DOCUMENT
GSM-G-CPL.003

DOCUMENT TITLE
AERODYNAMICS 2

CHAPTER 3 – DIRECTIONAL & LONGITUDINAL STABILITY

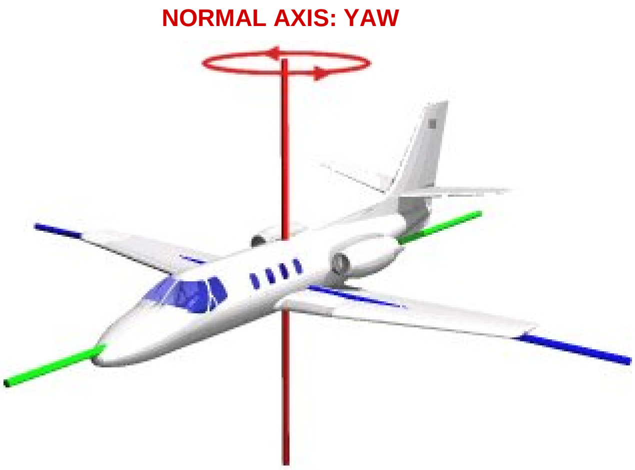
Version 1.0
September 2012

CONTENTS ....PAGE

DIRECTIONAL STABILITY

INTRODUCTION

Static stability refers to the behavioural tendency that an object (aircraft), displays after its state of equilibrium has been disrupted. If an aircraft is stable/unstable about the normal axis ***(yaw)***, it is said to have directional stability/instability.



Positive Static Stability

When an object is displaced from its position by an external force, and then returns to its original position after the force is removed, it is said to have positive static stability.

Negative Static Stability

When an object is displaced from its original position by an external force, and then moves even further away from the original position, it is said to have negative static stability.

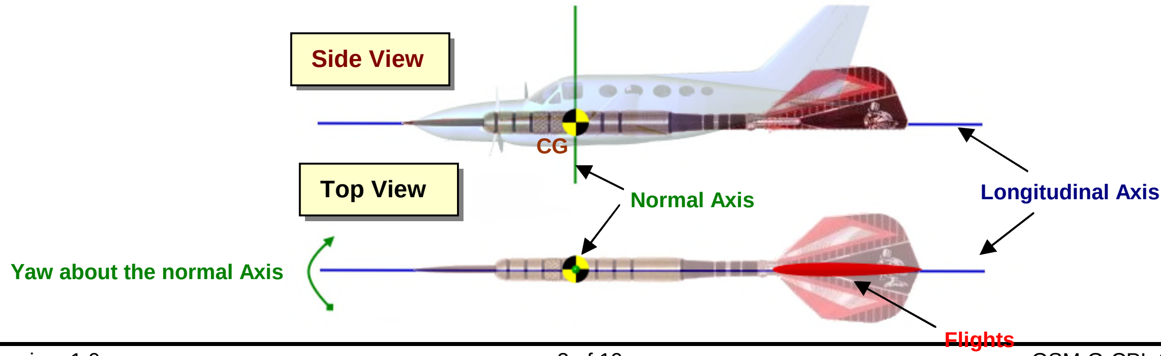
Neutral Static Stability

When an object is displaced from its original position by an external force, and then tends to remain in this displaced position, it is said to have neutral static stability.

Because Positive Static Stability is the most desirable, and Neutral and Negative Stability are undesirable, methods of achieving Positive Static Stability are sought when the aircraft is constructed. There are nearly as many fin and elevator configurations as what there are aircraft, and as aircraft are designed with different configurations, the stability characteristics will also differ.

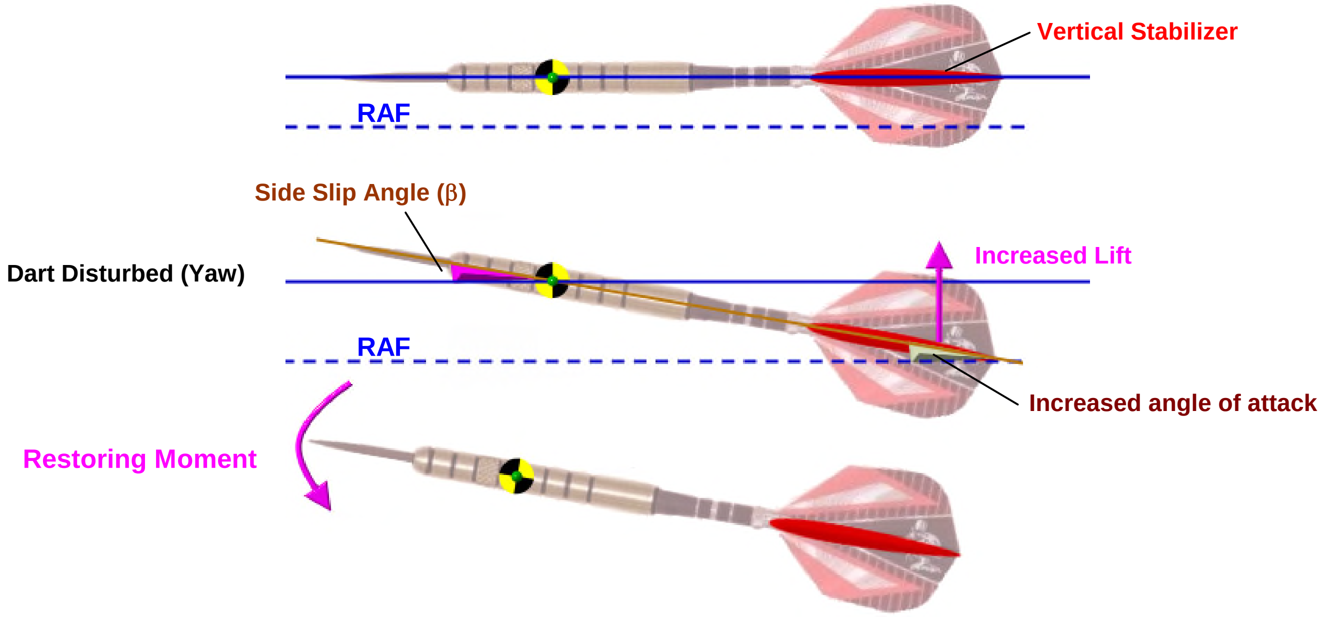
ACHIEVING DIRECTIONAL STATIC STABILITY

Directional stability and control refer to aircraft behaviour in the yawing plane or, in other words, movement of the longitudinal axis as it is rotated about the normal ***(vertical)*** axis and CG. Only pure yaw will be discussed ***(in pure yaw, there is no pitching and rolling)***.



A very simple way of explaining both directional and longitudinal stability is to consider a dart. The flights or vanes fitted to the dart keep it aligned with the flight path.

The set of vanes that impart the directional stability to the dart ***(as seen from the top)*** may be referred to as the vertical stabilizers.
If the dart is disturbed during flight and a displacement in yaw about the CG ***(remember that the normal axis runs through the CG)*** occurs, a sideslip angle (β) is produced.

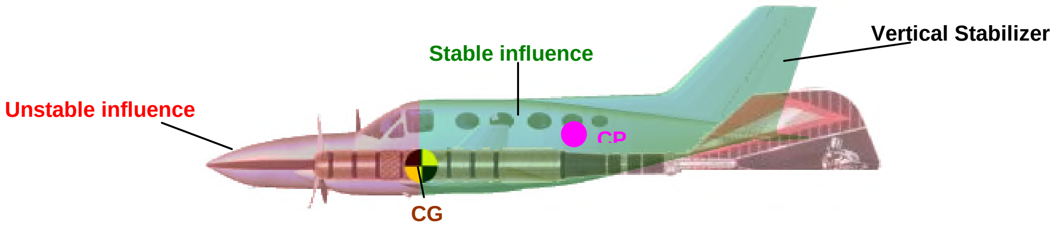


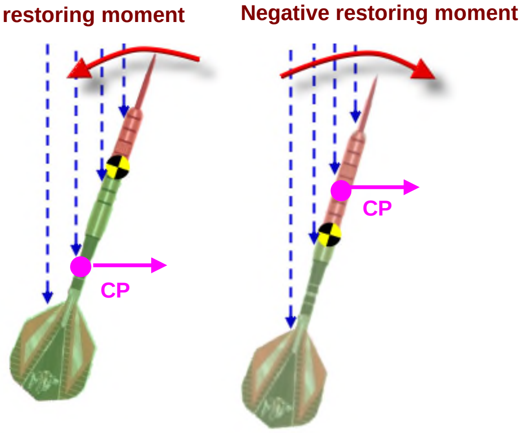
The sideslip angle causes a restoring moment due to the force produced by the increase in angle of attack. Note that:

- The dart rotates about the CG.
- The inertia of the dart momentarily carries it along the original flight path ***(RAF is equal and opposite to the velocity of the dart).***

KEEL SURFACE

With the addition of the vertical stabilizer ***(rudder locked for reasons of simplicity),*** to the fuselage we are ensuring that the CP of the body of the aircraft lies behind the CG in the area producing a stable influence. ***The fuselage area ahead of the CG generally tends to produce an unstable influence, while the keel surface behind the CG produces a stable influence.***





If an aircraft that is trimmed for non-sideslip flight, is subjected to a sideslip condition and reacts by turning into the new relative wind (reducing the sideslip angle β), it has **POSITIVE DIRECTIONAL** static stability.

If the aircraft reacts by turning away from the new relative wind (increasing the sideslip angle β), it has **NEGATIVE DIRECTIONAL** static stability.

Lastly, if the aircraft maintains the sideslip condition without reducing or increasing the sideslip angle (β), it has **NEUTRAL DIRECTIONAL** static stability.

FACTORS AFFECTING THE DIRECTIONAL STABILITY

Achieving directional static stability (i.e. the size of the restoring moment), is affected by:

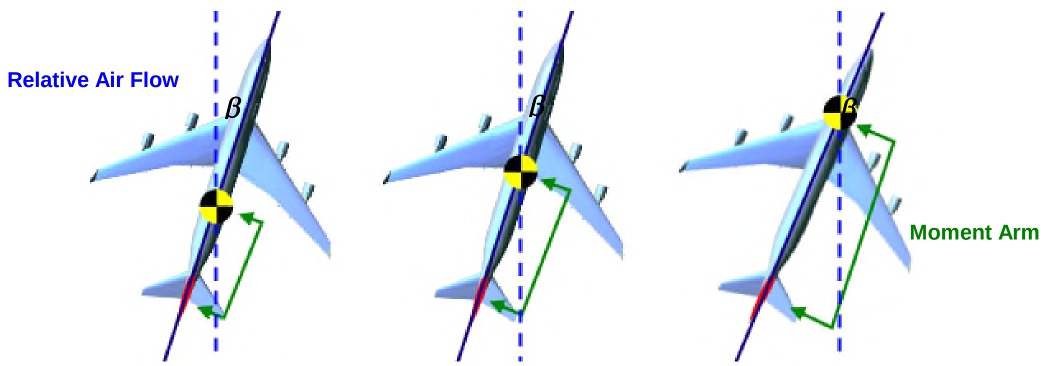
- The position of the CG
- Design of the vertical stabiliser

POSITION OF THE CG

With some aircraft the pilot can control the CG. This is especially true for large transport aircraft. As fuel is burned off or stores are released, the CG will move and by transferring internal fuel, the pilot keeps the CG movement within limits.

Forward movement of the CG lengthens the moment arm thereby increasing the directional stability.

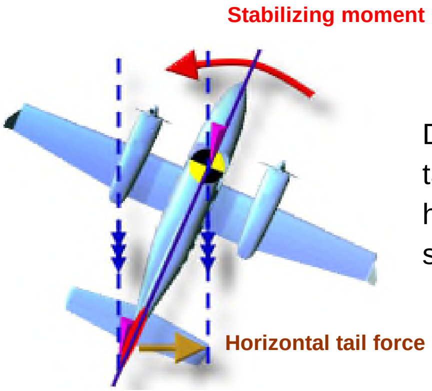
On the other hand, should the CG move aft, the moment arm is shortened, thereby reducing the directional static stability.



As the CG moves forward the longer the moment arm gets, and the more directional stability.

THE VERTICAL STABILISER

The vertical stabilizer is normally located behind the CG and due to the relative long moment arm it produces a very strong stabilizing force.

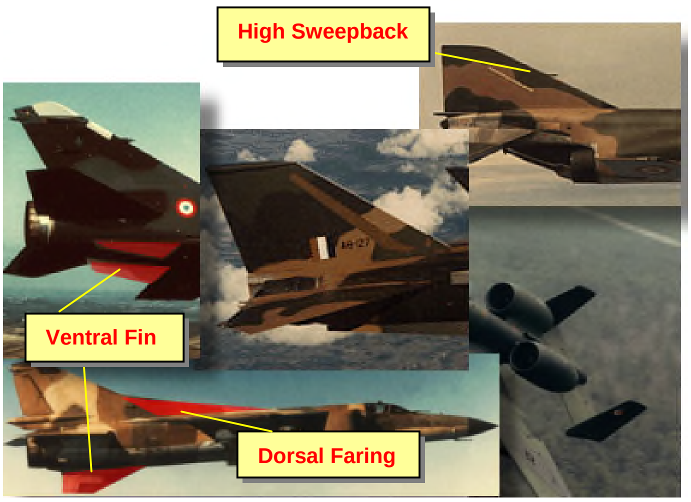


During any sideslip condition, the aerodynamic shape of the tail surface will change the lift of the tail and create a horizontal tail force. This force in turn creates a very strong stabilizing yawing moment about the CG.

For a given displacement ***(sideslip angle)***, the degree of positive stability depends on the size of the restoring moment.

Normally the vertical stabilizer is a symmetrical aerofoil and therefore it will produce an aerodynamic force at positive angles of sideslip.

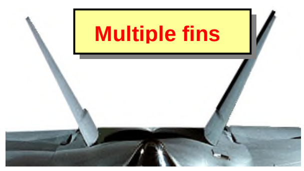
At a constant speed and for a constant angle of sideslip the lift force produced by the vertical stabilizer will thus depend on the **coefficient of lift** and **area** of the vertical stabilizer.



As the vertical stabilizer is also an aerofoil, the C_L will therefore vary as the aspect ratio and sweepback varies.

Different design considerations for different aircraft will thus lead to different shapes and configurations.

Designers have several possible designs to choose from when creating a tailfin for a specific aircraft. They may increase the sweepback on the fin, reduce aspect ratio, fit two or more fins of low aspect ratio, or fit a dorsal fairing or/and ventral fin(s).



FIXED AND FLOATING RUDDER

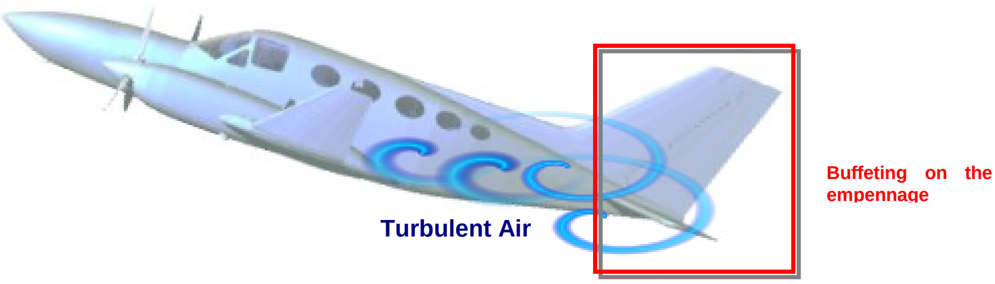
When the rudder of an aircraft is by any means held in a fixed position, it is known as Stick Fixed Stability ***(In aircraft with powered, irreversible control systems, the rudder cannot float free from the fixed position. When subjected to a sideslip, the pilot will not need to use rudder pedal pressure to prevent rudder float)*.**

If the rudder is allowed to float free ***(When subjected to a sideslip in an aircraft with conventional, non-powered control systems, the rudder will float free from the fixed position. The pilot has to use rudder pedal pressure to keep the rudder in the neutral position and thus increase the directional stability.)***, it will be moved from the neutral position by any outside disturbance. The total stabilizing surface will be reduced and the yawing moment produced by a "free floating" rudder will be reduced.

An aircraft with a fixed rudder ***(rudder fixed stability)*** has greater directional stability than an aircraft with a free rudder ***(rudder free stability).***

Stalling

One of the symptoms of the approaching stall in an aircraft is a **high angle of attack**. A second symptom is the buffet that can be felt by the pilot. The buffet is caused by stalled air ***(turbulent airflow breaking away from the main wings)*** engulfing the empennage ***(vertical and horizontal stabilizers).***



At high angles of attack the stalled air reduces the effectiveness of the vertical stabilizer and it will not be able to effectively develop sideward lift; thus reducing directional static stability.

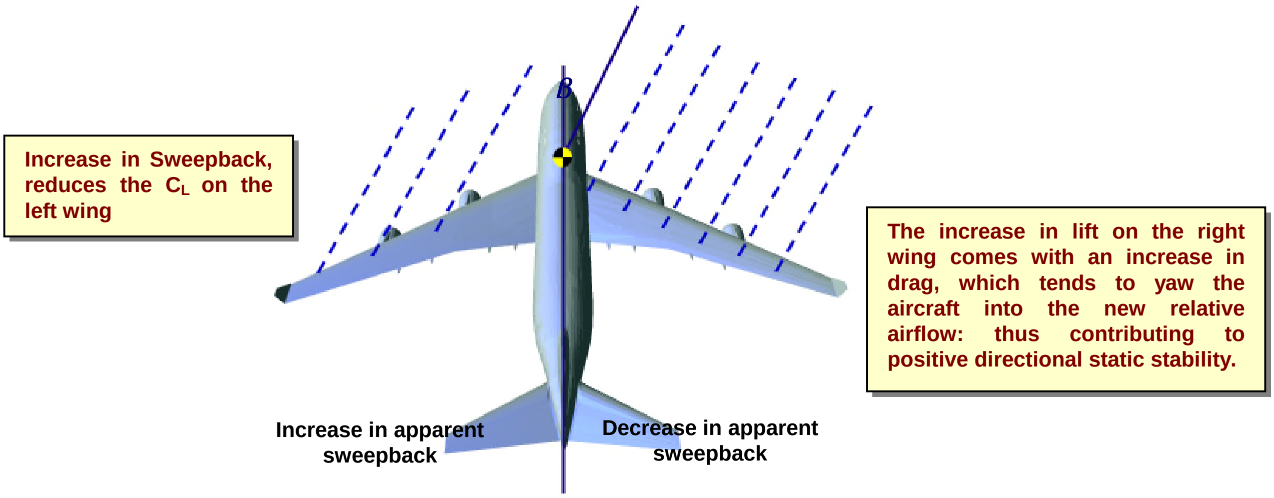
The reduction in directional stability has a negative effect on the ability of the aircraft to recover from spins and it also increases the possibility of adverse yaw.

Sweepback on the wings

Although the contribution of the main wings to directional static stability is very small, it does increase with an increase in sweepback.

AN AIRCRAFT, IN A SIDESLIP TO THE RIGHT.

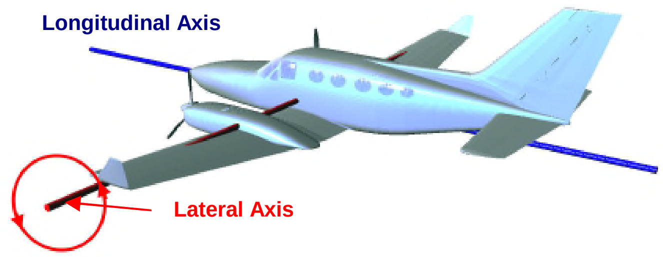
The sweepback of the right wing is reduced due to the sideslip angle, while the left wing experiences an apparent increase in sweepback.



LONGITUDINAL STABILITY

INTRODUCTION

Longitudinal stability and control refer to aircraft behaviour in the pitching plane or, in other words, movement of the longitudinal axis as it is rotated about the lateral axis and CG.



Static longitudinal stability deals with a disturbance at a constant load factor (n=1) and speed (trim speed)

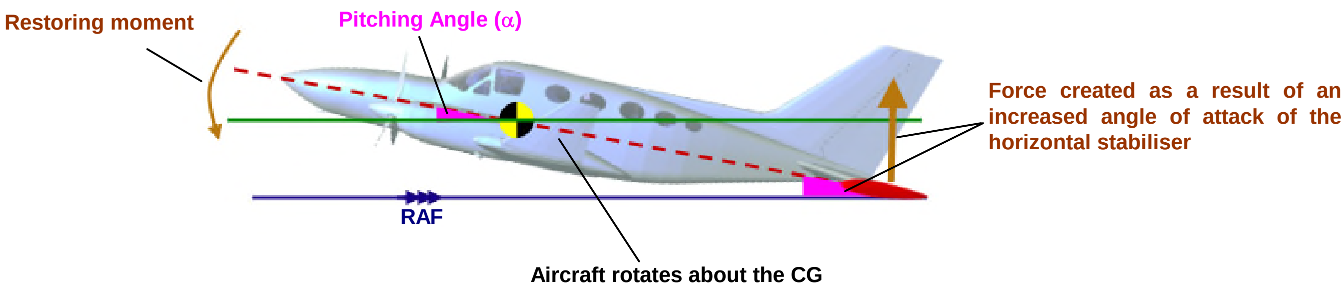
The trim speed of an aircraft, is that speed at which the pitching moments are zero. At the trim speed an aircraft will maintain a certain attitude without any inputs from the pilot.

If the speed decreases a nose-down pitching moment results and the speed will again increase until the original trim speed is reached. If the speed is increased a nose-up pitching moment results and the speed will decrease to the original trim speed.

Manoeuvre stability deals with a change in angle of attack and load factor (n) at a constant speed.

LONGITUDINAL STABILITY

When the aircraft is displaced in pitch, the horizontal stabilizers will produce a restoring moment that tends to reduce the pitching angle, which represents the displacement in pitch. ***This is then positive longitudinal stability***.



When dealing with longitudinal stability, the elevators are considered to be locked (stick-fixed stability) for simplicity.

LONGITUDINAL STATIC STABILITY

If an aircraft that is trimmed for zero pitching moments at a certain angle of attack, is displaced in pitch and tends to return to the trimmed angle of attack (reducing the pitch angle α), it has ***POSITIVE LONGITUDINAL STATIC STABILITY.***

If the aircraft continues to pitch away from the trimmed angle of attack (increasing the pitch angle α), it has ***NEGATIVE LONGITUDINAL STATIC STABILITY.***

If the aircraft maintains the new angle of attack caused by the disturbance, it has ***NEUTRAL LONGITUDINAL STATIC STABILITY.***

FACTOR AFFECTING LONGITUDINAL STABILITY

DESIGN OF THE HORIZONTAL STABILISER

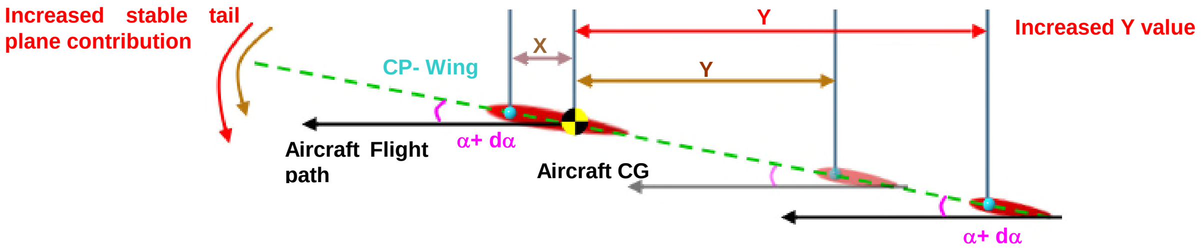
As the whole tailplane is an aerofoil, the lift force resulting from any change in angle of attack will be proportional to the $C_L$tail and the area of the tailplane. This lift force will have a direct effect on the restoring moment ***(longitudinal stability).*** The main tailplane design considerations affecting the restoring moment are:

- Moment arm
- Tail Area
- Tail Volume
- Planform
- Downwash

MOMENT ARM

The moment produced by the tailplane depends on the distance between the CPtail and the CG of the aircraft. If this distance increases, the moment will increase. ***(Tail moment = Y x Total Lift of the tail)***

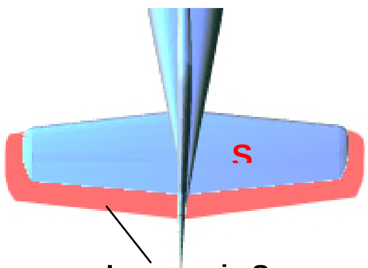
The degree of positive stability for a given angle of attack depends on the difference between the moments produced by the wing and the tailplane, this difference is called the ***Restoring Moment***. ***Net pitching moment = Y x (Total Lift of tail) - X x (Total Lift of the wing)***



The tail moment ***(Y x Total Lift of the tail)*** will be increased due to the fact that Y increased. Therefore the restoring moment will increase or reduce accordingly as the moment arm is lengthened or shortened.

TAIL AREA

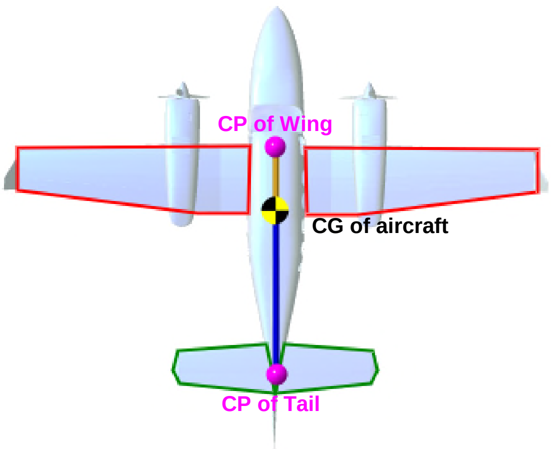
The lift produced by the tail = C_L**tail**qs. Where q is the EAS, and s is the area. C_L for an aerofoil with a given planform will only change with a change in angle of attack (α) if the EAS (q) remains constant. Therefore to measure the effect of tail area on an aerofoil with a given angle of attack at a given EAS, it is only necessary to look at s.



From this it can be seen that any increase in tail area and thus tail lift, will lead to an increase in the tail moment which in turn will increase the restoring moment.

TAIL VOLUME

The **wing volume : tail volume** ratio is the main parameter that designers use to determine the longitudinal stability of an aircraft.



The **wing volume** is the product of the **wing area x moment arm**.

The **tail volume** is the product of the **tailplane area x moment arm**.

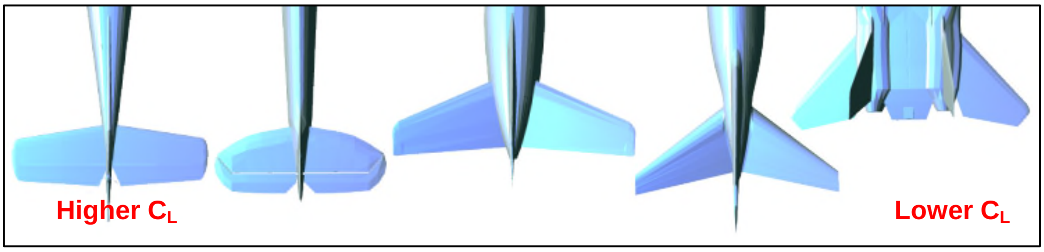
Therefore any change in either tailplane area or the length of the moment arm will affect the tail volume and the overall longitudinal stability.

PLANFORM

The C_L curve is affected by the planform of an aerofoil. As **aspect ratio** is increased, C_L is increased, while increased **sweepback** results in a decrease of C_L .

As the tailplane is an aerofoil, its C_L is also affected by the planform ***(aspect ratio, sweepback and taper)*** when the angle of attack is changed during a displacement in pitch.

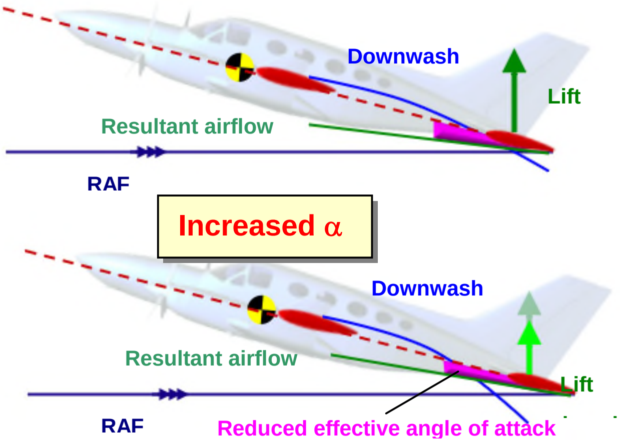
Highly swept tailplanes (on the right) will have lower increments of C_L than the tailplanes on the left (rectangular planform).



As $C_L$tail is reduced ***(lower increments of C_L),*** the CG has to be further forward ***(longer moment arm)*** to compensate for the reduced tail moment.

DOWNWASH

Downwash increases with an increase in angle of attack, but the downwash angle from the wings also changes. As the downwash affects the airflow over the tail, the change in downwash angle causes the effective angle of attack of the tail to change.

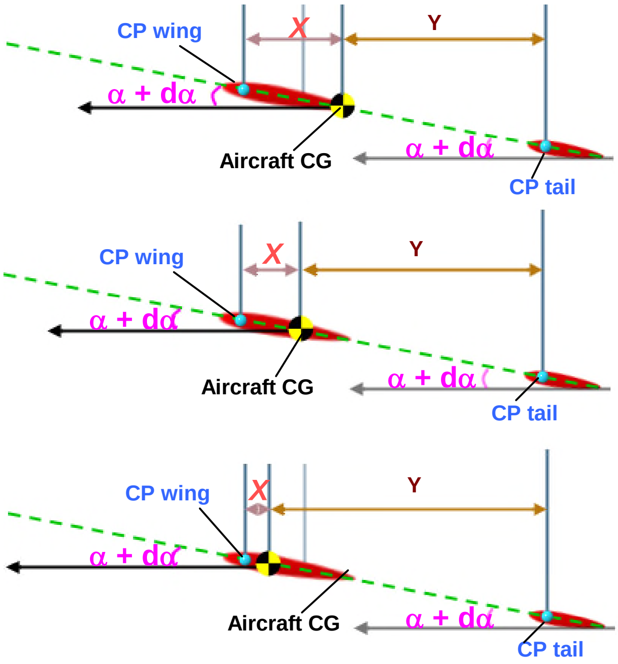


If, at a constant speed, angle of attack is increased, C_L and therefore lift is increased. As lift increases, lift dependent drag increases ***(which is caused by induced downwash - which must therefore also have increased).***

An increase in the angle of attack of the aircraft reduces the effective angle of attack of the tail, which in turn reduces the total tail lift. The loss of total tail lift reduces the restoring moment and therefore longitudinal stability. ***(The only way to compensate for the loss of stability is to move the CG further forward to increase the length of the tail moment arm Y).***

POSITION OF CG

The position of the CG has a large effect on the restoring moment due to damping in pitch. To a certain extent, the pilot of an aircraft has a measure of control over the position of the CG.



Aft movement of the CG decreases the length of the tail moment arm (y), while increasing the length of the wing moment arm (x) and this leads to a decrease in positive longitudinal static stability.

Forward movement of the CG increases the length of the tail moment arm (y), while decreasing the length of the wing moment arm (x) and this leads to an increase in positive longitudinal static stability.

The position of the CG affects the tail moment : wing moment ratio, and therefore the degree of stability.

The position of the CG not only has an effect on longitudinal static stability, but also on aircraft handling characteristics in pitch because the aerodynamic force produced by an elevator deflection has to override the restoring moment due to stability.

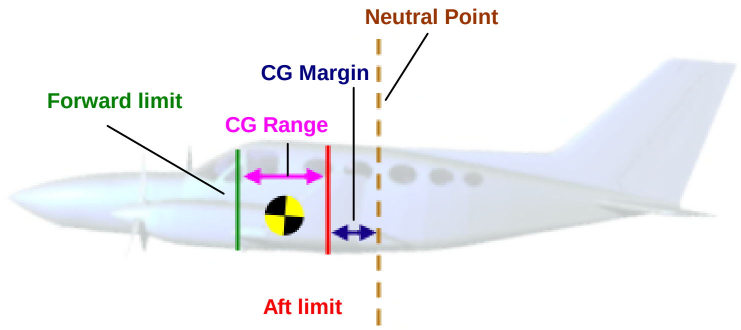
STABILITY opposes MANOEUVRE.

NEUTRAL POINT AND CG MARGIN

As the CG of an aircraft is not fixed, two important aspects relating to the movement of the CG have to be pointed out. The permitted range of movement for the CG is published in the Aircrew or Operating Manual for every aircraft type.

The degree of manoeuvrability required by a specific aircraft type normally determines the limit of the forward position of the CG. With fighter type aircraft the CG is normally situated relatively far aft so as to increase the manoeuvrability of the aircraft in combat situations. The aft limit is also the more important one of the two.

If the CG is moved too far aft (outside the permitted limits), a position will eventually be reached where the wing moment ***(INCREASING due to longer moment arm)*** is equal to the tail moment ***(REDUCING due to shorter moment arm)***.
This CG position, where the restoring moment is zero and the aircraft is neutrally stable is known as the **NEUTRAL POINT**.



The quoted aft limit of the CG is always safely forward of the neutral point. The distance the CG can be moved aft of the quoted limit, to reach the neutral point, is called the **static or CG margin.** This margin is an indication of the degree of longitudinal stability and thus the greater the CG Margin, the greater the stability. Training and fighter aircraft such as the F/A-18 Hornet may have a fairly short CG Margin measured in inches; whereas large transport aircraft can have a CG Margin measured in feet.

If the loading limits of an aircraft are exceeded the position of the CG can be on or even aft of the Neutral Point. This unsafe situation will be further aggravated by "trailing" (stick free) controls.

The modern fighter, with its dart-like shape, has most of its weight concentrated in the rear ***(engines, wings are positioned aft, weapons, etc)*** and is therefore relatively unstable in pitch ***(negative longitudinal stability).***

STICK-FREE LONGITUDINAL STABILITY

A freely trailing elevator will tend to trail with the relative airflow and this in turn will change the tail force because the displacement depends on the position taken up by the elevator. If the tail moment is reduced, the balance between the wing and tail moments changes and the CG will need to be further forward because a less effective tail requires a longer moment arm.

The neutral point also shifts forward ***(closer to CG),*** which reduces the stick-free CG margin. As the stick-free CG margin is a measure of the longitudinal stability, it follows that **longitudinal stability reduces when the elevators are allowed to trail freely**.

MANOEUVRE STABILITY

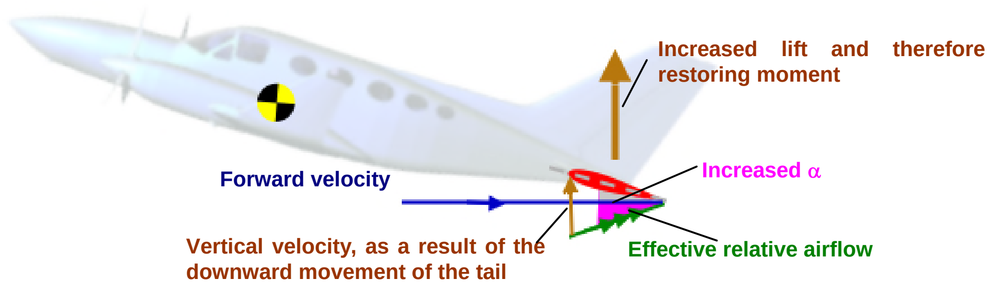
Longitudinal static stability deals with a disturbance in angle of attack (α) at a constant speed and load factor (n = 1).

Manoeuvre stability on the other hand, deals with a disturbance in angle of attack (α) and load factor (n) at a constant speed.

If an aircraft is climbed from steady level flight, dived and then pulled out of the dive to level off at the original values of speed and height (the aircraft describes a curved flight path), it can be considered to have been "disturbed" in two ways which both contribute to overall manoeuvre stability:

- The aircraft has an increased angle of attack (increased α) to produce the additional lift that is required to maintain the curved flight path (L = nW).
- The aircraft has a nose-up rotation about its CG that is equal to the rate of rotation about the centre of pull-out.

With the aircraft that is rotating about its own CG, the tailplane can be considered to be moving downwards relative to the air flow. Therefore the effective angle of attack (α) of the tailplane is increased, and it can be said that the longitudinal manoeuvre stability is greater than the longitudinal static stability in level flight.

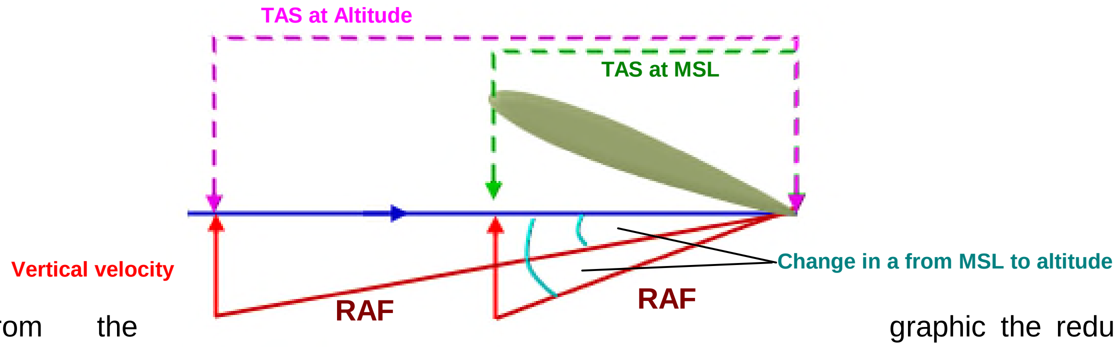


With the longitudinal stability greater in manoeuvre, the CG position for neutral stability is also further aft than for level flight. This CG position is known as the Manoeuvre Point and the distance between the CG and the Manoeuvre Point is known as the Manoeuvre Margin. For a given position of the CG, Manoeuvre Margin is greater than the CG Margin.

EFFECT OF ALTITUDE

It was stated that when an aircraft pitches nose-up in a manoeuvre (about the CG) from level flight, the tailplane has a vertical airflow component from below. This vertical airflow component increases the longitudinal stability in manoeuvre.

If the same aircraft is considered at two different altitudes, but at the same IAS ***(C_L value is same)*** and a nose-up pitch is initiated at the same load factor, the rate of pitch at altitude will be less than that at low level due to an increase in TAS as altitude increases.

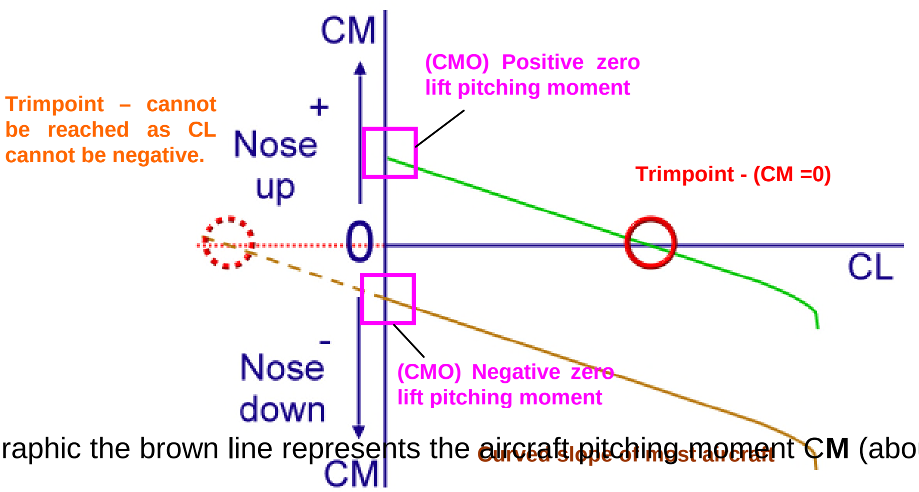


From the graphic the reduction in tailplane angle due to increase in TAS with an increase in altitude and lower rate of pitch, becomes apparent. An aircraft will therefore have less manoeuvre stability at high altitude than at MSL due to the reduction of the tailplane contribution.

TRIMPOINT

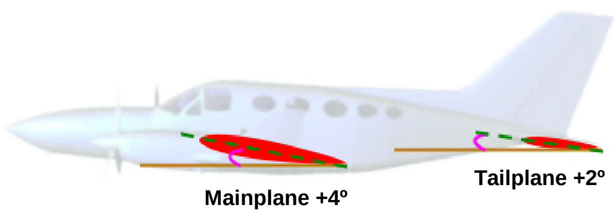
The trimpoint is that point at which the aircraft neither has a nose up or a nose down pitching moment ***(zero lift pitching moment)***. For most aerofoil sections the zero-lift pitching moment (C**MO**) is negative ***(nose down).***

Although the curved slope of most aircraft **(**C_M**)** denote stability ***(Increase in C_L (pitch up) will generate a nose-down restoring moment about the CG),*** the point at which C_M =0 cannot be reached as C_L cannot be a negative value, and the curve will never cross the positive horizontal axis. As a result of this trim point will never be in achieved.

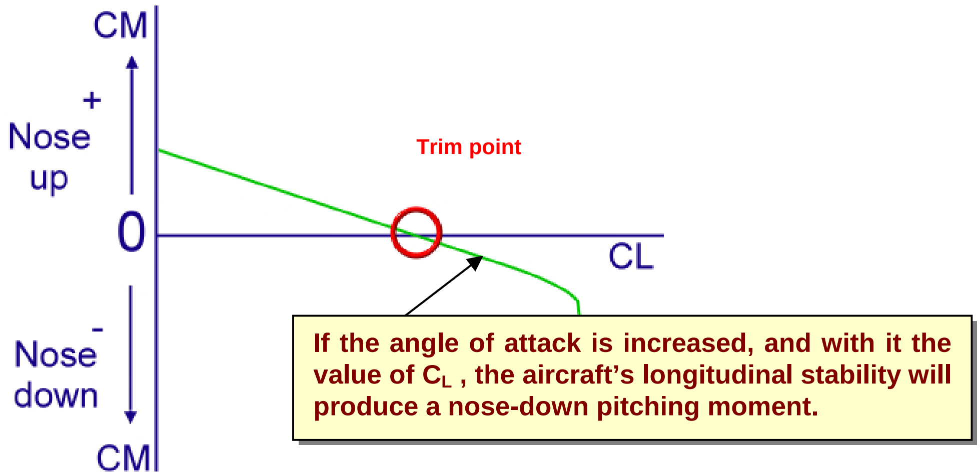


On the graphic the brown line represents the aircraft pitching moment C**M** (about the CG) vs C_L.

The aircraft can be brought into trim (C**M** = 0) by introducing a nose-up pitching moment (C**MO** is now positive) which will raise the C**M** curve (green). By rigging the tailplane at a lower angle of incidence than the mainplane, it generates a down-load at the tail which will produce a nose-up pitching moment.



The mainplanes of most aircraft are normally set at more or less +4º angle of incidence. To alleviate a nose-down zero-lift pitching moment, the tailplane has to be set to a lower angle of incidence (+2º). The difference of +2º between the two settings is known as **longitudinal dihedral** and has no effect on the stability of the aircraft. The variation of tailplane incidence will only shift the position of the Trim Point.



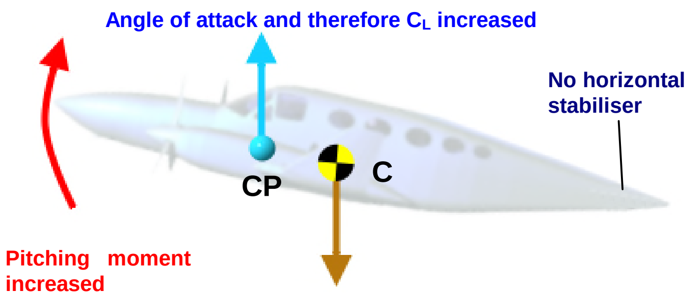
If this new, increased angle of attack is maintained, an equal and opposite moment ***(nose-up)*** is required from the elevators to counter this nose down moment. This is done by deflecting the elevators upwards ***(nose-up).***

When the new angle of attack is maintained, a new trim point is established at the higher angle of attack of the mainplane, the tailplane is made to produce a greater nose-up pitching moment by changing the camber of the tail ***(up-deflection)***.

The reverse applies when the angle of attack is reduced on the mainplane. The new elevator angle to trim the aircraft does however not affect the longitudinal stability of the aircraft.

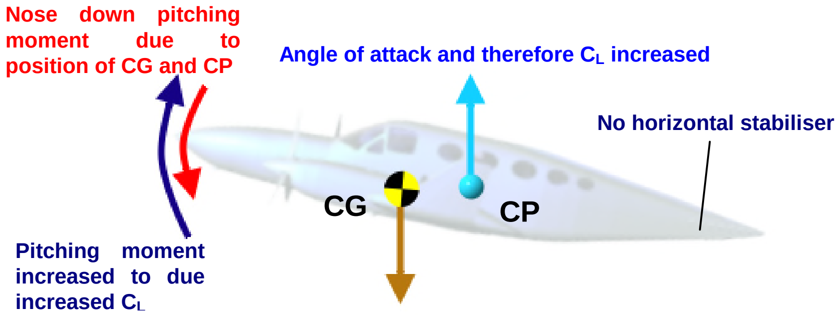
CENTRE OF PRESSURE (CP) AND AERODYNAMIC CENTRE (AC)

CENTRE OF PRESSURE



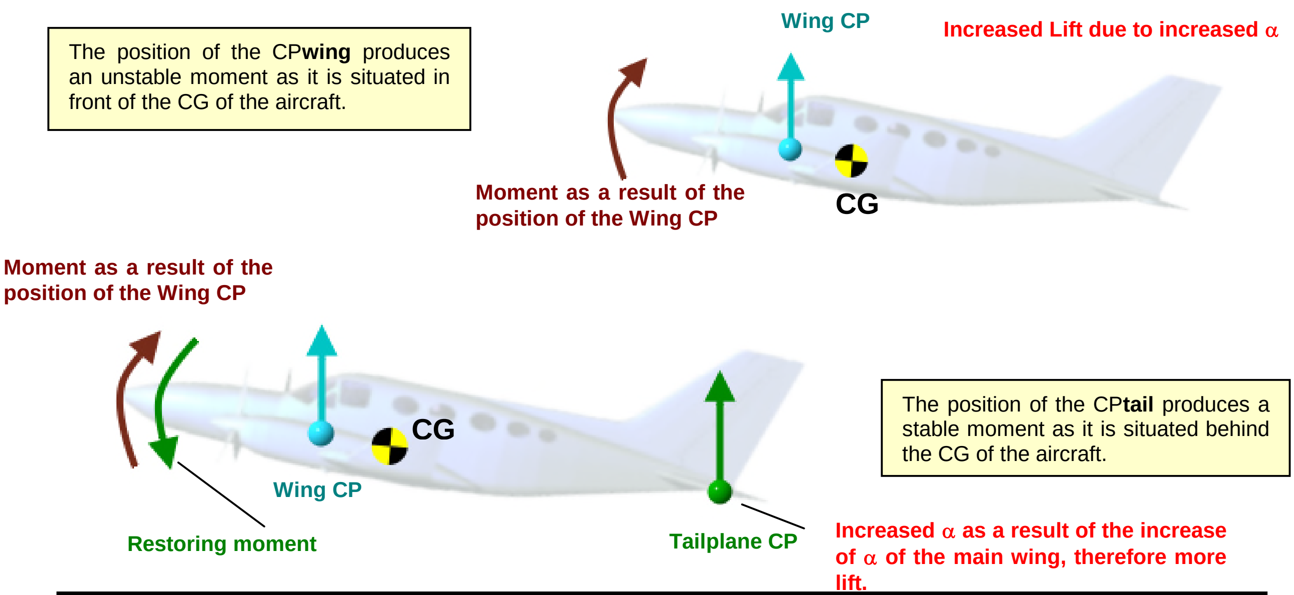
When, ***(with the CP in front of the CG),*** an aircraft without a horizontal tail is disturbed in pitch (α), a nose-up displacement increases the angle of attack and thus the lift force (L) increases. The pitching moment of the wing will also increase and worsen the nose-up displacement, which is an unstable contribution.

However, at the same angle of attack, but with the CP behind the CG, the tendency will be to reduce the nose-up displacement (α); thus a stable contribution.



The pitching moment of a wing will be affected by the movement of the CP with change in angle of attack. The position of the CP relative to the CG determines whether a wing has a stable or unstable influence when disturbed in the pitching plane. At worst a wing has an unstable influence and therefore a horizontal stabilizer is required to overcome this unstable influence.

This diagram shows how the lift forces of the wing and tail increase due to displacement in pitch when the angle of attack increases (α+dα).



The stable tail contribution must overcome the unstable wing contribution ***(as well as all other unstable contributions)*** to assure positive longitudinal static stability. The difference between the wing and tail moment is called the **restoring moment**.

Aerodynamic Centre

When the angle of attack of an aerofoil is increased, the CP moves toward the leading edge. This movement of the CP with a change in angle of attack of a cambered aerofoil makes any mathematical calculation involving stability and stress analysis extremely difficult.

However, there is a point on an aerofoil where the pitching moments are constant with a change in angle of attack ***(provided the velocity is constant).*** This point is known as the Aerodynamic Centre (AC).

The AC, as opposed to the CP, does not move with a change in angle of attack and if lift and drag are considered to act through the AC calculations are greatly simplified. The location of the AC varies from wing to wing, but at subsonic speeds it is at about 23% - 27% of MAC. Supersonically it is at about 50% of the MAC.