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The Newtonian Description of Lift of a Wing-Revised

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Abstract

The explanations we use to teach the principles of flight more often than not merely propagate long-held myths. A description of flight should focus on the angle of attack and not the shape of the wing. By explaining flight as an application of Newton's principles, one can understand lift, power, wing efficiency and other principles of flight. The Newtonian description of lift and an understanding of flight are presented here. The myths and some misconceptions of the application of Bernoulli's equation are also discussed.

I. INTRODUCTION

There are few physical phenomena, so generally studied, which are as misunderstood as the phenomenon of flight. In general what we have been taught and what we often teach as the physical explanation of lift is incorrect. As you will see, most explanations do not even make sense. We have also studied, often in a fairly superficial way, the Bernoulli theorem in a constricting tube, and have gone on to misapply it to unconfined airflow. Because our view has been misguided, there has been little to teach about flight, which is a very interesting and important part of our lives. Here we will show that when the physics of lift is understood, flight becomes much more interesting; rich with topics to be considered.

We have all been taught, in one form or another, what we will call the *popular description of lift*. The popular description of lift is really a family of descriptions with the unifying factor that they all rely on Bernoulli's equation and the acceleration of air over the wing to explain lift. Before and shortly after WWII most flight manuals taught the Newtonian view of flight, but sometime shortly thereafter the popular description dominated. This latter description of lift of a wing has three major parts. The first is that it fixates on the shape of the wing. The wing is viewed as being asymmetric with a kind of hump on the top.

The second part of the description is that the air accelerates over the top of the wing without any comment on the mechanism that causes the acceleration. The most common explanation for this acceleration is that, when the air separates at the leading edge of the wing, that air going over the top and that going under the wing must rejoin at the trailing edge. Since the air going over the top has to go over the hump, it has farther to travel and thus must go faster. Of course, no one has ever given a physical reason why this *principle of equal transit times* must be obeyed. In some cases this rule is softened a little to just state that since the air must go farther it must go faster. In reality, equal transit times holds only for a wing without lift. The greater the lift the greater the different in arrival times at the trailing edge with the air going over the top of the wing arriving considerably before the air below the wing.

The third part of the popular description employs the Bernoulli equation:

$$p + \frac{1}{2}\rho v^2 = C, \qquad (1)$$

Here p is the pressure (not well defined at the moment), ρ is the air density, v is the speed of the air, and C is a constant. In aerodynamics the potential energy term (ρgh) is neglected because of the small height differences and the small value of density. The argument of the Bernoulli description of lift is that since the air goes faster over the top of the wing it has a lower pressure and thus we have lift. At this point one might wonder (though it is unlikely) about Newton's first law: a body at rest will remain at rest, and a body in motion will continue in straight-line motion unless acted on by an external applied force. In the case of a fluid this external force is a pressure difference. To say that the decrease in pressure is caused by the acceleration of the air is a clear violation of Newton’s first law.

Another fundamental problem with this description is that the air’s pressure and speed are not related by the Bernoulli equation for a real wing in flight! The Bernoulli equation is a statement of the conservation of energy. For it to be applied the system must be in equilibrium and no energy added to the system. As you will see in the discussion below, a great deal of energy as added to the air. Before the wing came by the air was standing still. After the passage of the wing there is a great deal of air in motion. A 250-ton jet at cruse speed is doing a lot of work to stay in the air. Much of the fuel that is burned is adding energy to the air to create lift. Thus the Bernoulli equation is not applicable.

We said that the popular description of lift fixates on the shape of the wing. Picture in your mind several wings: an asymmetric wing in normal flight, the same wing in inverted flight, a symmetric wing and a flat plate. For each one, an orientation into the wind can be found which gives zero lift. We call this orientation the zero *effective angle of attack*. Now if one were to measure the lift of these wings as a function of the effective angle of attack, the results for all of them would be similar to Figure 1 which shows the results for two different wing profiles. The lift is linear with angle, both positive and negative, until the wing reaches the critical angle and a stall begins. The negative lift for negative angles of attack is the lift that the wing would experience in inverted flight. It is hard to reconcile this information with the popular description of lift.

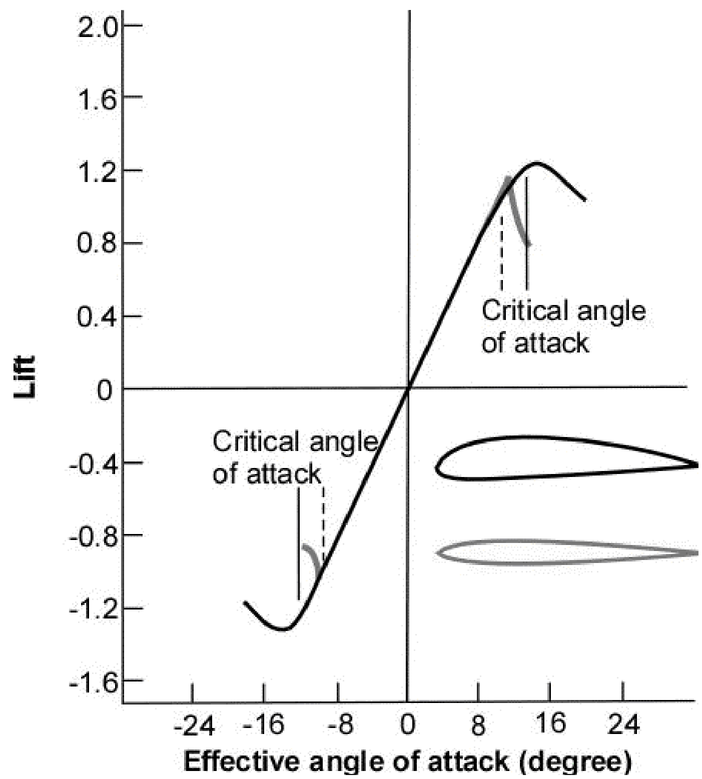

Fig. 1. Lift as a function of effective angle of attack for two wing profiles.

We should point out that the shape of the wing does affect the stall characteristics and efficiency of the wing, but it is not the primary factor in determining its lift. Also, the data in the figure are for infinite wings and the response of real, 3-D wings would have to be corrected for area and aspect ratio. But the key factor shown here is that the shape of the wing has nothing to do with the lift. It all depends on the angle of attack.

Some of us have worked problems in a physics class calculating the lift of a wing. Let us revisit the calculations with real numbers. Take as an example the lift of the wing of a Cessna 172, a common four-seat, high-wing airplane. It weighs 2300 lb at gross weight, has a wing area of 174 ft^2, and can fly in slow flight at 65 mph. The path length over the top of the wing is 1.5% greater than the path length under the wing. A calculation assuming that the air's velocity over the top of the wing is 1.5% greater than for the air going under the wing yields a lift of about 2% of that needed for flight. Following the same logic, the minimum speed to produce the necessary lift would be about 400 mph. Or working the other way around, the difference in path length would have to be about 50% to produce the necessary lift at 65 mph. This wing would be almost as thick as its chord length (distance from leading edge to trailing edge).

There is another mistaken description of lift, which we will call the *wrong-Newtonian description of lift*, although those that teach it just call it the Newtonian description of lift. This description of lift states that diverting air down produces lift, and that lift is a reaction force. This part is true. Unfortunately, in the wrong-Newtonian description of lift the air is diverted down by impact with the bottom of the wing. It is interesting to note that this was the view of lift held by Sir Isaac Newton himself. Although there is a little of this kind of lift for most wings, it is minimized for efficient wings. The amount of air impacted by the bottom of the wing is far too small to account for the lift.

Yet another common description of lift is that of circulation theory. Here the air is seen to rotate around the wing. This is sometimes used to explain the acceleration of the air over the top to the wing. There is a great deal of jargon, such as "starting vortex" and "bound vortices", associated with this description. Circulation theory is a mathematical abstraction useful and accurate for aerodynamic calculations. Mathematically, circulation is a non-zero curl in the airflow in a closed line integral around a wing, which is simply a statement that the wing bends the air. Circulation theory, like Bernoulli's theorem, can be misapplied. For example, statements have been made that classical aerodynamic theory proves that insects cannot fly. In all examples that we are familiar with, the flight of insects is expressed in terms of circulation. Circulation is a model developed for large aircraft that does not apply to small insects.

What follows is a brief and correct Newtonian description of the lift of a wing. A more detailed discussion can be found in our book “Understanding Flight”. In brief, the lift of a wing is a reaction force and is proportional to the amount and vertical velocity of air is diverted from the horizontal to the vertical, with almost all of the air diverted from above the wing. But, before we get to Newton we must discuss viscosity, a key to understanding flight.

II. The importance of viscosity

In understanding the physics of lift, it is important to understand why air bends around the top of the wing with enough force to produce lift. The answer is viscosity. The simplest demonstration of the effect of viscosity on a flowing fluid is to touch a small stream of water from a faucet with the side of a glass held horizontally. The water wraps part way around the glass. Newton's first law says that there must be a force on the stream of water, in the direction of the glass. Newton's third law says that there must be an equal and opposite force on the glass. The glass feels a force towards the water, not away as one might guess.

The flow of water around the glass is a demonstration of viscosity. Because of viscosity, the velocity of the fluid is exactly zero at the surface of an object. (This is why one cannot hose dust off of a car.) A short distance from the surface the fluid has a non-zero velocity. The velocity increases with distance from the surface until the *free-stream* velocity is reached. Think of two adjacent streamlines with different speeds. Since these streamlines have different velocities forces between them trying to speed up the slower streamline and slow down the faster streamline. The speed of air at the surface of the wing is exactly zero with respect to the surface of the wing. This is an expression of viscosity. The speed of the air increases with distance from the wing. Now imagine the first non-zero velocity streamline that just grazes the highpoint of the top of the wing. If it were initially to go straight back and not follow the wing, there would be a volume of zero velocity air between it and the wing. Forces would strip this air away from the wing and without a streamline to replace it, the pressure would lower. This lowering of the pressure would bend the streamline until it followed the surface of the wing.

The streamlines are bent by a lowering of the pressure. This is why the air is bent by the top of the wing and why the pressure above the wing is lowered. This lowered pressure decrease with distance above the wing but is the basis of the lift on a wing. The lowered pressure propagates out at the speed of sound, causing a great deal of air to bend around the wing.

Two streamlines communicate on a molecular scale. This is an expression of the pressure and the viscosity of air. Without viscosity there would be no communication between streamlines and no boundary layer. Often, calculations of lift are made in the limit of zero viscosity. In these cases viscosity is re-introduced implicitly with the *Kutta-Joukowski condition*, which requires that the air come smoothly off at the trailing edge of the wing. Also, the calculations require that the air follows the surface of the wing which is another introduction of the effects of viscosity. One result of the near elimination of viscosity from the calculations is that there is no boundary layer calculated.

We have seen why air bends around the top of the wing. The question is why this thin boundary layer can pull the amount of air necessary to produce lift. First, one must understand that for flight speeds below about Mach 0.3 (30% of the local speed of sound), the forces are so small that air is considered an incompressible fluid. This means that the volume does not change and that voids cannot form in the flow. (This may seem like a strange assumption but that assumption is also made in calculation of the flow of gas through a venturi using the Bernoulli equation.) The boundary layer is pulled from the horizontal flow of air over the wing pulling down the adjacent streamline and causing a lowering of the pressure over the wing. This propagates outwards causing a great deal of air to be accelerated down. The lowered pressure above the wing draws in the air from in front of the wing, produces the upwash (see below) and accelerates it. The acceleration of the air over the wing is caused by the lowering of the pressure and not the other way around.

III. The Newtonian description of lift

The derivative form of Newton's second law describes the thrust of a rocket motor or of a jet engine:

$$F = \dot{m}v \,. \qquad (2)$$

Here $\dot{m}$ is the time derivative of the expelled mass and v is the velocity of the gas. Like the rocket and the jet, propellers produce thrust and helicopter rotors produce lift by the expulsion of air according to Newton's second law. Propellers and rotors are just rotating wings. It should not be surprising that wings also produce lift by accelerating air in the downward direction. As we will soon see, the wing diverts a great deal of air to produce lift.

Let us now look at the airflow over the wing. Figure 2 shows the airflow around the wing as depicted in many textbooks, flight manuals, and even a NASA website. This figure might be considered a Bernoulli description's view of airflow. This wing in reality has no lift. The air approaches from the horizontal and leaves in the same direction. There has been no net change to the air's direction and therefore no change (lift) to the wing. From a Newtonian point of view, the net bending of the air is zero so there is no net force acting on it (Newton's first law). Since there was no net force acting on the air there can be no net force acting on the wing (Newton's third law).

Fig. 2. The popular description's view of airflow around a wing.

Figure 3 shows the true airflow around a wing with lift. The air is drawn up from below the wing producing *upwash*. The air leaves the wing with a downward component, called *downwash*. Since the air is bent downward, Newton's first law states that there is a downward force on that air. Newton's third law states that there is an equal upward force on the wing. We have lift.

Fig. 3. The true airflow around a wing with lift.

Two rest frames

We are used to looking at the wing in a rest frame where the wing is stationary and the air is moving. This is the perspective in a wind tunnel or of a pilot. We will call this the *wing's rest frame*. But, few consider the rest frame where the air is originally standing still and the wing is moving. This we will call the *air's rest frame*. This is the rest frame of a person standing on a mountaintop who is able to take a picture of the velocity distribution around a passing wing. That person would see that the air is going almost straight down behind the wing. The fact that the air is accelerated almost straight down behind the wing in the air's rest frame should not be surprising. It has been accelerated in the opposite direction of the force of lift satisfying Newton's third law.

Figure 4 shows how the two rest frames are related. The horizontal arrow is the speed and direction of the oncoming air in the wing's rest frame. The other two arrows are the downwash as seen in the wing's and air's rest frames. The small vertical arrow, labeled v_v, is the component of velocity given to the air to produce lift. In the figure, the Greek letter α represents the effective angle of attack of the wing.

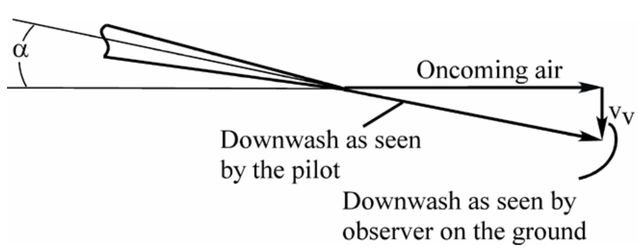

Fig. 4. The relationship between the wing and air rest frames.

In the wing's rest frame the wing is seen to bend the airflow down to produce lift. In the air's rest frame the air sees the wing as a receding surface drawing down on the air. This is sort of like the action of a receding piston. The air accelerates towards the wing and at the last minute the wing gets out of the way.

One might ask if it makes sense that in the air's rest frame the air goes straight down. It certainly makes sense from the point of view of efficiency. This puts the force parallel to gravity. In fact, the air has a slight forward direction due to frictional forces. But these forces are quite small. The fictional drag on the wing of a Boeing 747 is the same as that of a 0.5-inch cable of the same length.

One can easily demonstrate that the air comes vertically off the trailing edge of the wing. Examine the air from a small household fan, the blades of which are legitimate wings. The airflow is in a tight column. If the air were coming off the trailing edge at an angle it would form a cone rather than a column. It is fortunate that airfoils work this way. If, in the case of a propeller, the air came off the trailing edge at an angle, the transverse component of that air would cost energy but would not contribute to the net thrust.

It is worth noting that the wing produces lift by transferring momentum to the air. In straight-and-level flight this momentum is directed towards the ground. If the airplane were to fly over a large scale the weight of the airplane would be measured. The earth does not get lighter when the airplane takes off.

We would like to point out that insects obey the same laws of physics as airplanes and helicopters. They produce lift by blowing air down. When you have a chance, observe a bumblebee feeding on flowers. You will see that when it flies over a leaf, the leaf is depressed just as if it had landed on it.

The adjustment of lift

We are now able to consider how a wing can adjust the lift, L, for varying situations. We will rewrite eqn. (2) to read:

$$L = \dot{m} v_v , \qquad (3)$$

where v_v is the vertical velocity of the downwash in the air's rest frame. One can adjust the lift by adjusting $\dot{m}$, v_v or both. As we will see, the value of v_v changes with distance above the wing so it should more accurately be looked at as an average velocity. Let us start with the adjustment of v_v.

Referring to figure 4, one should have little trouble seeing that doubling the speed of the airplane, while keeping the angle of attack constant, doubles v_v. Likewise doubling the angle of attack of the wing, while keeping the speed of the airplane constant, also doubles v_v. Thus is follows that v_v is proportional to the wing’s

- speed
- angle of attack

For those that are not familiar with the operation of an airplane, the angle of attack is adjusted by tilting the entire aircraft.

Now let us look at the adjustment of $\dot{m}$. We would first like the reader to view the wing as a kind of "virtual scoop" as illustrated in figure 5. The amount of air intercepted by the wing is related to the lift distribution along the wing. The shape of the virtual scoop is half of an ellipse with the major axis equal to the wingspan and the minor axis proportional to the chord length (distance from leading to trailing edges) of the wing. The air intercepted is diverted down with the highest downward velocity near the wing and the deflection speed tapering to zero as the distance above the wing increases, as shown in the figure. This is not intended to imply that there is a real, physical scoop with clearly defined boundaries, and uniform flow. But this visualization aid does allow for a clear understanding of how the amount diverted air is affected by speed and density. The concept of the virtual scoop does have a real physical basis. In aeronautics the area of this scoop can be calculated with the Biot-Savart law, which solves a "fluid potential", similar to an electric potential.

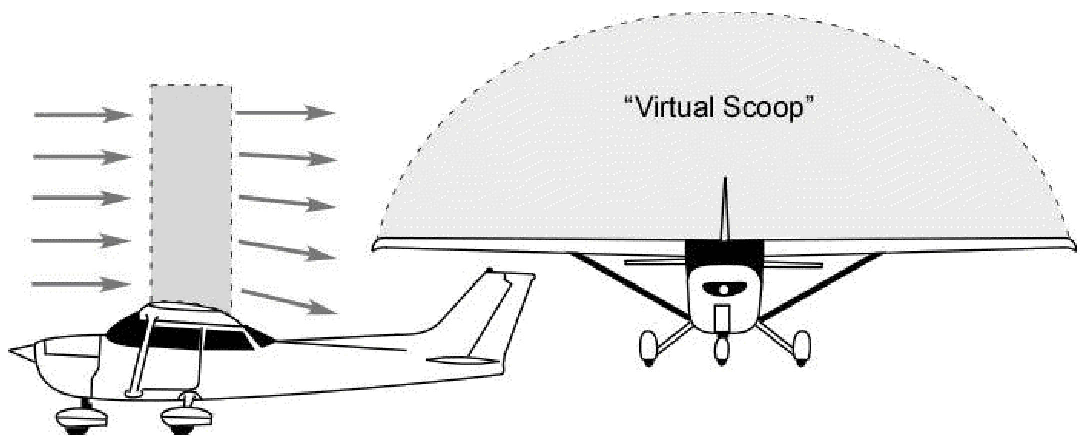

Fig. 5. The wing as a "virtual scoop" for air.

The amount of air intercepted by the scoop, $\dot{m}$, is proportional to the

- area of the wing
- wing's speed
- air's density

To a good approximation, neither the angle of attack nor the load on the wing affects the amount of intercepted air.

We are now in a position to understand the adjustment of lift. Let us look at three situations.

Situation 1: the speed of the airplane has doubled. If the angle of attack were not corrected both $\dot{m}$ and v_v would double. So, to maintain a constant lift, the pilot reduces the angle of attack to a value of half of the initial value of v_v. This requires a reduction in the angle of attack by a factor of four.

Situation 2: the load on the wing has doubled in a 2-g turn, but the speed of the airplane remains constant. The value of $\dot{m}$ has not changed so the wing adjusts for the increased load by doubling the angle of attack, doubling v_v.

Situation 3: the airplane flies at a constant speed but has climbed to an altitude where the air density is halved. Since $\dot{m}$ is now halved the angle of attack must be doubled in order to double v_v and thus maintain a constant lift.

One might ask how large $\dot{m}$ is for a typical airplane. Take for example the 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 then we calculate $\dot{m}$ to be 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. A 250-ton jumbo jet in cruise is diverting about its own weight per second.

If for convenience we assume a rectangular scoop for the 36-foot wingspan of the Cessna 172, we calculate that the air is diverted from about 18 feet (7.3 m) above the wing. Thus, one can see that the production of lift is not a surface effect as implied by the popular description of lift, but extends far above the wing. This is one of the reasons that biplanes are less efficient than monoplanes. The lower wing is reducing the pressure on the bottom of the upper wing making it less effective. Because of this, many biplanes have the upper wing (or sometimes the wing's root) placed forward of the lower wing.

Power and lift

In aerodynamics, the subject of power requirements is seldom considered. Some introductory textbooks do not even have power listed in the index. In aeronautics this discussion would be about drag, which is a retarding force, the effect of which is proportional to the speed of the airplane. Unfortunately, drag is difficult to derive and is usually presented without derivation.

It is through the understanding of power that flight, as well as drag, can be better understood. We will consider two kinds of power. *Induced power*, P_i, is the power associated with lift. Before the wing arrives, the air is standing still. After the wing's passing, the air is headed towards the ground. Induced power is the rate that kinetic energy is given to the air to producing lift. *Parasitic power*, P_p, is the power lost due to the impact of the air with airplane's structure and to frictional losses.

Although it is difficult to calculate P_i exactly it is easy to state its functional form. Since P_i is the rate that kinetic energy is give to the air,

$$P_i \propto \dot{m} v_v^2. \qquad (4)$$

We can substitute equation (3) into equation (4) to get:

$$P_i \propto L v_v. \qquad (5)$$

A useful function for pilots is the *power curve*, which is the total power requirement for flight as a function of the airplane's speed. The total power is the sum of P_i and P_p. We are now in a position to derive the P_i term of the power curve. We know that if the airplane doubles its speed, $\dot{m}$ is doubled and thus v_v is adjusted to half of its original value to maintain a constant lift. Since the lift is constant, equation (5) tells us that P_i is halved. Thus doubling the wing's speed halves P_i. It follows that

$$P_i \propto \frac{1}{\text{speed}}. \qquad (6)$$

This is the dotted line in Figure 6. As the airplane flies slower $\dot{m}$ decreases so v_v must be adjusted by increasing the angle of attack. P_i dominates at low speed.

The functional form of P_p is also easy to understand. The energy given to an air molecule on collision with the airplane is 1/2 mv^2. This yields a speed^2 term. The rate of collisions with the air is proportional to the speed of the airplane. Therefore

$$P_p \propto \text{speed}^3. \tag{7}$$

The dashed line in Figure 6 represents the functional form of P_p. The total power is the solid line in the figure. The interesting point to be taken from equation (7) is that the top speed of an airplane, where P_p dominates, increases as $\sqrt[3]{P_p}$. The engine's power must be increased by a factor of eight in order to double the speed.

Now let us consider what happens when an airplane goes to a higher altitude, where the air density has decreased by 25%. If the speed is kept constant $\dot{m}$ is reduced by 25%

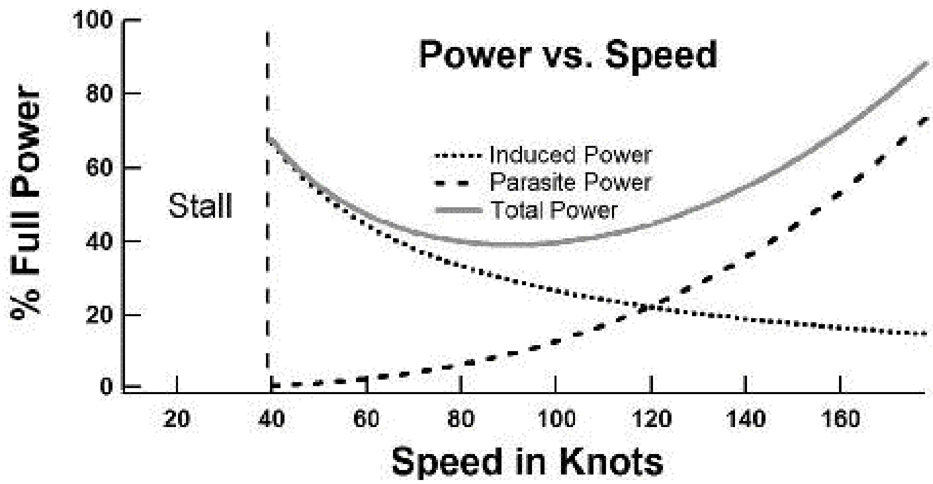

Fig. 6. Power requirement for flight as a function of speed.

and v_v must be increased by 33% to maintain a constant lift. Thus P_i has increased by 33%. On the other hand, P_p has been reduced by 25% because of a lower rate of collisions with the air. Since P_p dominates at cruise speeds, it requires less power to fly at higher altitudes, but more power at takeoff and landing speeds.

We know that aircraft manufacturers go to great efforts to make airplanes light. Now we can understand the relationship between P_i and load. Consider the case where the load has been increased by a factor of two in a 2-g turn at a constant speed. The angle of attack must be doubled to double v_v since $\dot{m}$ is constant. Since both L and v_v have doubled, equation (5) tells us the P_i has increased by a factor of 4. Thus we have the relationship:

$$P_i \propto L^2.$$

Thus, lightening the structure of the airplane is rewarded in substantial power savings. This is particularly true in takeoffs and climb where P_i dominates.

Since drag is part of the jargon of flight, we should not completely neglect it in our discussion. Power is drag times speed. Or the other way around, drag is power/speed. So from equation's (6) and (7) we can write the functional form of induced drag, D_i, and parasitic drag, D_p:

$$D_i \propto \frac{1}{\text{speed}^2},$$

and

$$D_p \propto \text{speed}^2.$$

It should be noted that propellers produce an approximately constant propulsive power and jet engines produce a constant thrust. Thus the maximum speed of a propeller-driven airplane is determined by P_p, while D_p determines the maximum speed of a jet airplane.

Efficiency

The efficiency of the production of lift is a fundamental concept that also applies to the subject of propulsion. Consider a wing with a fixed speed and load. If the area of this wing is doubled, $\dot{m}$ is doubled, v_v is halved and P_i is likewise halved. Thus the power requirement to produce the lift decreases linearly with the increase of the size of the wing. Lift is proportional to the rate of momentum transfer, and P_i is proportional to the rate of kinetic energy transferred. The larger $\dot{m}$ is for a given lift, or thrust for a propulsion system, the smaller the value of P_i. One can consider P_i as wasted energy. Ideally, one would like to produce lift with an almost infinite $\dot{m}$ and an almost zero value of v_v. This explains why the propeller cannot produce enough thrust to lift the airplane directly, while the wing produces the required lift with a small fraction of the engine’s power. The propeller, being small, must accelerate a small amount of air to a very high velocity.

Fanjet engines, as seen on all the large two-engine jets (i.e. the Boeing 747, 757, etc) have a large fan in front of the jet engine. Only about one part in nine of the air that goes into the large intake goes through the combustion chamber. The rest blows by the outside of the turbine engine like the air from a propeller. Ideally the energy removed from the jet's core exhaust, to drive the fan, is sufficient to match the jet’s core exhaust velocity with the fan's exhaust velocity. Thus, the jet engine's core exhaust is only producing about 11% of the thrust. This increases the engines efficiency by greatly increasing $\dot{m}$ for the same thrust. There is the additional advantage that these engines are much quieter.

IV. Misapplication of Bernoulli's equation

Many of the misconception of the physics of flight come from a misunderstanding of the application of Bernoulli’s principle. We feel that we should give at least a brief discussion of this topic.

Most of the misapplication of Bernoulli's equation and general confusion when discussing the physics of moving air, outside of the confines of a pipe, are due to the fact that most physics textbooks stop about one paragraph too soon. Earlier we stated that the pressure in equation (1) was not well defined. In most textbooks it is presented as the pressure at a point. In reality, it is the *static pressure*, p_s, which is measured perpendicular to the direction of flow. The second term ($1/2\ \rho v^2$) is referred to as the *dynamic pressure* in aeronautics. In unconfined flow, C in equation (1) is not necessarily a constant and is referred to as the *total pressure*, p_t. Thus a more general statement of Bernoulli's equation (still neglecting the ρgh term) is:

$$p_s + \frac{1}{2}\rho v^2 = p_t\,. \tag{8}$$

If energy is added to unconfined air, such as the exhaust from a hair drier or by your breath, the dynamic and total pressures of the air increase but not p_s. At the exit from the hairdryer or from your lips the stream of air adjusts itself by expanding or contracting to have the same value of p_s as the surrounding air.

A good demonstration of this is the static port on the side of an airplane. The static port is a small hole on the side of the fuselage used to provide the air pressure for the altimeter and other instruments. Although the air passes over the static port at hundreds of miles per hour, the correct pressure is still measured. Only when fast moving, unconfined air bends is p_s different from the surrounding environment. The belief that just because air is moving faster that the value of p_s is lower is wrong in general. The exceptions are if the air is confined in a pipe without the addition of energy, or if the unconfined air is bending.

Let us look at a few misapplications of Bernoulli's principle. The first example we will examine is the *Bernoulli strip*, which is often give as a demonstration of lift of a wing. This is a thin strip of paper, held at one end by both hands. It first hangs down but when one blows along the top, it rises. This is a demonstration of lift, but certainly not of Bernoulli's principle. The breath does not have lower p_s. Viscosity causes the breath to follow the curved surface, Newton's first law says there a force on the air and Newton’s third law says there is an equal and opposite force on the paper. Momentum transfer lifts the strip.

A second example is the confinement of a ping-pong ball in the vertical exhaust from a hair dryer. We are told that this is a demonstration of Bernoulli's principle. But, we now know that the exhaust does not have a lower value of p_s. Again, it is momentum transfer that keeps the ball in the airflow. When the ball gets near the edge of the exhaust there is an asymmetric flow around the ball, which pushes it away from the edge of the flow. The same is true when one blows between two ping-pong balls hanging on strings. They swing together because of the viscosity and momentum transfer, not Bernoulli’s principle.

The curve of a spinning ball is a little more difficult. In brief, it is an asymmetric stall that causes asymmetric airflow around the ball. The airflow looks very much like that around a wing.

V. Conclusion

We have demonstrated the power of the Newtonian description of lift of a wing. The key points are that the lift of the wing is proportional to $\dot{m} v_v$ and the induced power is proportional to Lv_v. Also, $\dot{m}$ is proportional to the wing's area and speed, and the air density, while v_v is proportional to the wing's speed and angle of attack. With these simple tools, most relations in aerodynamics can be understood, and often the functional form derived. It is also easy to understand how a wing adjusts for speed, load, and altitude. With the knowledge that efficiency means a large $\dot{m}$ and a small v_v, one has an additional tool for understanding flight and aircraft propulsion systems. An important result, which contradicts what most of us have been taught, is that the shape of the wing is of no significance in determining its lift as a function of effective angle of attack. In addition, we find that the acceleration of the air over the wing cannot be the cause of lift since the acceleration of the air requires a difference in pressure by Newton's second law. In other words, the pressure difference drives the acceleration of the air, not the other way around.

Although circulation theory can be used for accurate calculations of lift, it does not give a simple, intuitive description of the lift on the wing. We have also shown that the pressure and velocity of the air over a real wing in flight at not related by Bernoulli's equation. Newton's laws hold without exception for both subsonic and supersonic flight, and can be used to yield an understanding of many concepts without complicated mathematics. It is our hope that teachers will return to the basics and use Newton's laws to describe lift. Then students can explore flight in much more depth than was possible with the popular explanation using Bernoulli.