

Aerodynamics 101

An aircraft flies because it is able to generate lift equal to its own weight. Lift is created by the wing due to a phenomenon described by an early scientist by the name of Bernoulli...he found that when you pass a fluid through a constricted area, the molecules of the fluid have to speed up so that they can go through. This in turn causes the pressure of the fluid to drop as it passes through the constriction. This effect can be demonstrated quite clearly by a venturi...a piece of pipe that has been 'pinched' in the middle. If a small hole is drilled where the pipe is pinched, and this hole is connected with a tube to a pressure guage, it will be found that when air or water is pumped through the pipe, the pressure guage will register a decline in pressure. This seems to be counter-intuitive...one might expect that the air or water would want to escape from the pipe and would try to squirt out of the hole, thus creating an area of higher pressure. Quite the reverse is true, however, and rather than fluid being squirted out of the pipe, if the pressure guage is disconnected, air will be drawn into the hole.

This 'venturi effect' can be used to create a bilge 'pump' to draw water out of the bottom of a boat, and it is commonly used in spray cans...the pump squeezes air through a venturi, and the paint, cleaner, or whatever, is drawn up into the airstream.

A wing creates lift by using exactly this principle. The curved upper portion of the wing surface acts like a venturi, and creates an area of low pressure. The wing is, in effect, "sucked into" this area of lower pressure. The amount of lift that can be generated is a function of:

- the curvature of the wing,
- the speed of the airflow, and
- the area of the wing.

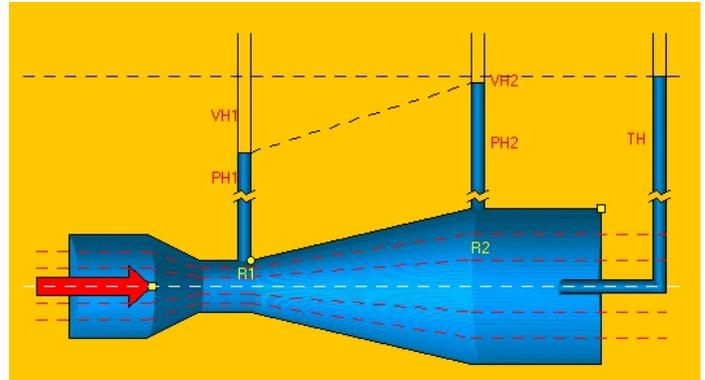
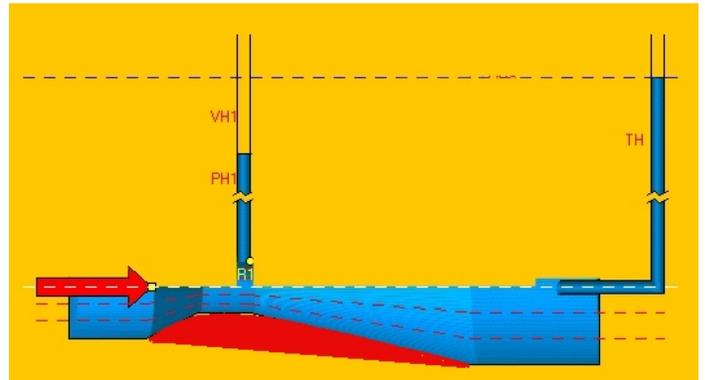


Fig. 1. Fluid passing through a venturi. The small vertical pipes represent the pressure experienced at different points. It is clear that the pressure at the narrowest point is quite a bit less than it is at the tail end of the pipe.

If the top of the pipe is removed, as in Fig. 2. below, the same effect is still evident. You will note that the shape of the remaining part of the tube is remarkably similar to the cross section of a wing (shaded in red).



To be able to stay in straight and level flight, the lift generated by the wing must be exactly equal to the weight of the aircraft. Not only that, but the centre of lift must be exactly above the centre of gravity. This is a very tricky thing to accomplish with a fixed wing, and consequently additional surfaces are provided in order to provide "trim" to adjust the centre of lift, and these in turn are the mechanism that provides vertical control. The Wright brothers put these lift-adjusting surfaces ahead of the wing, although the normal practice has been to put them behind. (It is sort of like putting the rudder of a boat on the bow, rather than at the stern...it will still turn the boat, but structurally it is a lot easier to stick the rudder on the back).

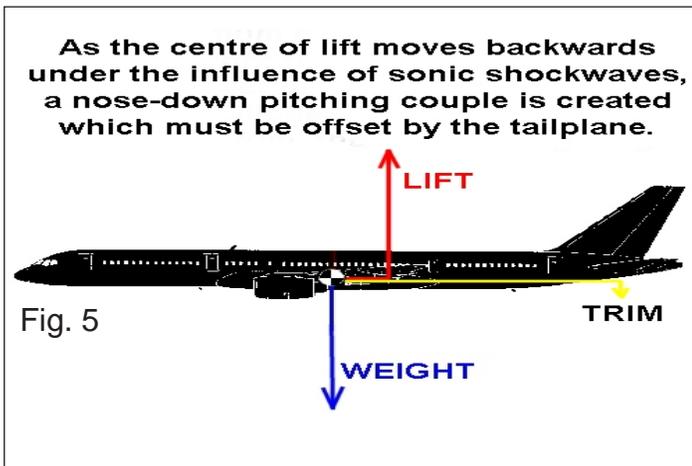
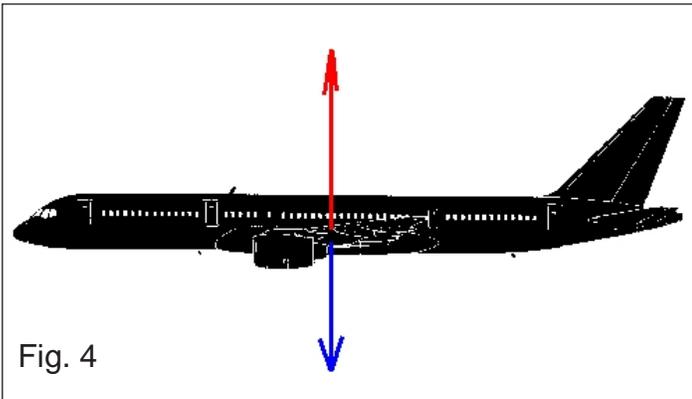
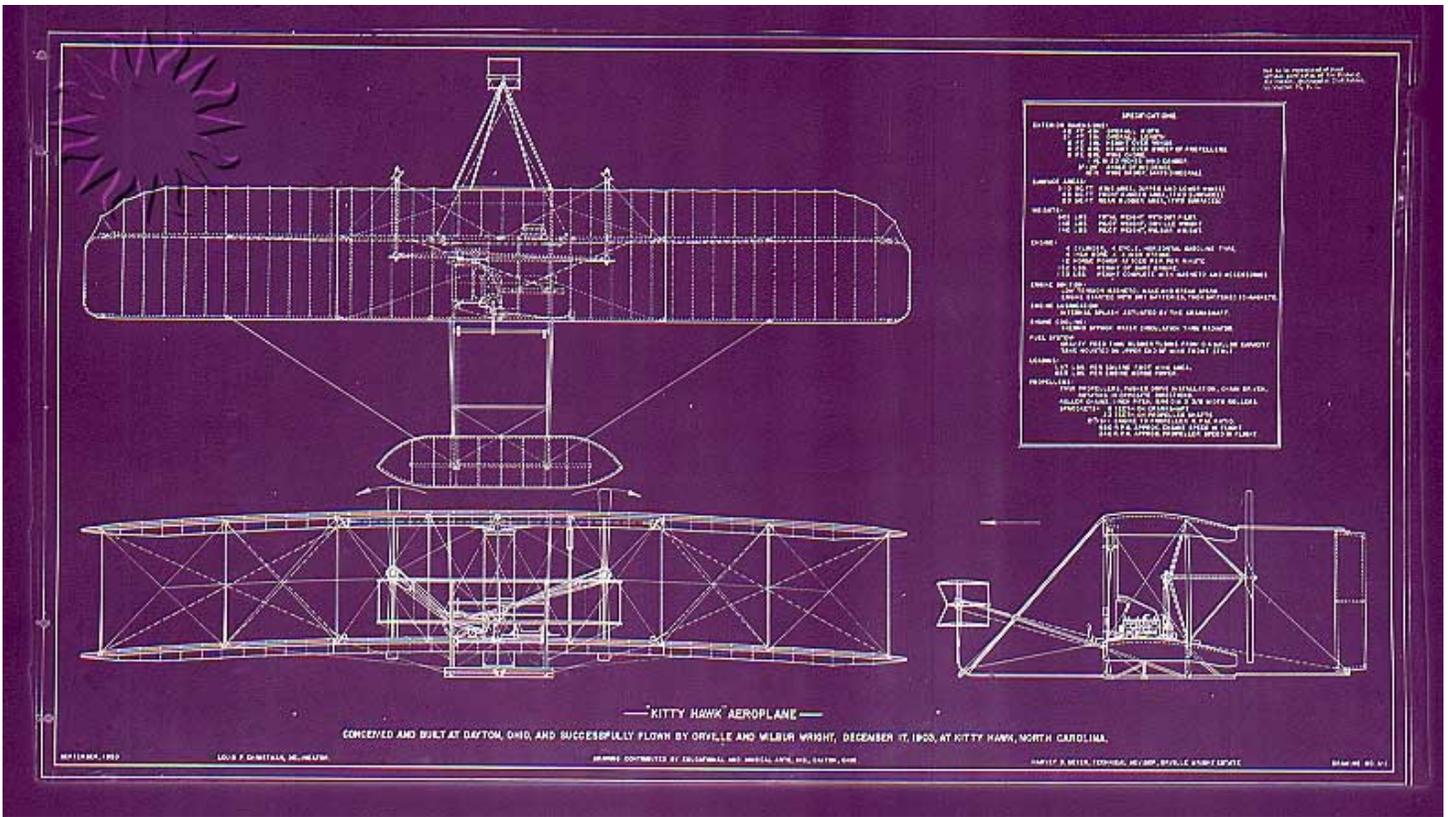


Fig 3. A 3-view drawing of the Wright Flyer. The elevators, which provide pitch control, were stuck out in front of the wing.

Fig. 4. Side view of a B757, showing the ideal situation where the centre of lift is exactly over the centre of gravity.

Fig 5. If the centre of gravity is ahead of the centre of lift, there will be a nose-down pitching moment, which must be counteracted by a downward force on the elevators. Apart from causing more drag, this effectively increases the weight of the aircraft, thus demanding that the lift generated be greater.

If the centre of lift is not directly over the centre of gravity, then 'trim' forces need to be applied by the horizontal stabilizer (also known as the elevator, or tail-plane) to balance out the nose-up or nose-down pitching moment caused by the discrepancy. (Imagine that the aircraft is suspended by a string through the centre of lift. If the C of G is ahead of the string, then the weight [downward force] will have to be applied to the tail to achieve balance. Similarly, if the C of G is behind the wing, then an upward force will have to be exerted by the tailplane to

achieve balance]. From this, two things can be discerned:

- (1) The position of the C of G is quite critical because it is limited by the amount of trim that can be exerted by the tailplane, and
- (2) Having the C of G behind the C of L is more desirable than having it in front.

To expand on the latter point—if the C of G is ahead of the C of L, then the tailplane must exert a downward force, which effectively adds to the weight of the aircraft, thus demanding that the lift be increased by an equivalent amount. Ultimately, this will reduce the amount of payload that can be carried. Furthermore, the fuel consumption will be increased because of trim drag induced by the deflection of the tailplane surface. On the other hand, if the C of G is behind the C of L, the upward force that will have to be exerted by the tailplane effectively shares the load between the wing and the tail and can improve the maximum payload. Nevertheless, there are serious limitations. Any deflection of the tail surfaces at all results in trim drag, and if the deflection is too great, the airflow over the surface will be completely disrupted, destroying its lift, and resulting in loss of control of the aircraft. Every aircraft has well defined limits for the Centre of Gravity that must be strictly adhered to.

Because an aircraft operates in three dimensions, (unlike a boat, which only operates in two), it has to have control surfaces that will enable it to be steered in all three dimensions. There are three axes about which the aircraft may be turned: the longitudinal axis which runs from nose to tail, about which the aircraft can be rolled; the pitch axis running horizontally through the centre of gravity, about which the aircraft may be pitched nose up or nose down; and the yaw axis, running vertically through the centre of gravity, about which the aircraft can be yawed

left or right. Roll control is achieved through the use of ailerons on the outboard trailing edges of the wings. These work in conjunction with one another. Moving the aileron up on one wing (causing that wing to be pushed down), while the aileron on the opposite will move down, causing that wing to rise. Pitch control, as we have discussed earlier, is effected by the horizontal stabilizer, or tailplane. Yaw control is exercised by the rudder (or vertical stabilizer) at the rear of the aircraft.

For an aircraft to turn in a circle while maintaining level flight, it is not sufficient to simply apply left or right rudder. Doing so would cause the aircraft to 'skid' left or right rather than turn. To make a smooth, coordinated turn, all three control surfaces must be applied: the ailerons; the rudder must be applied to initiate a turn; and elevator must be applied to keep the nose from dropping so that the aircraft remains at the same altitude while turning. As soon as the aircraft starts to bank, the vertical component of lift is reduced. The weight of the aircraft does not change, however, so the net effect is that weight becomes greater than lift, and following the laws of physics the aircraft must descend. To compensate, the amount of lift generated by the wings must be increased until its vertical component equals the aircraft's weight...this is done by increasing the angle of attack of the wing by pulling back on the control column.

As mentioned earlier, the amount of lift generated by a wing is a function of the curvature of the wing (its camber), its size (area), the speed at which it is passing through the air, and its angle relative to the on-coming air (angle of attack). The shape of the wing, (i.e. whether it is long and slender, short and stubby, swept back, or straight) has a big impact on how it behaves as well, but we will ignore this aspect of lift for the time being because it is not something that can be readily changed in flight.

Camber

The curvature of the wing affects the amount of lift that can be generated because, as we saw with the venturi, it controls the degree of “constriction” of the airflow, and thus the change in pressure, which in turn controls the amount of lift.

Modern airliners have the ability to make significant changes to the camber of their wings for take off and landing. They do this by extending both leading and trailing edge flaps. This enables the aircraft to takeoff and land at much lower speeds, which improves safety, and thus enables the aircraft to use much shorter runways than would otherwise be required.



Fig 6. An Emirates B777 after touchdown with spoilers raised and reverse thrust engaged. It can be seen how much the leading and trailing edge flaps have altered the curvature of the wing.

Area

If we were to suppose that our wing was one half of a venturi, and that it generated “one unit” of lift, then it is logical to assume that if we placed two, three, or four half-venturi’s side by side we would be able to generate two, three, or four units of lift. Simply put, the amount of lift generated is directly proportional to the wing area available to produce it.

On most light aircraft, flaps are just movable portions of the trailing edge that can adjust the camber of the wing by changing position, but do nothing to change the size of the lifting surface.

Modern airliners, by contrast, have flaps that extend and make the wing area significantly larger.



Fig 7. This Evergreen B747 has its flaps fully extended for landing and it is clear that the size of the wing has been considerably increased.

Speed

In the case of the venturi, the change in pressure is a function of the speed of the fluid flowing through it. The faster the flow, the greater the pressure differential. The same is true of a wing...the faster the airflow, the greater the lift it will generate. When the aircraft is standing still at the end of the runway, it is generating no lift. To get airborne, it must accelerate along the runway until the wings are generating lift equal to the weight of the aircraft. It must go faster still in order to be able to climb.

Angle of Attack

Angle of attack is the angle between a line joining the leading and trailing edges of the wing (the “mean aerodynamic chord”), and the direction of the oncoming air. As the angle of attack increases, so does the lift. However, if the angle of attack is increased too much, a point will be reached where the airflow is unable to follow the change in direction smoothly. It will break away and become turbulent, and the wing will lose its lift. This point is known as the “stall”. If we were to graph lift vs. angle of attack, we would see a line similar to that in Fig 10.

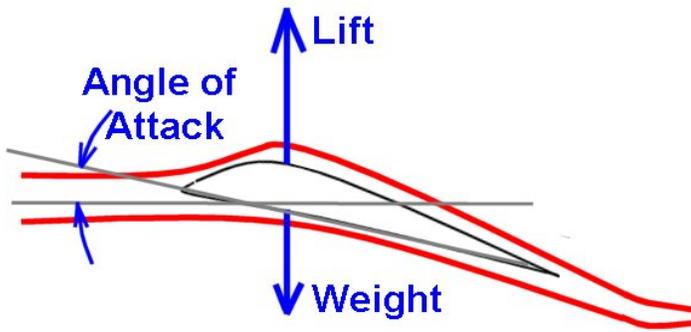


Fig 8. The amount of lift produced by the wing is dependant upon its angle-of-attack, and will increase as the angle of attack is increased.

Wing in Stalled Condition

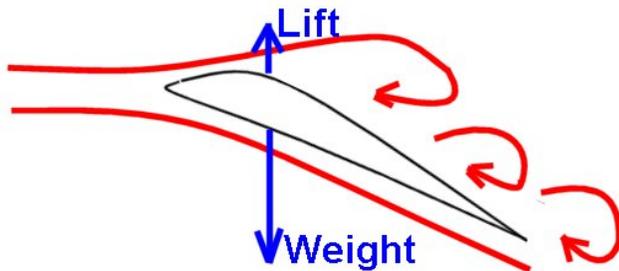


Fig 9. If the angle of attack exceeds a critical point the airflow is no longer able to adhere to the wing. It breaks away and becomes turbulent, and lift is destroyed.

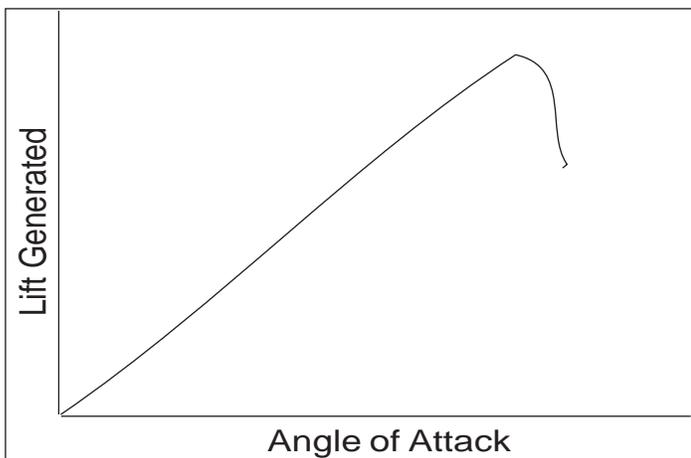


Fig 10. This simple graph illustrates the relationship between angle of attack and lift. Once the wing has stalled, lift drops dramatically, making the wing incapable of supporting the weight of the aircraft.

Thrust and Drag

We have talked about the need for lift to equal weight, and the requirement for the centre of gravity (C of G) to be in the right place. There are two other forces that act on an aircraft in flight which are equally important. These are Thrust and Drag, the forces which cause an aircraft to accelerate or slow down, and which control how fast it can fly.

Thrust

Thrust is generated by the engines, and regardless of whether the aircraft is powered by a piston engine, a jet, a ramjet, or a rocket, they all operate on the same principal of moving air (or gas) rapidly in the direction opposite to the the one in which the aircraft is to move. Newton's Third Law of Physics, "For every action there is an equal and opposite reaction," then comes into play, and the aircraft is driven forward.

Drag

Any time you attempt to move an object (such as an aircraft) through a fluid (such as air), there is resistance because the fluid in front of the object has to move out of the way. The more difficult it is for the fluid to get out of the way, the greater the drag. The faster the aircraft moves, the more difficult it is for the air to get out of the way, and so the higher the drag becomes. The maximum speed of an aircraft is usually defined by the point at which drag equals the maximum available thrust from the engines.

Other things that affect drag are how streamlined the aircraft is, and how 'thick' the air is that it is flying through. When the aircraft is landing and has flaps and wheels down, it has a great deal more drag than when the wheels and flaps are retracted. Similarly, when an aircraft is flying in denser air at low altitude, there is a

great deal more drag than when the aircraft is operating in the rarified air at jet cruising altitudes of 30-40,000 feet. Drag is roughly proportional to the square of the speed...in other words, if you double the speed, you get four times as much drag. This is not to say that drag cannot be high at lower speeds as well...an aircraft flying at a high angle of attack with wheels and flaps down can create an enormous amount of drag, and could get into a situation where the drag exceeds the thrust available. Unless the aircraft is high enough that it can trade altitude for speed, being in such a "behind the power curve" condition is extremely dangerous.

If thrust must equal drag for an aircraft to remain in straight and level flight, how can a glider, which has no thrust, stay airborne? It must convert altitude (potential energy) to forward motion (kinetic energy) as it descends under the influence of gravity. To get airborne in the first place, it must rely on the thrust of a tow-plane, or the thrust provided by a winch and tow-line. Once at altitude, it can only remain airborne or maintain altitude by finding places where the air is moving upwards faster than it needs to descend in order to maintain the forward motion required to generate lift. It must find the "thermals" where warm air is rising due to solar heating of the landscape, or the currents of air rising over hills or mountains. If it fails to find these pockets of rising air, it will inevitably have to descend and come back to land. Gliders typically have a 40:1 glide ratio, i.e. they travel forward 40 feet for every foot they descend. This means that from an altitude of 6,000 feet they could glide about 40 miles. On a good day, a glider can stay airborne for hours, and might travel several hundred miles.

Stability

The configuration of an aircraft is defined by a number of things, not the least of which is the

need for stability. An aircraft which has positive stability will tend to return to straight and level flight after any upset if the controls are neutralized, whereas an unstable aircraft would continue to diverge from the straight and level until active control measures were taken. Stability is a good thing for airliners, which spend most of their time in straight and level flight. The drawback to too much stability is that you need bigger control surfaces to make the aircraft change direction when you want it to. For this reason fighter aircraft are typically designed with very little stability...the smallest control surface deflection will have an immediate effect. In extreme cases (such as the F117 Nighthawk), they are so unstable that they could not be flown at all without computer stability augmentation.



Fig 11. The F-117 Nighthawk is so inherently unstable that it would be uncontrollable without a computer assisted stabilization system.

The most stable configuration for an aircraft would appear to be one with the wing on top of the fuselage, so that the pendulum effect of the body would tend to keep the wings level. Very few airliners have adopted this form, however. The vast majority (including all Boeing and Airbus aircraft) have their wings on the bottom of the fuselage. Why? Because of other considerations such as the length of undercarriage struts, ease of maintenance, and simpler access to fuel tanks in the wings. Stability is maintained by bending the wings up (applying 'dihedral'). About the only aircraft you will find with high wings are specialized freighters such as the C-17 Globemaster, the C-

5 Galaxy, and C-130 Hercules, or propeller-driven airliners such as the Dash 8 and Fokker F-27 that needed to mount the engines high to provide clearance for the props. For the freighters it was important to get the body as low to the ground as possible for ease of loading and off-loading, and they have the wheels retract into the sides of the fuselage, rather than into the wings.



Fig12. Most airliners use a low wing configuration. This shortens the landing gear, and keeps the wings and engines lower to the ground for ease of maintenance and refuelling. They rely on the dihedral (upward bend) of the wings for stability.



Fig 13. The high wing configuration used on the Dash-8 keeps the propellers clear of the ground, and eliminates the need for air-stairs, but look how long the main undercarriage has to be.

The vertical tail fin provides directional stability, and its size is dependant on the length of the fuselage. Generally, the longer the fuselage, the smaller the tail needs to be because it will have a longer moment arm (i.e. greater leverage).

Pitch stability is provided by the horizontal stabilizer or tailplane. For positive pitch stability this should have a slightly negative angle of attack, so that if the aircraft starts a dive the tendency will be for the nose to be pulled up as speed increases. The size of the tailplane will be

dictated by its displacement from the centre of gravity...on a short, stubby aircraft it will need to be relatively large; on a long aircraft it can be smaller. Because jet airliners fly close to the speed of sound where they encounter the effects of sonic shock waves, they require powerful pitch control, and so the entire tail surface is moveable, rather than just the trailing edges as on slower prop-driven aircraft.

The tailplane is normally mounted on the aft fuselage because this makes for good structural strength with the least complications for control lines. In some cases the tailplane will be mounted on the top of the vertical stabilizer. This was done with the B-727 and DC-9/MD-80 series aircraft because their engines were in the way of a fuselage mount. In the case of the Dash 8, a T-tail configuration was used to keep the tailplane out of the turbulent propwash.



Fig 14. The horizontal stabilizer of the B-727 had to be mounted on top of the fin in order to be clear of the rear-fuselage mounted engines. Note that the entire surface is moveable to be able to provide the required degree of control effectiveness. A big advantage of mounting the engines so close to the centre-line is the improvement in handling quality in the event of an engine failure.

Air Density

We mentioned before that one of the primary factors controlling the amount of lift generated by a wing was airspeed...the faster you go, the more lift you produce. If we examine this in a little more detail we will find that while speed is important, the density of the air also plays a very significant part. Reduced to simple terms, it is the number of molecules of air per second passing over the wing that determine the amount of lift. This means that as an aircraft climbs to a higher altitude where the air is thinner (less dense), it must fly faster in order to produce the same amount of lift. This is actually a good thing, because if the air was of uniform density at all altitudes it would be necessary to find a way to “shrink” the size of the wings in order to go faster without generating more lift.

Trim

For an aircraft to maintain level flight the centre of lift must be directly above the centre of gravity. The centre of lift is a combination of the lift provided by the main wings and the lift provided by the tailplane. The centre of gravity will move during flight as fuel is burned off, and the angle of attack of the tailplane (horizontal stabilizer) must be adjusted accordingly to keep the lift and weight vectors properly aligned. In order that this adjustment does not need the constant application of pressure on the control column (which would be very tiring for the crew), “trim tabs” are used to allow the pilot to make fine adjustments to the control surface so that the aircraft can be flown “hands off”. Trim tabs are also provided for ailerons and rudder to allow for the fact that due to normal wear and tear on the airframe it may become ‘bent’ and require small control inputs in order to fly straight and level.

Autopilot