This material can be found in more detail in "Understanding Flight",
by David Anderson and Scott Eberhardt, McGraw-Hill, 2001, ISBN: 0-07-136377-7

A Physical Description of Flight©

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Almost everyone today has flown in an airplane. Many ask the simple question "what makes an airplane fly?" The answer one frequently gets is misleading and often just plain wrong. We hope that the answers provided here will clarify many misconceptions about lift and that you will adopt our explanation when explaining lift to others. We are going to show you that lift is easier to understand if one starts with Newton's laws rather than the Bernoulli principle. We will also show you that the popular explanation that most of us were taught is misleading at best and that lift is due to the wing diverting air down. Most of this diverted air is pulled down from above the wing.

Let us start by defining three descriptions of lift commonly used in textbooks and training manuals. The first we will call the Mathematical Aerodynamics Description of lift, which is used by aeronautical engineers. This description uses complex mathematics and/or computer simulations to calculate the lift of a wing. It often uses a mathematical concept called "circulation" to calculate the acceleration of the air over the wing. Circulation is a measure of the apparent rotation of the air around the wing. While useful for calculations of lift, this description does not lend themselves to an intuitive understanding of flight.

The second description we will call the Popular Description, which is based on the Bernoulli principle. The primary advantage of this description is that it is easy to understand and has been taught for many years. Because of its simplicity, it is used to describe lift in most flight training manuals. The major disadvantage is that it relies on the "principle of equal transit times", or at least on the assumption that because the air must travel farther over the top of the wing it must go faster. This description focuses on the shape of the wing and prevents one from understanding such important phenomena as inverted flight, power, ground effect, and the dependence of lift on the angle of attack of the wing.

The third description, which we are advocating here, we will call the Physical Description of lift. This description of lift is based primarily on Newton's three laws and a phenomenon called the Coanda effect. This description is uniquely useful for understanding the phenomena associated with flight. It is useful for an accurate understanding the relationships in flight, such as how power increases with load or how the stall speed increases with altitude. It is also a useful tool for making rough estimates ("back-of-the-envelope calculations") of lift. The Physical Description of lift is also of great use to a pilot who needs an intuitive understanding of how to fly the airplane.

The popular description of lift

Students of physics and aerodynamics are taught that an airplane flies as a result of the Bernoulli principle, which says that if air speeds up the pressure is lowered. (In fact this is not always true. The air flows fast over the airplane's static port but the altimeter still reads the correct altitude.) The argument goes that a wing has lift because the air goes faster over the top creating a region of low pressure. This explanation usually satisfies the curious and few challenge the conclusions. Some may wonder why the air goes faster over the top of the wing and this is where the popular explanation of lift falls apart.

In order to explain why the air goes faster over the top of the wing, many have resorted to the geometric argument that the distance the air must travel is directly related to its speed. The usual claim is that when the air separates at the leading edge, the part that goes over the top must converge at the trailing edge with the part that goes under the bottom. This is the so-called "principle of equal transit times".

One might ask if the numbers calculated by the Popular Description really work. Let us look at an example. Take the case of a Cessna 172, which is popular, high-winged, four-seat airplane. The wings must lift 2300 lb (1045 kg) at its maximum flying weight. The path length for the air over the top of the wing is only about 1.5% greater than under the wing. Using the Popular Description of lift, the wing would develop only about 2% of the needed lift at 65 mph (104 km/h), which is "slow flight" for this airplane. In fact, the calculations say that the minimum speed for this wing to develop sufficient lift is over 400 mph (640 km/h). If one works the problem the other way and asks what the difference in path length would have to be for the Popular Description to account for lift in slow flight, the answer would be 50%. The thickness of the wing would be almost the same as the chord length.

But, who says the separated air must meet at the trailing edge at the same time? Figure 1 shows the airflow over a wing in a simulated wind tunnel. In the simulation, smoke is introduced periodically. One can see that the air that goes over the top of the wing gets to the trailing edge considerably before the air that goes under the wing. In fact, the air is accelerated much faster than would be predicted by equal transit times. Also, on close inspection one sees that the air going under the wing is slowed down from the "free-stream" velocity of the air. The principle of equal transit times holds only for a wing with zero lift.

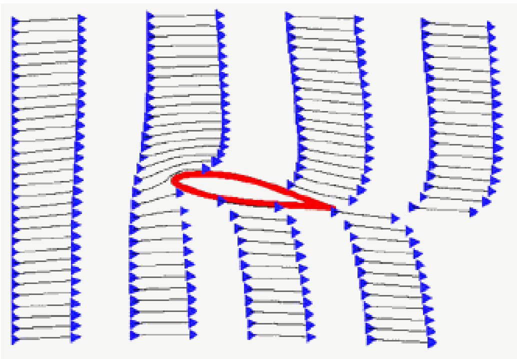

Fig 1 Simulation of the airflow over a wing in a wind tunnel, with "smoke".

The popular explanation also implies that inverted flight is impossible. It certainly does not address acrobatic airplanes, with symmetric wings (the top and bottom surfaces are the same shape), or how a wing adjusts for the great changes in load such as when pulling out of a dive or in a steep turn?

So, why has the popular explanation prevailed for so long? One answer is that the Bernoulli principle is easy to understand. There is nothing wrong with the Bernoulli principle, or with the statement that the air goes faster over the top of the wing. But, as the above discussion suggests, our understanding is not complete with this explanation. The problem is that we are missing a vital piece when we apply Bernoulli's principle. We can calculate the pressures around the wing if we know the speed of the air over and under the wing, but how do we determine the speed? As we will soon see, the air accelerates over the wing because the pressure is lower, not the other way around.

Another fundamental shortcoming of the popular explanation is that it ignores the work that is done. Lift requires power (which is work per time). As will be seen later, an understanding of power is key to the understanding of many of the interesting phenomena of lift.

Newton's laws and lift

So, how does a wing generate lift? To begin to understand lift we must review Newton's first and third laws. (We will introduce Newton's second law a little later.) Newton's first law states *a body at rest will remain at rest, or a body in motion will continue in straight-line motion unless subjected to an external applied force*. That means, if one sees a bend in the flow of air, or if air originally at rest is accelerated into motion, a force is acting on it. Newton's third law states that *for every action there is an equal and opposite reaction*. As an example, an object sitting on a table exerts a force on the table (its weight) and the table puts an equal and opposite force on the object to hold it up. In order to generate lift a wing must do something to the air. What the wing does to the air is the action while lift is the reaction.

Let's compare two figures used to show streamlines over a wing. In figure 2 the air comes straight at the wing, bends around it, and then leaves straight behind the wing. We have all seen similar pictures, even in flight manuals. But, the air leaves the wing exactly as it appeared ahead of the wing. There is no net action on the air so there can be no lift! Figure 3 shows the streamlines, as they should be drawn. The air passes over the wing and is bent down. Newton's first law says that them must be a force on the air to bend it down (the action). Newton's third law says that there must be an equal and opposite force (up) on the wing (the reaction). To generate lift a wing must divert lots of air down.

Fig 2 Common depiction of airflow over a wing. This wing has no lift.

Fig 3 True airflow over a wing with lift, showing upwash and downwash.

The lift of a wing is equal to the change in momentum of the air it is diverting down. Momentum is the product of mass and velocity (mv). The most common form of Newton's second law is F= ma, or force equal mass times acceleration. The law in this form gives the force necessary to accelerate an object of a certain mass. An alternate form of Newton's second law can be written: *The lift of a wing is proportional to the amount of air diverted down times the vertical velocity of that air.* It is that simple. For more lift the wing can either divert more air (mass) or increase its vertical velocity. This vertical velocity behind the wing is the vertical component of the "downwash". Figure 4 shows how the downwash appears to the pilot (or in a wind tunnel). The figure also shows how the downwash appears to an observer on the ground watching the wing go by. To the pilot the air is coming off the wing at roughly the angle of attack and at about the speed of the airplane. To the observer on the ground, if he or she could see the air, it would be coming off the wing almost vertically at a relatively slow speed. The greater the angle of attack of the wing the greater the vertical velocity of the air. Likewise, for a given angle of attack, the greater the speed of the wing the greater the vertical velocity of the air. Both the increase in the speed and the increase of the angle of attack increase the length of the vertical velocity arrow. It is this vertical velocity that gives the wing lift.

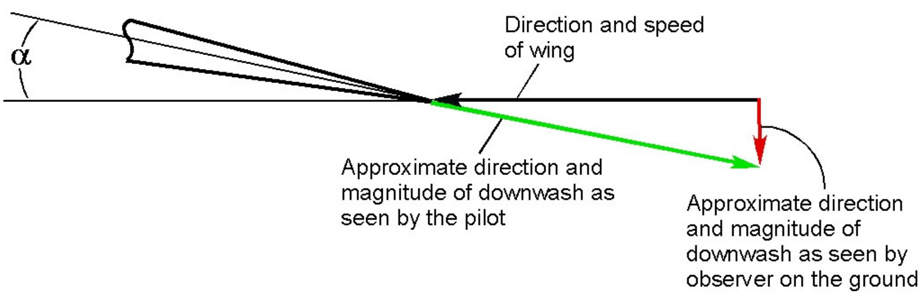

Fig 4 How downwash appears to a pilot and to an observer on the ground.

As stated, an observer on the ground would see the air going almost straight down behind the plane. This can be demonstrated by observing the tight column of air behind a propeller, a household fan, or under the rotors of a helicopter; all of which are rotating wings. If the air were coming off the blades at an angle the air would produce a cone rather than a tight column. The wing develops lift by transferring momentum to the air. For straight and level flight this momentum eventually strikes the earth in. If an airplane were to fly over a very large scale, the scale would weigh the airplane.

Let us do a back-of-the-envelope calculation to see how much air a wing might divert. Take for example a Cessna 172 that weighs about 2300 lb (1045 kg). Traveling at a speed of 140 mph (220 km/h), and assuming an effective angle of attack of 5 degrees, we get a vertical velocity for the air of about 11.5 mph (18 km/h) right at the wing. If we assume that the *average* vertical velocity of the air diverted is half that value we calculate from Newton's second law that the amount of air diverted is on the order of 5 ton/s. Thus, a Cessna 172 at cruise is diverting about five times its own weight in air per second to produce lift. Think how much air is diverted by a 250-ton Boeing 777 on takeoff.

Diverting so much air down is a strong argument against lift being just a surface effect (that is only a small amount of air around the wing accounts for the lift), as implied by the popular explanation. In fact, in order to divert 5 ton/sec the wing of the Cessna 172 must accelerate all of the air within 18 feet (7.3 m) above the wing. One should remember that the density of air at sea level is about 2 lb per cubic yard (about 1kg per cubic meter). Figure 5 illustrates the effect of the air being diverted down from a wing. A huge hole is punched through the fog by the downwash from the airplane that has just flown over it.

Fig 5 Downwash and wing vortices in the fog. (Photographer Paul Bowen, courtesy of Cessna Aircraft, Co.)

So how does a thin wing divert so much air? When the air is bent around the top of the wing, it pulls on the air above it accelerating that air downward. Otherwise there would be voids in the air above the wing. Air is pulled from above. This pulling causes the pressure to become lower above the wing. It is the acceleration of the air above the wing in the downward direction that gives lift. (Why the wing bends the air with enough force to generate lift will be discussed in the next section.)

As seen in figure 3, a complication in the picture of a wing is the effect of "upwash" at the leading edge of the wing. As the wing moves along, air is not only diverted down at the rear of the wing, but air is pulled up at the leading edge. This upwash actually contributes to negative lift and more air must be diverted down to compensate for it. This will be discussed later when we consider ground effect.

Normally, one looks at the air flowing over the wing in the frame of reference of the wing. In other words, to the pilot the air is moving and the wing is standing still. We have already stated that an observer on the ground would see the air coming off the wing almost vertically. But what is the air doing below the wing? Figure 6 shows an instantaneous snapshot of how air molecules are moving as a wing passes by. Remember in this figure the air is initially at rest and it is the wing moving. Arrow "1" will become arrow "2" and so on. Ahead of the leading edge, air is moving up (upwash). At the trailing edge, air is diverted down (downwash). Over the top the air is accelerated towards the trailing edge. Underneath, the air is accelerated forward slightly.

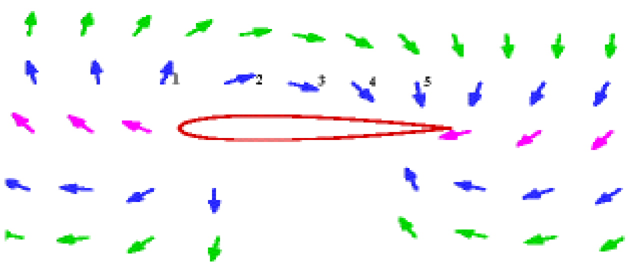

Fig 6 Direction of air movement around a wing as seen by an observer on the ground.

So, why does the air follow this pattern? First, we have to bear in mind that air is considered an incompressible fluid for low-speed flight. That means that it cannot change its volume and that there is a resistance to the formation of voids. Now the air has been accelerated over the top of the wing by of the reduction in pressure. This draws air from in front of the wing and expels if back and down behind the wing. This air must be compensated for, so the air shifts around the wing to fill in. This is similar to the circulation of the water around a canoe paddle. This circulation around the wing is no more the driving force for the lift on the wing than is the circulation in the water drives the paddle. Though, it is true that if one is able to determine the circulation around a wing the lift of the wing can be calculated. Lift and circulation are proportional to each other.

One observation that can be made from figure 6 is that the top surface of the wing does much more to move the air than the bottom. So the top is the more critical surface. Thus, airplanes can carry external stores, such as drop tanks, under the wings but not on top where they would interfere with lift. That is also why wing struts under the wing are common but struts on the top of the wing have been historically rare. A strut, or any obstruction, on the top of the wing would interfere with the lift.

Coanda Effect

A natural question is "how does the wing divert the air down?" When a moving fluid, such as air or water, comes into contact with a curved surface it will try to follow that surface. To demonstrate this effect, hold a water glass horizontally under a faucet such that a small stream of water just touches the side of the glass. Instead of flowing straight down, the presence of the glass causes the water to wrap around the glass as is shown in figure 7. This tendency of fluids to follow a curved surface is known as the Coanda effect. From Newton’s first law we know that for the fluid to bend there must be a force acting on it. From Newton’s third law we know that the fluid must put an equal and opposite force on the glass.

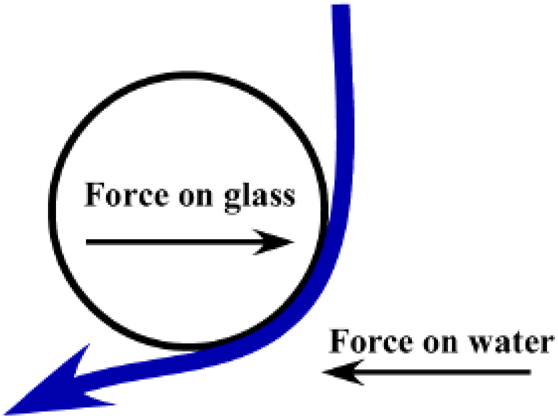

Fig 7 Coanda effect.

So why should a fluid follow a curved surface? The answer is viscosity; the resistance to flow which also gives the air a kind of "stickiness". Viscosity in air is very small but it is enough for the air molecules to want to stick to the surface. At the surface the relative velocity between the surface and the nearest air molecules is exactly zero. (That is why one cannot hose the dust off of a car.) Just above the surface the fluid has some small velocity. The farther one goes from the surface the faster the fluid is moving until the external velocity is reached. Because the fluid near the surface has a change in velocity, the fluid flow is bent towards the surface by shear forces. Unless the bend is too tight, the fluid will follow the surface. This volume of air around the wing that appears to be partially stuck to the wing is called the "boundary layer" and is less than one inch (2.5 cm) thick, even for a large wing.

Look again at Figure 3. The magnitude of the forces on the air (and on the wing) are proportional to the "tightness" of the bend. The tighter the air bends the greater the force on it. One thing to notice in the figure is that most of the lift is on the forward part of the wing. In fact, half of the total lift on a wing is typically produced in the first 1/4 of the chord length.

Lift as a function of angle of attack

There are many types of wing: conventional, symmetric, conventional in inverted flight, the early biplane wings that looked like warped boards, and even the proverbial "barn door". In all cases, the wing is forcing the air down, or more accurately pulling air down from above. (Though the early wings did have a significant contribution from the bottom.) What each of these wings has in common is an angle of attack with respect to the oncoming air. It is the angle of attack that is the primary parameter in determining lift.

To better understand the role of the angle of attack it is useful to introduce an "effective" angle of attack, defined such that the angle of the wing to the oncoming air that gives zero lift is defined to be zero degrees. If one then changes the angle of attack both up and down one finds that the lift is proportional to the angle. Figure 8 shows the lift of a typical wing as a function of the effective angle of attack. A similar lift versus angle of attack relationship is found for all wings, independent of their design. This is true for the wing of a 747, an inverted wing, or your hand out the car window. The inverted wing can be explained by its angle of attack, despite the apparent contradiction with the popular explanation of lift. A pilot adjusts the angle of attack to adjust the lift for the speed and load. The role of the angle of attack is more important than the details of the wings shape in understanding lift. The shape comes into play in the understanding of stall characteristics and drag at high speed.

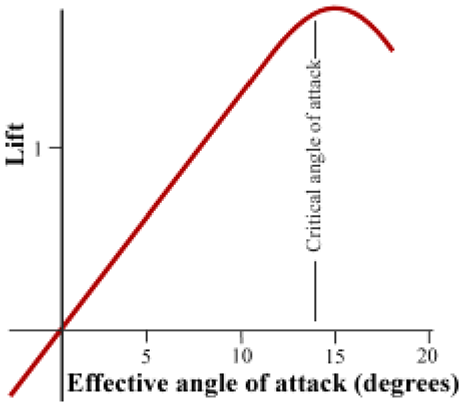

Fig 8 Lift versus the effective angle of attack.

Typically, the lift begins to decrease at a "critical angle" of attack of about 15 degrees. The forces necessary to bend the air to such a steep angle are greater than the viscosity of the air will support, and the air begins to separate from the wing. This separation of the airflow from the top of the wing is a stall.

The wing as air "scoop"

We now would like to introduce a new mental image of a wing. One is used to thinking of a wing as a thin blade that slices though the air and develops lift somewhat by magic. The new image that we would like you to adopt is that of the wing as a scoop diverting a certain amount of air from the horizontal to roughly the angle of attack, as depicted in Figure 9. For wings of typical airplanes it is a good approximation to say that the area of the scoop is proportional to the area of the wing. The shape of the scoop is approximately elliptical for all wings, as shown in the figure. Since the lift of the wing is proportional to the amount of air diverted, the lift of is also proportional to the wing's area.

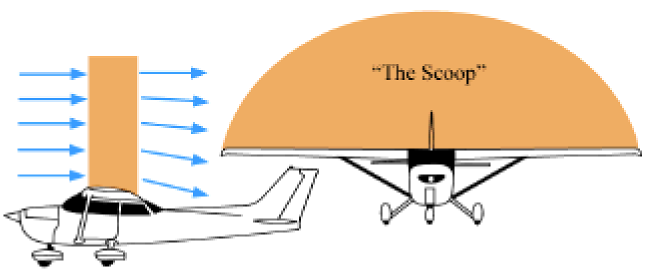

Fig 9 The wing as a scoop.

As stated before, the lift of a wing is proportional to the amount of air diverted down times the vertical velocity of that air. As a plane increases speed, the scoop diverts more air. Since the load on the wing does not increase, the vertical velocity of the diverted air must be decreased proportionately. Thus, the angle of attack is reduced to maintain a constant lift. When the plane goes higher, the air becomes less dense so the scoop diverts less air at a given speed. Thus, to compensate the angle of attack must be increased. The concepts of this section will be used to understand lift in a way not possible with the popular explanation.

Lift requires power

When a plane passes overhead the formally still air gains a downward velocity. Thus, the air is left in motion after the plane leaves. The air has been given energy. Power is energy, or work, per time. So, lift requires power. This power is supplied by the airplane's engine (or by gravity and thermals for a sailplane).

How much power will we need to fly? If one fires a bullet with a mass, m, and a velocity, v, the energy given to the bullet is simply $\frac{1}{2}mv^2$. Likewise, the energy given to the air by the wing is proportional to the amount of air diverted down times the vertical velocity squared of that diverted air. We have already stated that the lift of a wing is proportional to the amount of air diverted times the vertical velocity of that air. Thus, *the power needed to lift the airplane is proportional to the load (or weight) times the vertical velocity of the air*. If the speed of the plane is doubled the amount of air diverted down doubles. Thus to maintain a constant lift, the angle of attack must be reduced to give a vertical velocity that is half the original. The power required for lift has been cut in half. This shows that the power required for lift becomes less as the airplane's speed increases. In fact, we have shown that this power to create lift is proportional to 1/speed of the plane.

But, we all know that to go faster (in cruise) we must apply more power. So there must be more to power than the power required for lift. The power associated with lift is often called the "induced" power. Power is also needed to overcome what is called "parasitic" drag, which is the drag associated with moving the wheels, struts, antenna, etc. through the air. The energy the airplane imparts to an air molecule on impact is proportional to the speed^2 (form $\frac{1}{2}mv^2$) . The number of molecules struck per time is proportional to the speed. The faster one goes the higher the rate of impacts. Thus the parasitic power required to overcome parasitic drag increases as the speed^3.

Figure 10 shows the "power curves" for induced power, parasitic power, and total power (the sum of induced power and parasitic power). Again, the induced power goes as 1/speed and the parasitic power goes as the speed^3. At low speed the power requirements of flight are dominated by the induced power. The slower one flies the less air is diverted and thus the angle of attack must be increased to increase the vertical velocity of that air. Pilots practice flying on the "backside of the power curve" so that they recognize that the angle of attack and the power required to stay in the air at very low speeds are considerable.

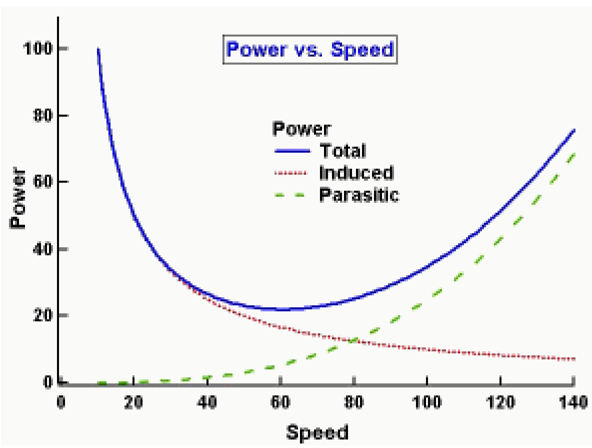

Fig 10 Power requirements versus speed.

At cruise, the power requirement is dominated by parasitic power. Since this goes as the speed^3 an increase in engine size gives one a faster rate of climb but does little to improve the cruise speed of the plane. Doubling the size of the engine will only increase the cruise speed by about 25%.

Since we now know how the power requirements vary with speed, we can understand drag, which is a force. Drag is simply power divided by speed. Figure 11 shows the induced, parasitic, and total drag as a function of speed. Here the induced drag varies as 1/speed^2 and parasitic drag varies as the speed^2. Taking a look at these figures one can deduce a few things about how airplanes are designed. Slower airplanes, such as gliders, are designed to minimize induced power, which dominates at lower speeds. Faster propeller-driven airplanes are more concerned with parasite power, and jets are dominated by parasitic drag. (This distinction is outside of the scope of this article.)

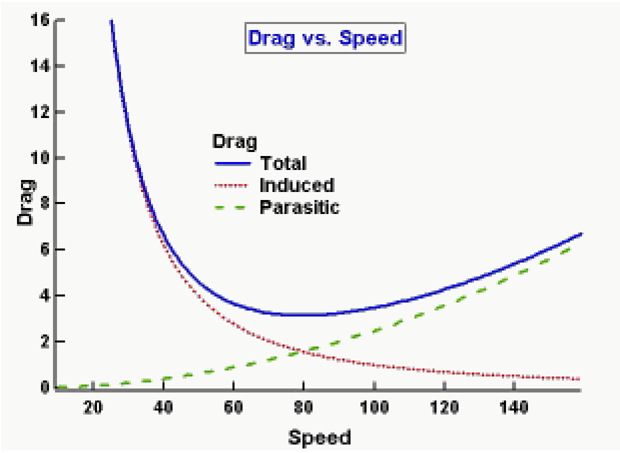

Fig 11 Drag versus speed.

Wing efficiency

At cruise, a non-negligible amount of the drag of a modern wing is induced drag. Parasitic drag of a Boeing 747 wing is only equivalent to that of a 1/2-inch cable of the same length. One might ask what affects the efficiency of a wing. We saw that the induced power of a wing is proportional to the vertical velocity of the air. If the area of a wing were to be increased, the size of our scoop would also increase, diverting more air. So, for the same lift the vertical velocity (and thus the angle of attack) would have to be reduced. Since the induced power is proportional to the vertical velocity of the air, it is also reduced. Thus, the lifting efficiency of a wing increases with increasing wing area. The larger the wing the less induced power required to produce the same lift, though this is achieved with and increase in parasitic drag.

As will be briefly discussed in the section on ground effect, the additional loading on the wing in straight and level flight due to upwash is equal to the weight of the airplane time 2/AR. Where AR is the wing's aspect ratio (span divided by the mean chord). Thus, when considering two wings with the same area but different aspect ratios, the wing with the greater aspect ratio will be the most efficient.

There is a misconception by some that lift does not require power. This comes from aeronautics in the study of the idealized theory of wing sections (airfoils). When dealing with an airfoil, the picture is actually that of a wing with infinite span. Since we have seen that the power necessary for lift decrease with increasing area of the wing, a wing of infinite span does not require power for lift. If lift did not require power airplanes would have the same range full as they do empty, and helicopters could hover at any altitude and load. Best of all, propellers (which are rotating wings) would not require power to produce thrust. Unfortunately, we live in the real world where both lift and propulsion require power.

Power and wing loading

Now let us consider the relationship between wing loading and power. At a constant speed, if the wing loading is increased the vertical velocity must be increased to compensate. This is accomplished by increasing the angle of attack of the wing. If the total weight of the airplane were doubled (say, in a 2g turn), and the speed remains constant, the vertical velocity of the air is doubled to compensate for the increased wing loading. The induced power is proportional to the load times the vertical velocity of the diverted air, which have both doubled. Thus the induced power requirement has increased by a factor of four! So induced power is proportional to the load^2.

One way to measure the total power is to look at the rate of fuel consumption. Figure 12 shows the fuel consumption versus gross weight for a large transport airplane traveling at a constant speed (obtained from actual data). Since the speed is constant the change in fuel consumption is due to the change in induced power. The data are fitted by a constant (parasitic power) and a term that goes as the load^2. This second term is just what was predicted in our Newtonian discussion of the effect of load on induced power.

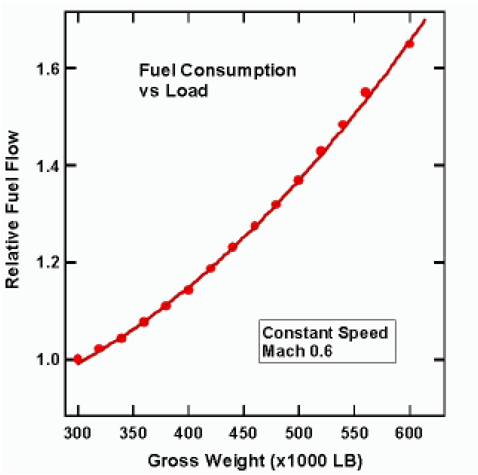

Fig 12 Fuel consumption versus load for a large transport airplane traveling at a constant speed.

The increase in the angle of attack with increased load has a downside other than just the need for more power. As shown in figure 8 a wing will eventually stall when the air can no longer follow the upper surface. That is, when the critical angle is reached. Figure 13 shows the angle of attack as a function of airspeed for a fixed load and for a 2-g turn. The angle of attack at which the plane stalls is constant and is not a function of wing loading. The angle of attack increases as the load and the stall speed increases as the square root of the load. Thus, increasing the load in a 2-g turn increases the speed at which the wing will stall by 40%. An increase in altitude will further increase the angle of attack in a 2-g turn. This is why pilots practice "accelerated stalls" which illustrates that an airplane can stall at any speed, since for any speed there is a load that will induce a stall.

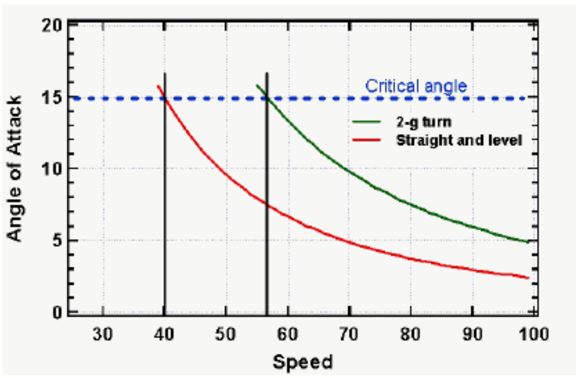

Fig 13 Angle of attack versus speed for straight and level flight and for a 2-g turn.

Wing vortices

One might ask what the downwash from a wing looks like. The downwash comes off the wing as a sheet and is related to the details on the load distribution on the wing. Figure 14 shows, through condensation, the distribution of lift on an airplane during a high-g maneuver. From the figure one can see that the distribution of load changes from the root of the wing to the tip. Thus, the amount of air in the downwash must also change along the wing. The wing near the root is "scooping" up much more air than the tip. Since the wing near the root is diverting so much air the net effect is that the downwash sheet will begin to curl outward around itself, just as the air bends around the top of the wing because of the change in the velocity of the air. This is the wing vortex. The tightness of the curling of the wing vortex is proportional to the rate of change in lift along the wing. At the wing tip the lift must rapidly become zero causing the tightest curl. This is the wing tip vortex and is just a small (though often most visible) part of the wing vortex. Returning to figure 5 one can clearly see the development of the wing vortices in the downwash as well as the wing tip vortices.

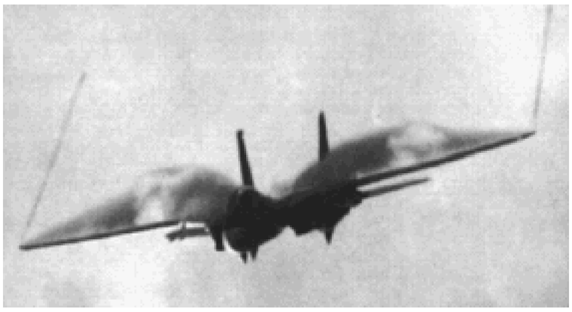

Fig 14 Condensation showing the distribution of lift along a wing. (from Patterns in the Sky, J.F. Campbell and J.R. Chambers, NASA SP-514.)

Winglets (those small vertical extensions on the tips of some wings) are used to improve the efficiency of the wing by increasing the effective length, and thus area, of the wing. The lift of a normal wing must go to zero at the tip because the bottom and the top communicate around the end. The winglet blocks this communication so the lift can extend farther out on the wing. Since the efficiency of a wing increases with area, this gives increased efficiency. One caveat is that winglet design is tricky and winglets can actually be detrimental if not properly designed.

Ground effect

Another common phenomenon that is often misunderstood is that of ground effect. That is the increased efficiency of a wing when flying within a wing length of the ground. A low-wing airplane will experience a reduction in drag by as much as 50% just before it touches down. This reduction in drag just above a surface is used by large birds, which can often be seen flying just above the surface of the water. Pilots taking off from deep-grass or soft runways also use ground effect. Many pilots mistakenly believe that ground effect is the result of air being compressed between the wing and the ground.

To understand ground effect it is necessary to look again at the upwash. Notice in Figure 15 that the air bends up from its horizontal flow to form the upwash. Newton's first law says that there must be a force acting on the air to bend it. Since the air is bent up the force must be up as shown by the arrow. Newton's third laws says that there is an equal and opposite force on the wing which is down. The result is that the upwash increases the load on the wing. To compensate for this increased load, the wing must fly at a greater angle of attack, and thus a greater induced power. As the wing approaches the ground the circulation below the wing is inhibited. As shown in Figure 16, there is a reduction in the upwash and in the additional loading on the wing caused by the upwash. To compensate, the angle of attack is reduced and so is the induced power. The wing becomes more efficient.

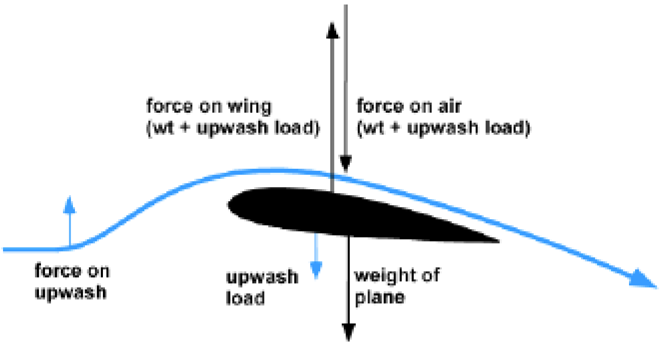

Fig 15 Wing out of ground effect

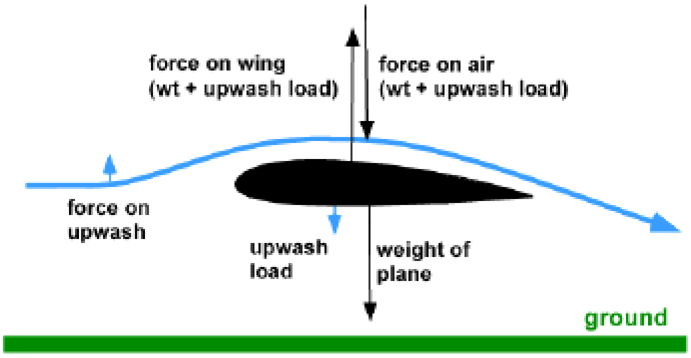

Fig 16 Wing in ground effect

The additional load due to upwash is equal to the weight of the airplane time 2/AR. Most small airplanes have aspect ratios of 7-8. An airplane with an aspect ratio of 8 can experience as much as a 25% reduction in wing loading due to ground effect. Since induced power is proportional to the load^2, this corresponds to a 50% reduction in induced power. Earlier, we estimated that a Cessna 172 flying at 110 knots must divert about 5 ton/sec to provide lift. In our calculations we neglected the contribution of upwash. The amount of air diverted is probably closer to 6 ton/sec.

Conclusions

Let us review what we have learned and get some idea of how the physical description has given us a greater ability to understand flight. First what have we learned:

- The *amount of air* diverted by the wing is proportional to the speed of the wing and the air density.
- The *vertical velocity* of the diverted air is proportional to the speed of the wing and the angle of attack.
- The *lift* is proportional to the amount of air diverted times the vertical velocity of the air.
- The *power* needed for lift is proportional to the lift times the vertical velocity of the air.

Now let us look at some situations from the physical point of view and from the perspective of the popular explanation.

- The plane's speed is reduced. The physical view says that the amount of air diverted is reduced so the angle of attack is increased to compensate. The power needed for lift is also increased. The popular explanation cannot address this.
- The load of the plane is increased. The physical view says that the amount of air diverted is the same but the angle of attack must be increased to give additional lift. The power needed for lift has also increased. Again, the popular explanation cannot address this.
- A plane flies upside down. The physical view has no problem with this. The plane adjusts the angle of attack of the inverted wing to give the desired lift. The popular explanation implies that inverted flight is impossible.

As one can see, the popular explanation, which fixates on the shape of the wing, may satisfy many but it does not give one the tools to really understand flight. The physical description of lift is easy to understand and much more powerful.

This material can be found in more detail in "Understanding Flight",
by David Anderson and Scott Eberhardt, McGraw-Hill, 2001, ISBN: 0-07-136377-7