Aircraft Forces, Moments, and stability

Force:

A force pushes something in a direction. It can be at a point (push with your finger), or distributed (wind blowing on a sail). Distributed forces (such as gravity) can be represented by a single point force at a single location. When this force is from gravity, the point is the center of gravity. When lift or drag, it is the center of pressure.

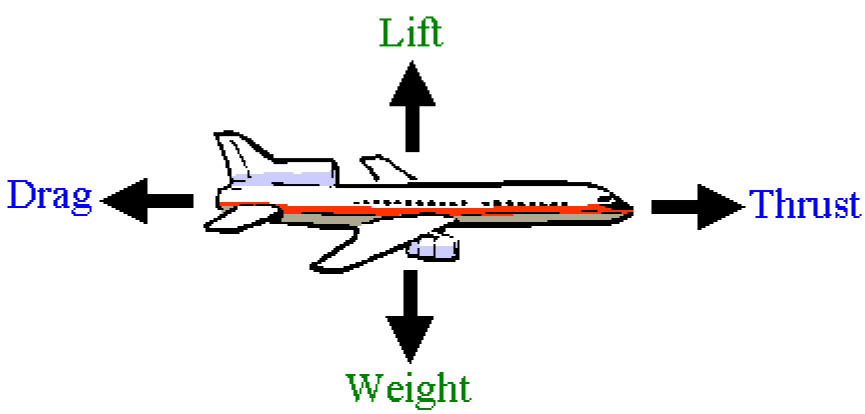
When a force acts on an object (body), that object will accelerate:

$$F=ma$$

Or

$$a=F/m$$

There are four forces in flight of an airplane:



1. Weight is the force of gravity. It acts in a downward direction—toward the center of the Earth.
2. Lift is the force that acts at a right angle to the direction of motion through the air. Lift is created by differences in air pressure.
3. Thrust is the force that propels a flying machine in the direction of motion. Engines produce thrust.
4. Drag is the force that acts opposite to the direction of motion. Drag is caused by friction and differences in air pressure.

Each pair of forces is in balance in steady state flight:

- Lift exactly equals weight. If lift > weight, the plane will climb. If less, it will come down.
- Thrust exactly equals drag. If thrust>drag, the plane will go faster (accelerate). If drag>thrust, the plane will slow down

Lift is related to speed. The faster a plane goes, if everything else stays the same, the more lift will be generated. Drag is related to speed. The faster the plane goes, the more drag is produced, and the more thrust needed to maintain speed.

For Wright Stuff, we want to maximize duration. The "fuel" is the winds in the rubber (energy). The rate at which we use this fuel is "power", which converts to thrust. Thus, if we have a lot of drag, we need more thrust (more power) to move at a given speed. Drag increases with the square of speed (speed * speed), so we want to fly as slow as possible. We also want as little drag as possible, in order to minimize the power we use. If we use less power, we use the total energy slower, and the flight is longer.

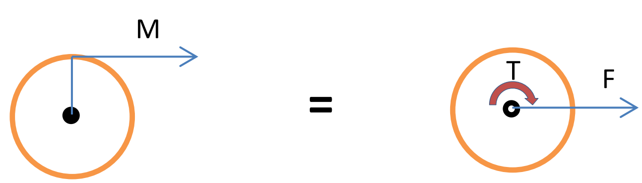
Lift can be generated in several ways:

- Airfoil shape. The curved top of the wing generates lift (Bernoulli principle). A highly cambered airfoil (highly curved) generates more lift at slow speeds, but also more quickly generates drag.
- Angle of attack. If you lift the leading edge, while moving forward, the wing generates more lift. Think of your hand out the car window. As you rotate your hand, it wants to go up or down.

If the angle of attack is increased too much, the air separates from the top of the wing, it no longer lifts, a condition called "stall". The wing then drops, picks up speed, creates lift, and again can approach stall.

<u>Moments</u>

Moments are a force at a distance about a pivot, very much like torque. In fact, torque is a moment about a physical axel. The "value' of the moment is the force times the distance. Generally torque is a special case of a moment, and torque is generally used when the driving force is rotation of an axel, while a moment is generally a force applied at a distance from the axel or a point of rotation. In addition, a moment causes both a torque and a linear force on a system:

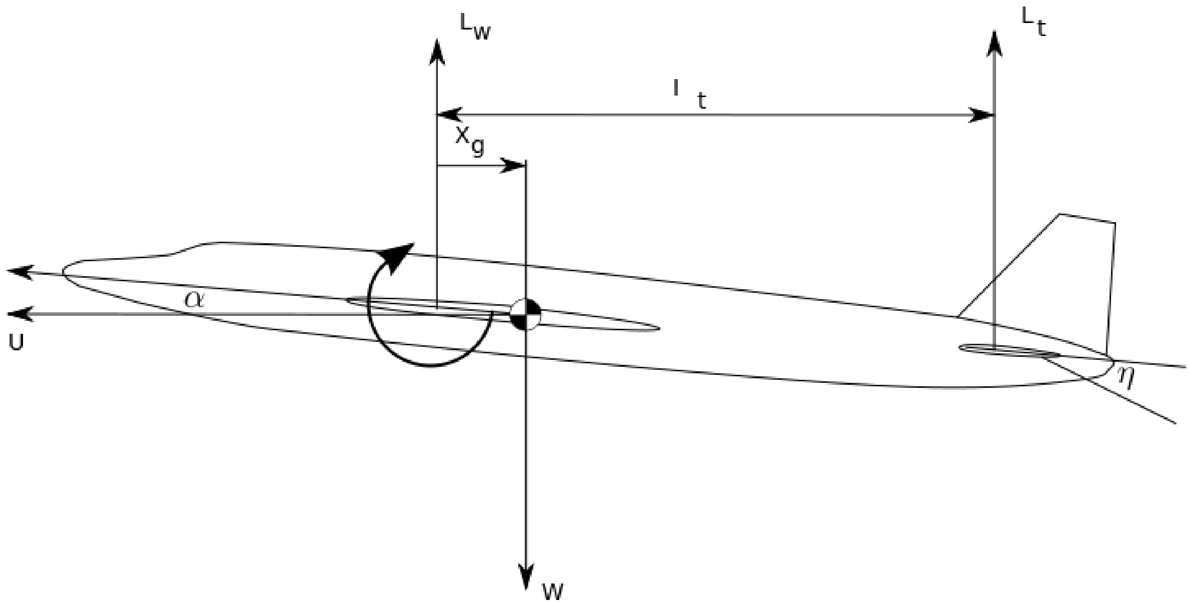


If the moments are not balanced, just like forces, the object will rotate about the pivot point. Thus, on an airplane, moments must be balanced as well.

The moments to be concerned with on an airplane are:

- Gravity on all the parts
- Lift from all the parts
- Note: Thrust and drag can also cause moments, but we'll ignore for now

The moments from all of these must sum to zero or the plane will rotate. If the moments sum to zero at one point, they sum to zero at all points.



Aircraft in Level Flight

In the above image, the weight is shown applied at the center of gravity, or balance point, which is a convenient location to sum all the moments.

- The moment of weight about the CG is zero, because the distance is zero
- The lift of the wing is generally in front of the CG, and so wants to rotate the nose of the plane up.
- The lift of the tail is small, but at great distance from the CG. The lift moment of the tail wants to lower the nose of the plane

When the moment of the wing and the moment of the tail about the CG exactly balance, the plane will not rotate.

Stability

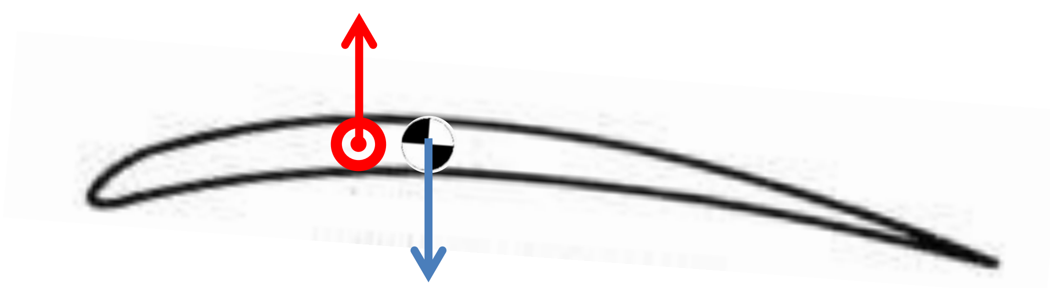
If a slight increase in angle of attack (nose points upward) results in an increase in the net moment, the plane wants to further increase the angle of attack, which is unstable. However, if a slight increase in the angle of attack results in a decrease in the net moment, the plane wants to decrease the angle of attack, restoring normal flight. This is stable.

A complicated analysis can be performed to find the “neutral point”. This is the point at which the CG should be for “neutral stability”. At this point, a slight increase in angle of attack cause no change to the net moment. Moving the CG forward of the neutral point makes the plane more stable. However, the angle of attack must be increased to counteract the forward CG, which also creates more drag.

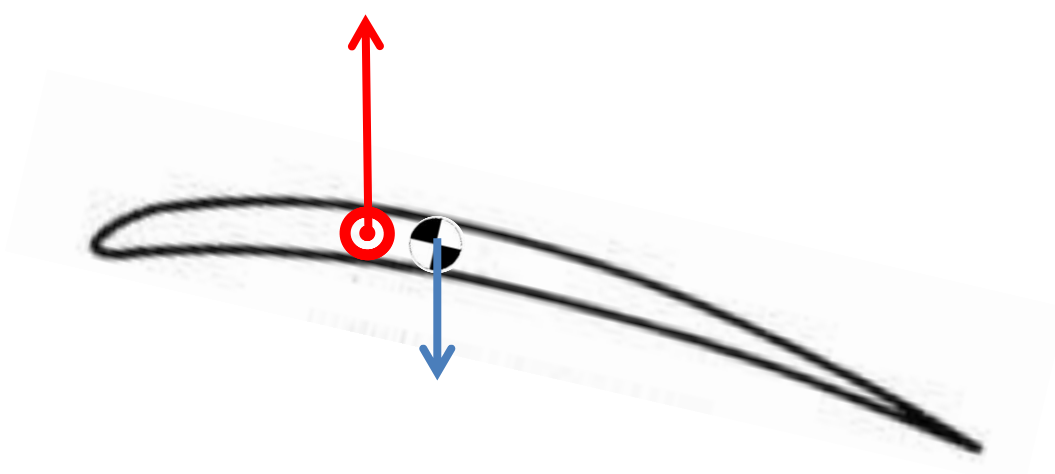
So, ideally, you want to minimize drag by flying with the CG as far back as possible, but this is at the expense of stability. We saw a less-than-stable aircraft will lose a lot of altitude when the forward progress is stopped by a ceiling hit. A neutral stability airplane will give a better time than a stable airplane, if there are no disturbances from girders, air gusts, and other interactions.

A simple way of looking at the stability involves a simplification, the “Center of Pressure”. (Note: this is not exactly correct, because the center of pressure moves with angle of attack). If the wing and tail have the same lift coefficient, the center of pressure is the geometric center of all the lifting surfaces (area moments of the surfaces sum to zero). However, the lift coefficient is not the same, and so the analysis is more complicated. But, let’s say we have found the Center of Pressure (or neutral point). All of the lift from the wing and the tail can be considered to act on this point.

First we will consider and unstable plane, where the CG is behind the CP:

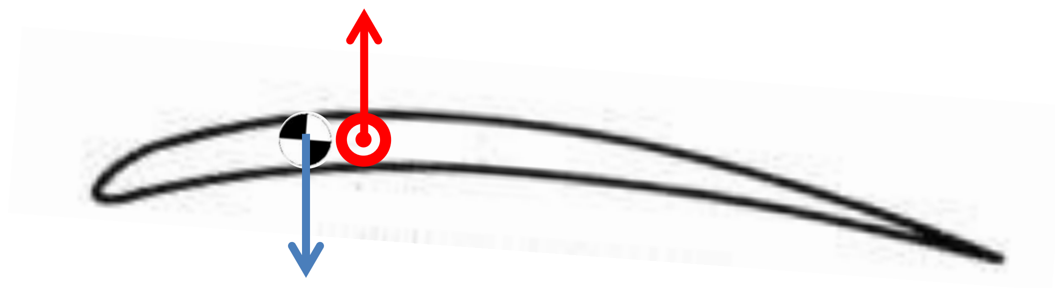


As we increase the angle of attack, the lift increases, but the gravity stays the same:

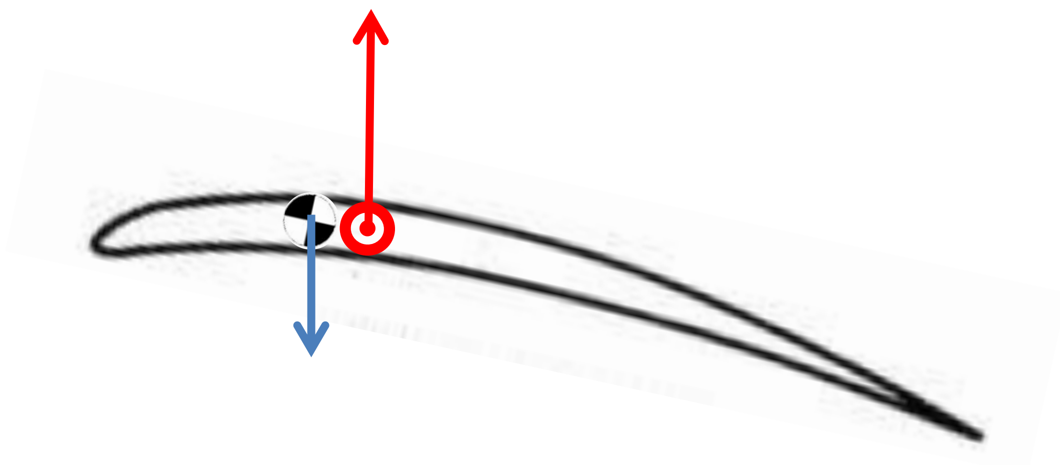


In this case, the moment about the CG due to lift increases in the clockwise direction, and so the plane wants to pitch up even more.

Now let’s look at the case where the CG is ahead of the CP (or NP):



Now we slightly increase the angle of attack, which increases the lift at the CP (NP):



This increases the moment about the CG in the CCW direction, forcing the wing to reduce angle of attack! This is stable, as disturbances are cancelled.

So, moving the CG forward makes a more stable airplane. However, the wing incidence must be increased to create more lift at the wing (moving the CP forward), or the nose rotates downward (dive). We want the plane "just stable enough". This means a girder hit or air gusts will not send it to the floor. Too much stability means we have a lot of incidence, which creates a lot of drag. This uses more power and shortens our flight.

We can calculate the ideal location of the CG based on "Static Stability Margin", SSM. However, to do this involves a lot of guesses and approximations. For one, you need to know the lift coefficients of the wing and the tail, which can be approximated. A spreadsheet analysis can give an approximate location for the CG. The SSM is expressed in percent, and is generally the fraction of the wing chord that the CG is in front of the neutral point. Generally for SO you start with a SSM around 15%.

In reality, you must fly many times making adjustments to find the ideal CG location. The stopwatch is part of it, but the possibility of a ceiling hit also factors in. If you can do a no-touch flight every time, then you can live with a further aft CG. However, as we saw at States, this can be very bad if the plane bumps something. Stability is also needed in "bumpy" air.

Things that may affect stability:

- The lift of the tail may be different on our two planes, effectively moving the CP. If we don't move the CG similarly, we can have instability. From this it *appears* that the wood tail may have less lift than the carbon tail, based on stability seen at the States vs. Regionals (Red, wood vs. Green, carbon)
- The tightness of the covering
- The overall trim: Twists, bends, etc.

Things that could affect drag:

- Twists and warps, they fight each other
- Tip plate: Intended to reduce drag. However, mis-alignment could lead to higher drag!
- Loose covering
- Repairs
- Too tight a turn radius