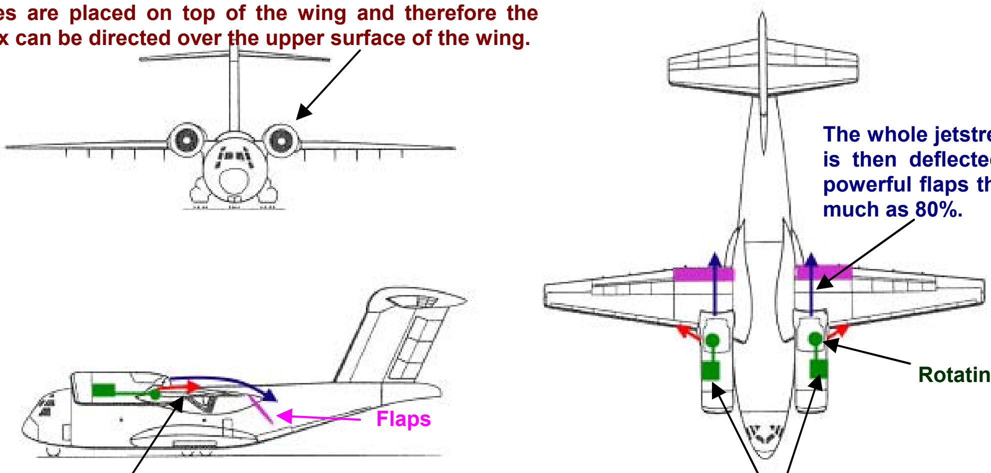
## BLOWN FLAPS

Blown Flap, as in the case of Jet Flap, makes use of jet efflux in combination with flap. Some of the more popular blown flaps are:

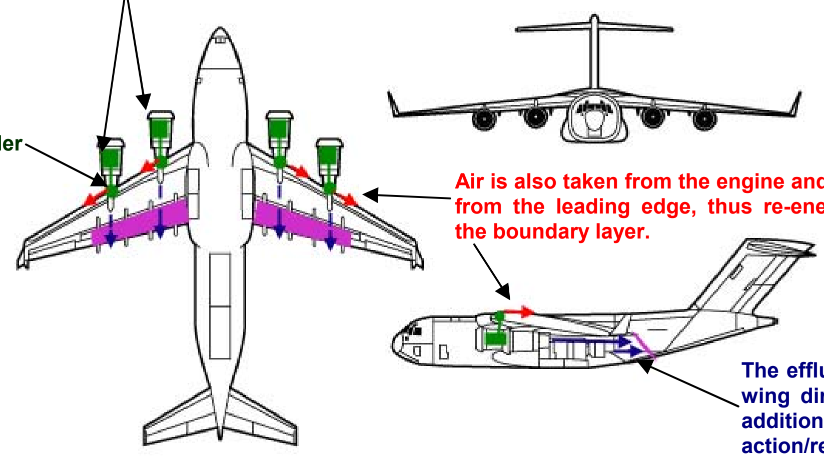
- **Upper Surface Blowing**
- **Externally Blown Flap**
- **Internally Blown Flap**

The $C_{Lmax}$ increase gained from these systems is very large and very short take-off and landing distances have been achieved by aircraft used for STOL research.

## Upper Surface Blowing (YC-14)



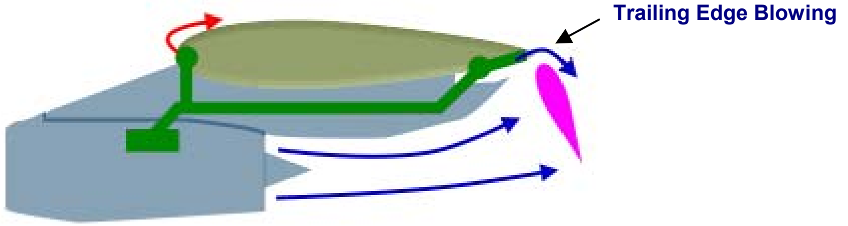

## Externally Blown Flap (C- 17)



The C-17 is equipped with an externally blown flap system that allows a steep, low-speed final approach and low-landing speeds for routine short-field landings. With this powered-lift system, the engine exhaust flow is directed below and through slotted flaps to produce additional lifting force and allow steeper landing descents.

## *Internally Blown Flaps*

In this case the engines are fitted underneath the wing. In addition to the external blowing onto the flaps and direct blow slots, trailing edge blowing is employed in the trailing edges of the wings to blow air directly onto the flaps. This is the most efficient combination of all the jet flap systems.



# EFFECT OF FLAP ON OPERATIONS

## Introduction

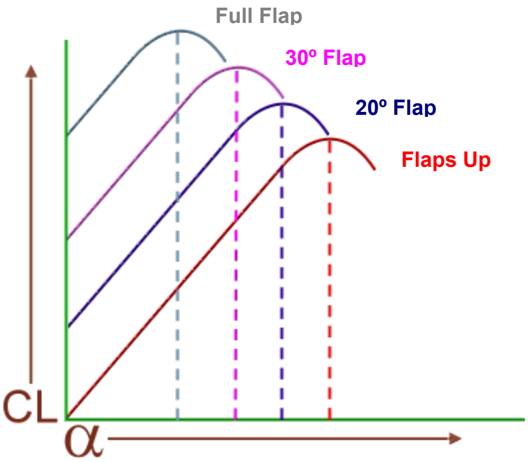
No matter what type of flap is incorporated into the design of the aircraft, its use will effect aircraft operations. Pilots must be made aware of these effects and the dangers and advantages associated with them. During the discussion, emphasis will be placed on the following:

- Effect on stalling angle
- Change in pressure distribution
- Change in pitching moment
- Lift/Drag ratio
- Flap for take-off
- Raising flap
- Leading edge flap
- Flap and sweepback
- Flap and wing tip stalling

# EFFECT ON STALLING ANGLE

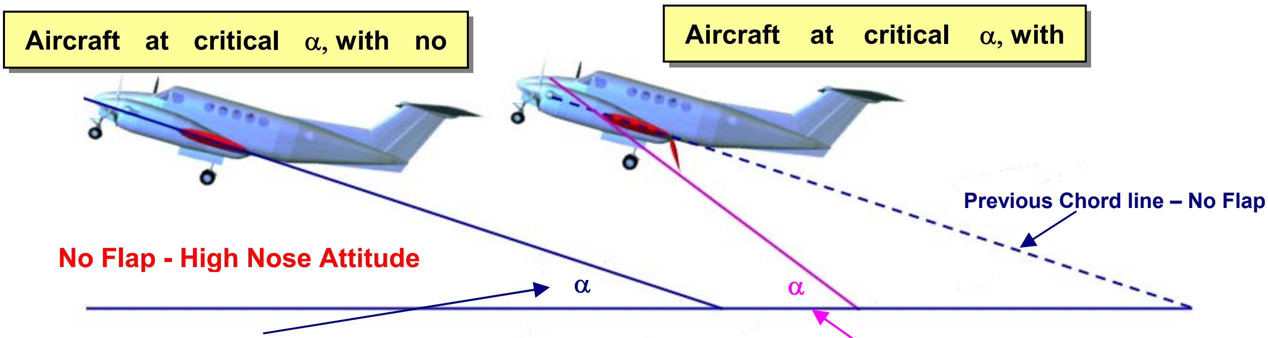
Note: For the following explanation it is important to know that all other factors that affect critical angle of attack are not considerd. Do not confuse angle of attack with attitude.

Angle of Attack is defined as the angle between the Chord Line ***(The straight line joining the centres of the curvature of the leading and trailing edges of an aerofoil.)*** and the Relative Airflow ***(RAF) and***, an aircraft will always stall at the same critical angle of attack in sub-sonic flight with a specific wing configuration. ***(e.g. Flaps up or Flaps down)*** .




By changing the camber of the wing (with flap for example), the $C_L$ vs $\alpha$ graph moves up and to the left.

**Although in reality, the critical angle of attack decreases with increased flap, for the purposes of this explanation, it will be assumed that the critical angle remains constant.**



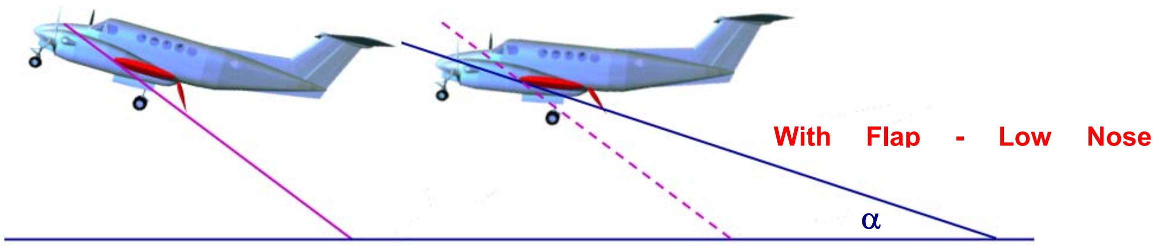

Under normal conditions (without any flaps) an aircraft stalls at an angle of attack of "α". ***(From the graphic it can be seen that angle "α" represents a relatively high nose attitude relative to the horizontal).***

If trailing edge flaps are now lowered, ***(according to the definition for chord line)***, the chord line will subsequently shift and the angle of attack will increase and will be greater than the critical angle.

**With Flap the angle of attack (α) is increased beyond the critical angle of attack, and has to be reduced the critical angle.**

In order to reduce this increased angle of attack to the critical angle (maintaining flaps down), the attitude of the aircraft will have to be lowered.

This leads to a lower nose attitude relative to the horizon although the critical angle of attack "α" remains the same.

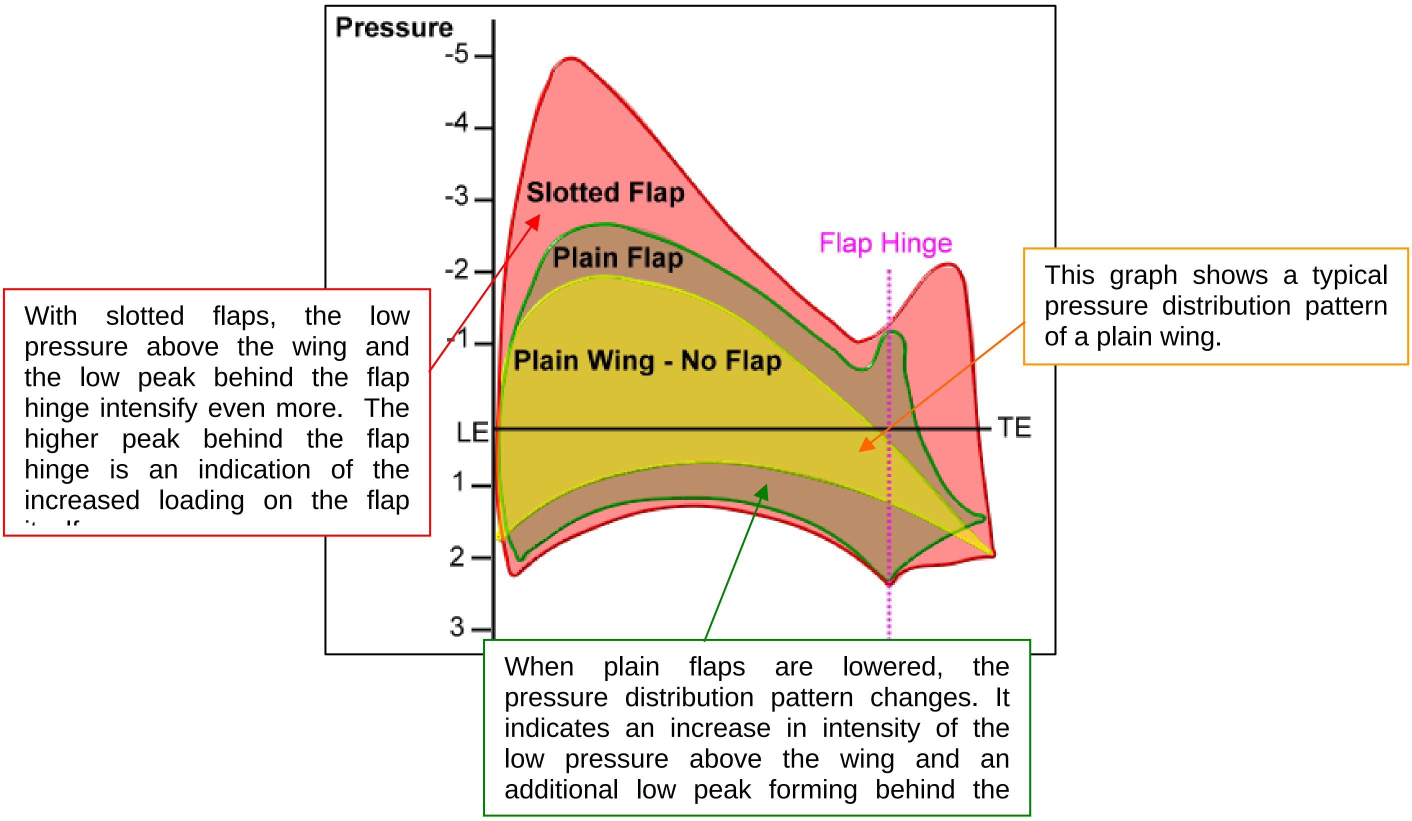



***The stalling angle (attitude of the aircraft) will be displayed on the aircraft's attitude indicator.***

Although factors affecting critical angle were ignored during this discussion, it must be remembered that in reality the lowering of flaps increases camber, and this increase has the effect of reducing the stalling angle. For each increasing flap angle there is a fixed and lower stalling angle which is caused by the change in section when flap is lowered.

## CHANGE IN PRESSURE DISTRIBUTION

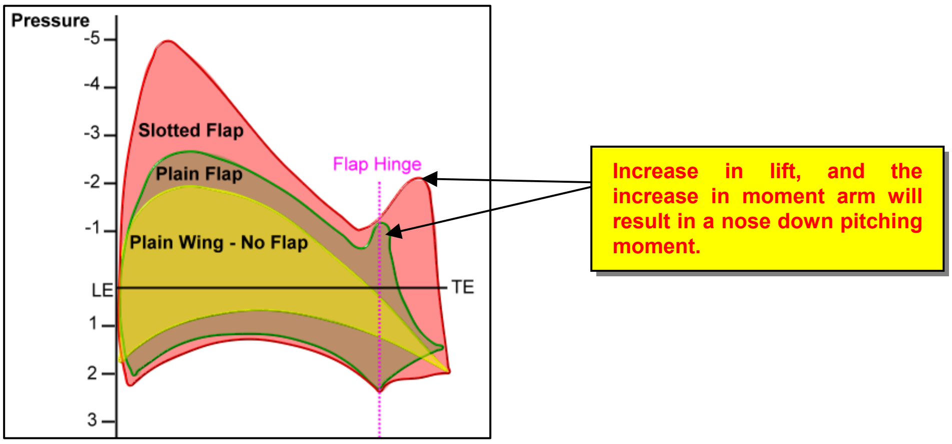
When flaps are deflected, lift increases. This lift increase is apparent when one looks at the pressure distribution around a wing.




## CHANGE IN PITCHING MOMENTS

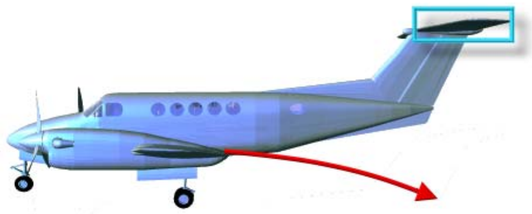
There will be a pitching moment when flaps are lowered. There are two reasons for this:

- Firstly, a pitching moment will occur due to the change in pressure distribution around a wing when trailing edge flaps are lowered.

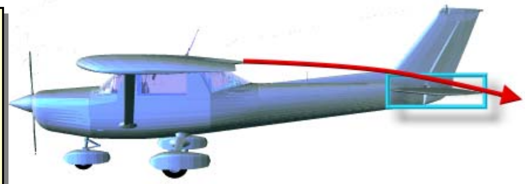


- Secondly, when lowered, trailing edge flaps cause an increase in the amount of downwash behind the wing. The position and size of the tail plane, will determine the amount by which the pitching moment is changed.

**In the case of this aircraft, all of the downwash will miss the horizontal tail plane and therefore the pitching moment of the flaps will have the overriding effect. (Nose Down)**



**Due to the high wing configuration of this aircraft, part of the downwash will strike the horizontal tail plane causing a nose-up pitching moment. The pitching moments due to the flaps and downwash will oppose each other and the overall moment will depend on which moment is the larger.**



**The moment due to pressure distribution and the moment due to the downwash generally oppose each other. The greater of the two will determine the overall pitching moment.**

**Leading edge flaps reduce the nose-down pitching moment.**

## LIFT /DRAG RATIO

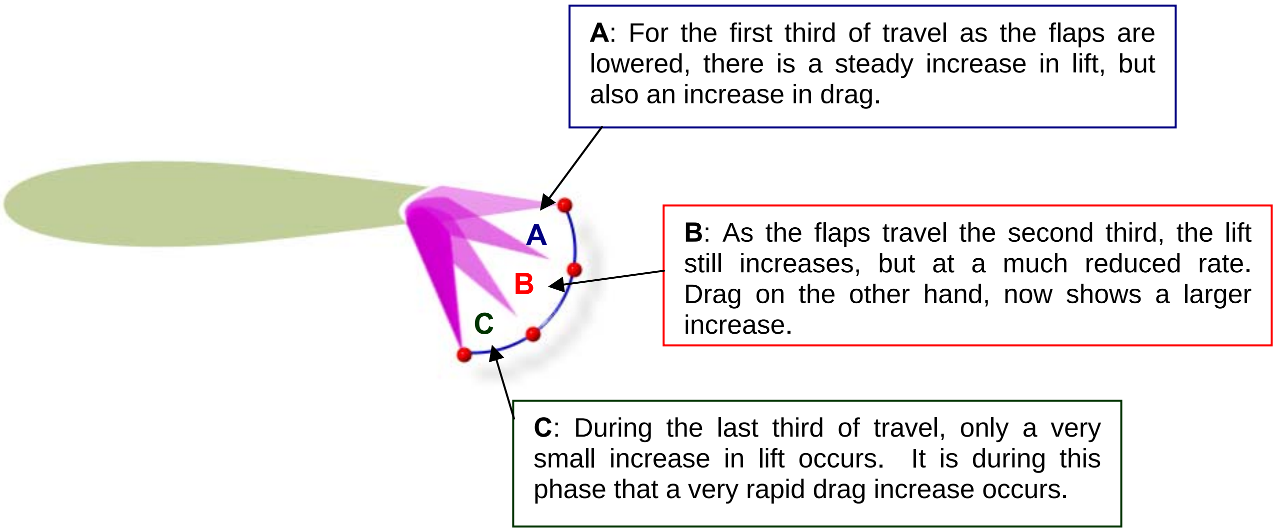
As flaps are lowered the value of $C_{Lmax}$ increases, and therefore lift increases. However as lift increases so too does drag.

- ***Lift Dependent drag***

  Lift Dependant ***(Lift Dependent Drag occurs due to the fact that the aircraft is producing lift, and when Lift is increased, Lift Dependent Drag is increased.)*** will increase due to the extra lift being produced by the lowering of flaps.

- ***Zero Lift Drag***

Because flaps are normally lowered into the free air stream, Zero Lift Drag, in specifically Form Drag, will also increase.




Therefore although lift increases when flaps are lowered, drag increases as well, and the lowering of flap almost invariably worsens the best lift/drag ratio. In fact the drag increase is proportionately more than the increase in lift at the angles of attack where the best L/D-ratio is found. Looking at the lift and drag increase during the lowering of flap. The increase is not a steady increase, and three stages can be identified during the travel of the flap as it is lowered.

The following are extremely important aspects to remember while using flaps during the various flight regimes:

- When flaps are used during **take-off** or **manoeuvres**, it is important to select a flap setting that will give the maximum lift advantage while ensuring the minimum drag penalty.

- When full flaps are used during **approach for landing**, the large amounts of drag produced by the fully lowered flaps are actually very useful. The additional drag allows a steeper approach path without the speed becoming excessive by acting as an airbrake. Forward visibility is also improved due to the lower nose attitude with flaps.

- When flaps are used during **landings**, the lowered flaps reduce the stalling speed and thus the speed at which the approach can be flown and the touchdown made. Full flaps also act as airbrakes ***(due to the excessive drag)*** and help to decelerate the aircraft during the round-out, float and landing.

## FLAPS FOR TAKE-OFF

During a take-off, the take-off run is shortened if the correct flap setting ***(The correct flap setting for take-off and landing is always found in the Aircrew Manual for each aircraft type)*** is selected.

The flap angle is that for the best L/D-ratio that can be obtained with the flaps in any position except fully up.

If any more flap is used, lift will still increase, but the increase in drag reduces acceleration and lengthens the take-off run. ***(Although it might still be shorter than a run without flaps.)***

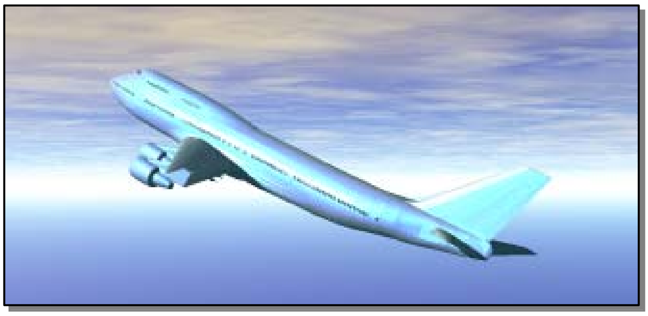
Pilots taking off at or near the MTOW (**Maximum Take-off Weight**) should select the flap setting to the recommended flap angle. In so doing the maximum lifting effort (L/D-ratio) will be obtained from the wing. This applies to all aircraft - whether they are fighters or large airliners.

## RAISING FLAP

Because lift decreases suddenly as the flaps are raised after take-off, the aircraft will lose height unless the angle of attack is increased to counter the decrease in $C_{\mathbf{Lmax}}$.

The aircraft stalling speed will also increase due to reduced $C_{LMAX}$. Take Off Safety Speed is based on stalling speed with take off flap selected.

If no attempt is made to increase the angle of attack, the aircraft will continue to lose height until it accelerates to a higher air speed ***(This counterbalances the effect of the decrease in CLmax).***



If the sink due to raising of flaps is countered by increasing the angle of attack, the aircraft attitude becomes distinctly nose-up. The more efficient the flaps, the greater the drop in $C_{\mathbf{Lmax}}$ and therefore the greater the corrections needed to counter the sink.

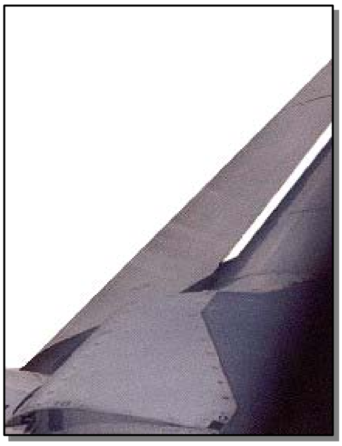
For large aircraft that usually have very efficient flaps and that operate at or near their MTOW it will not be wise to retract all the flaps at once.

The sink caused by raising all flaps at once will need large and exaggerated corrections to stop the aircraft from losing too much height. One way to prevent the sinking moment is to reduce the $C_L$ gradually by raising the flaps in stages.

On some aircraft it is recommended that the flaps be raised in stages. This gives the aircraft chance to accelerate and to counter the reduction of $C_{Lmax}$ before the next notch of flap is raised. (Generally this is good airmanship and flight safety practice)

## LEADING EDGE FLAP

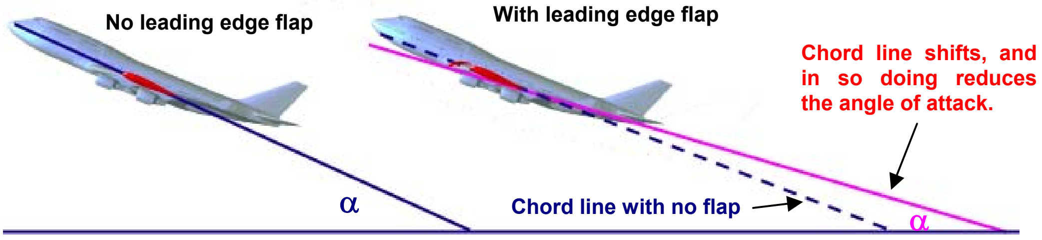
The use of leading edge flaps is becoming more prevalent with large swept-wing aircraft and normally they are used in conjunction with trailing edge flaps.



The operation of leading edge flaps can be controlled from the cockpit; or when coupled to an air speed measuring system that deploy the flaps when the speed falls below a certain value and vice versa. When the flaps operate automatically, they are normally referred to as manoeuvre flaps and are widely use on fighters.

Leading edge flaps, as with other flaps, increase the $C_{Lmax}$ and decrease the stalling speed when deployed. The increase in $C_{Lmax}$ is similar to that obtained with slats, but the stalling angle is not as high.

As with trailing edge flaps, if leading edge flaps are lowered, ***(and all other factors are ignored)*** the chord line will again shift. However due to the fact that the flaps are situated at the leading edge, the effect will be the opposite and therefore the **stalling angle will be higher, leading to a higher nose attitude.**



As with trailing edge flaps, leading edge flaps do not only affect the chord line, camber also increases ***(with the normal effect of increasing $C_{Lmax}$)*** and because leading and trailing edge flaps are normally used together, the overall pitching moment will also be affected by the amount of trailing edge flaps lowered.

### Flaps and Sweepback

A wing with sweepback produces less lift than an unswept wing. Sweepback will also reduce effectiveness of any trailing edge flaps and control surfaces.

Any sweepback incorporated on a wing, results in less lift being produced than is the case with a straight wing. However, with low values of sweepback, the reduction in lift is not as much as with higher values (40 – 45º). Also, as an overriding design feature, moderate sweepback presents distinct advantages with regards to stability.

***An aircraft with wings swept to the fully forward position and the flaps in the down position, will have maximum flap exposure as the whole flap span is exposed to the airflow and a maximum increase of $C_{Lmax}$ is achieved.***

***When the wings are swept fully back, the frontal area of the flaps exposed to the airflow reduces drastically and so does the increase in $C_{Lmax}$. (With 35º sweep, increase in $C_{Lmax}$ is only about 20%)***

**With these plan views of the aircraft with the wings in the fully forward and fully backswept positions, the difference in the frontal area of the flap exposed to the airflow, becomes apparent. The greater the sweep angle, the smaller the frontal area and therefore the less efficient the flaps become.**

## FLAP AND WING TIP STALLING

A desired aircraft-stalling characteristic is one where the wing stalls progressively from root to tip. With flaps down, the shape of the wing is changed over mainly the inboard section of the wing and more lift is produced in that area.

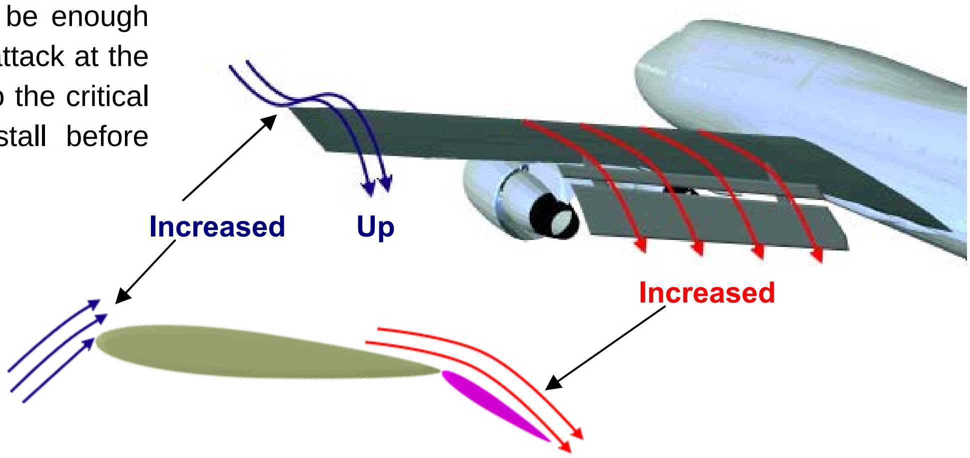
The lowering of flap may either increase or alleviate the tip stalling tendencies of a wing as follows:

- The increase in tip stalling tendency is due to increased downwash, while
- The decrease in tip stalling is due to increased suction effect on the boundary layer.

## INCREASE IN WING TIP STALLING TENDENCY

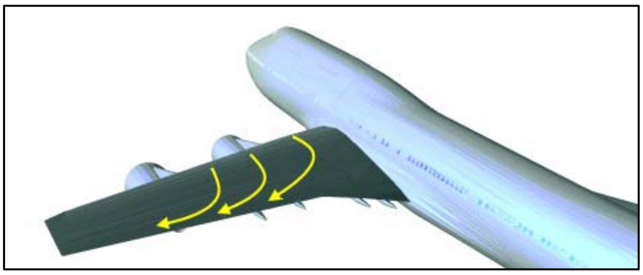
When flaps are lowered, the induced downwash increases. To balance this increased induced downwash, an up-wash is induced over the outer portions of the wings.

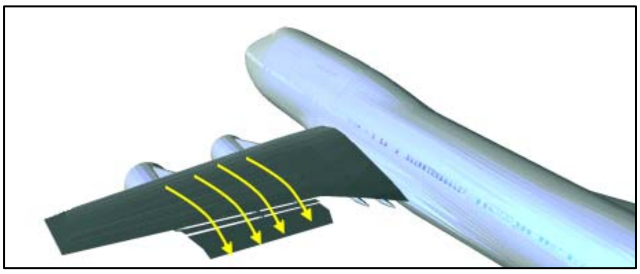
At high angles of attack this induced up-wash may be enough to cause the angle of attack at the wing tips to increase to the critical angle and therefore stall before the inboard sections.




## DECREASE IN WING TIP STALLING TENDENCY

With swept wings there is a tendency for the boundary layer to flow outwards towards the wing tips.





When flaps are lowered, the increased suction over the inboard sections of the wings restricts this outwards flow of the boundary layer and this has a beneficial effect on the wing tip stalling tendency.

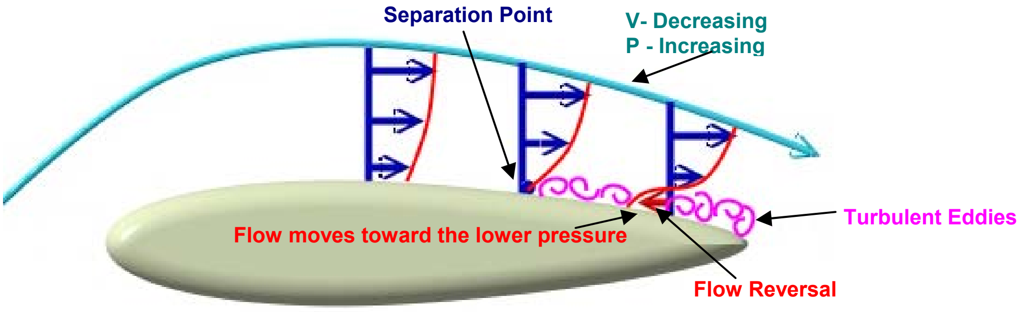
***The eventual outcome of these two opposing tendencies will depend on which of the two have the greater effect.***

# BOUNDARY LAYER CONTROL

## INTRODUCTION

Surface friction and the adverse pressure gradient decrease the velocity and the kinetic energy of the boundary layer. As the velocity and kinetic energy decrease, the boundary layer is affected as follows:

- When an amount of the Boundary Layer stops moving, the rest of the Boundary layer overshoots this point and causes the airflow to separate from the surface at the ***Separation Point***. Behind the Separation point, the air forms ***Turbulent Eddies***.
- Due to the Adverse Pressure Gradient the pressure increases in the direction of the flow. Air tends to flow from high to low pressure. Therefore, the air will flow forward towards the Separation Point. This condition is known as ***Flow Reversal***.
- This means that the ***air moves forward***, the Boundary Layer separates from the surface, lift is destroyed, and drag becomes excessively high.



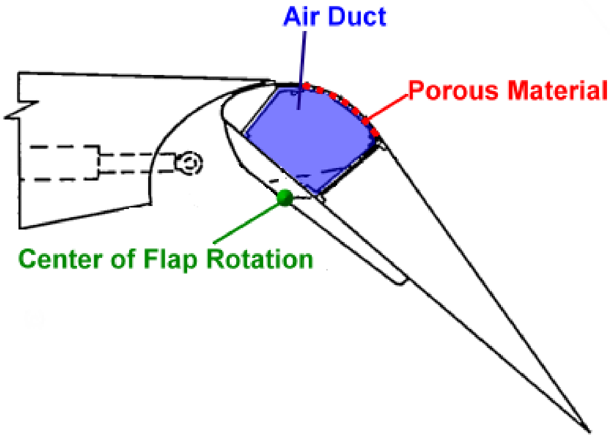

If the boundary layer can be made to remain laminar and attached, as it moves over the wing, $C_{Lmax}$ will increase and drag ***(in particular surface friction and form drag)*** will be reduced.

It was stated that the boundary layer separates because drag reduces the velocity of the flow and the adverse pressure gradient reduces kinetic energy level. Fortunately there are various methods of controlling the boundary layer so that it remains attached to the surface of the wing. All these methods rely on the principle of ***adding KINETIC ENERGY*** to the lower levels of the boundary layer ***(Re-energizing).***

There are various ways in which the boundary layer can be re-energized, but the more common methods are:

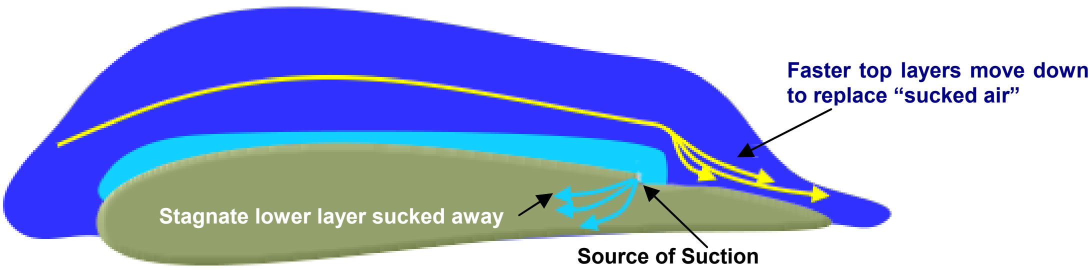
- ***Boundary Layer Suction.***
- ***Boundary Layer Blowing.***
- ***Vortex Generators.***
- ***Deflected Slipstream.***

## BOUNDARY LAYER SUCTION




The lower layer of the boundary layer (laminar sub-layer) is drawn off by means of suction. The suction is achieved by means of either a slot ***(or series of slots)*** in the wing surface or a porous surface over the area where the suction is needed. ***(Suction distributed over a porous area has a better effect than a slots or series of slots.)***

These devices are placed where the thickening effect due to the adverse pressure gradient becomes marked. As the lower levels are sucked off the upper part of the boundary layer now moves on to the surface of the wing. This reduces the thickness of the boundary layer and as the slow flowing sub-layer has been replaced by faster moving air, the speed ***(therefore the kinetic energy)*** of the boundary layer also increases.



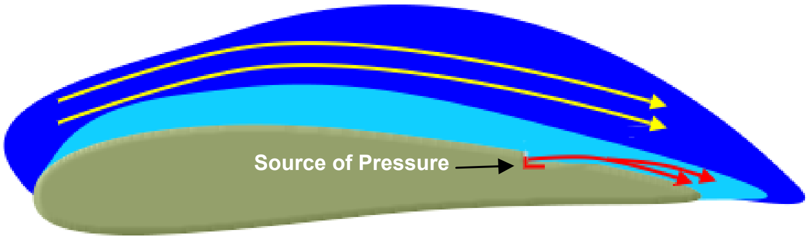

If enough suction could be applied, separation of the boundary layer could be prevented at almost all angles of attack. However, the power required to draw off the whole boundary layer, and replace it with completely undisturbed air is so large that the output of a very powerful engine would be needed.

Even small amounts of suction increase the strength and stability of the boundary layer and reduce the tendency of the boundary layer to separate at high angles of attack.


The F86 Sabre made use of boundary layer sucking

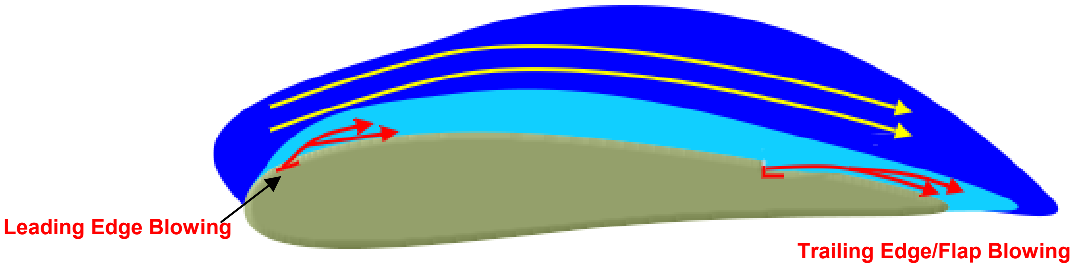
## BOUNDARY LAYER BLOWING

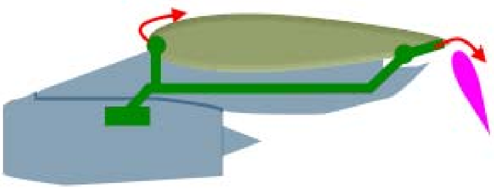
Another option to re-energize the boundary layer is to eject air at high speed in the same direction as the boundary layer. This is normally done at a suitable point close to the wing surface and speeds up the retarded sub-layer enabling it to penetrate further into the adverse pressure gradient before actually separating.



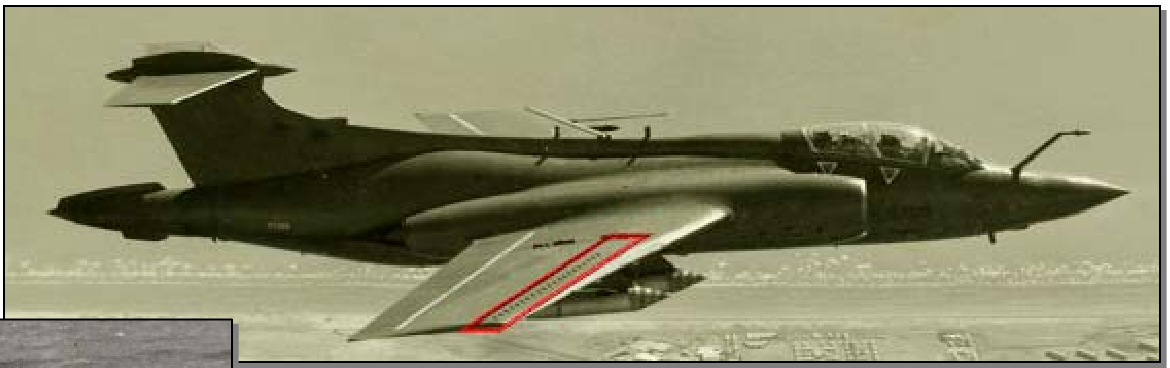

**The average $C_{Lmax}$ of a plain aerofoil is in the region of 1.5. With flap, this may be increased to around 2.5. If boundary layer control is applied over the flap, the $C_{Lmax}$ can rise to as much as 5 or even more.**

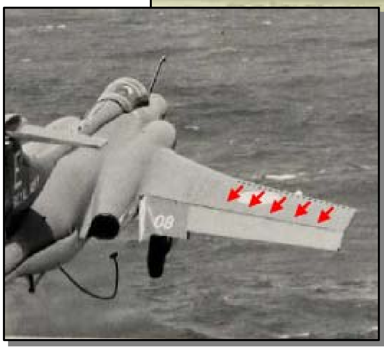
If, in addition to boundary layer control over flaps, blowing also takes place at the leading edge, even higher $C_{Lmax}$ increases can be obtained. However as with suction, large amounts of power are required to achieve such high $C_{Lmax}$ figures.



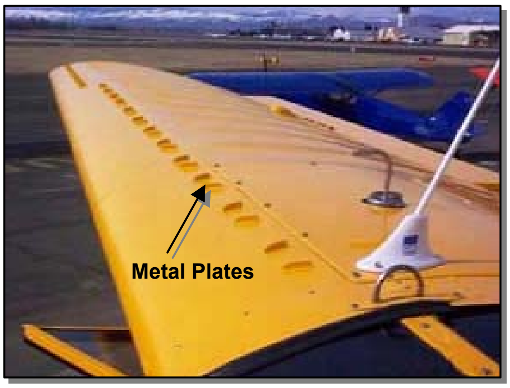
When suction or blowing is used in conjunction with flaps, very high $C_{Lmax}$ values can be achieved. The blowing of air takes place near the flap hinge line.





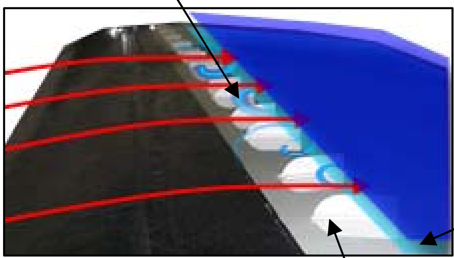
A good example of an aircraft that makes use of boundary layer blowing is the Buccaneer that has leading edge blowing. When maximum use is made of boundary layer control, the $C_{Lmax}$ increase can be such that landing speeds can be reduced from 100KIAS to around 60KIAS - sufficient evidence of the important role that boundary layer control plays in aerodynamics.

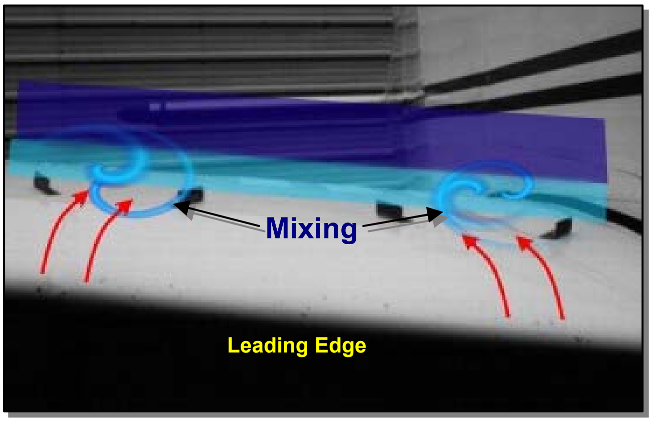
## VORTEX GENERATORS




Vortex generators can either consist of metal plates that project at right angles to the surface of the wing. ***(or small jets of air issuing normal to the surface).***

Transition to turbulence takes place and vortices are formed which, mix the more stagnant lower layers with the faster moving air near the top of the boundary layer; thus transferring kinetic energy to the lower layers. This enables the boundary layer to remain attached further back on the wing.




These vortex generators make full aileron control at very low speeds possible.

However, the $C_{Lmax}$ increase at low speeds is more than offset by the extra drag caused at normal cruising speeds. ***(The advantage of air jets, are that they can be turned off when not required and thus avoid the increase in drag).***

## DEFLECTED SLIPSTREAM

The Breguet 941S STOL transport is perhaps an extreme example of an aircraft that used the deflected slipstream effect, but it demonstrates the principle well. The entire wing of the 941 is at all times in the slipstream of the propellers. When lowered, the flaps gain in effectiveness from the increased airflow velocity in the slipstream, which is deflected