An Aerodynamicist's View of Lift, Bernoulli, and Newton

Charles N. Eastlake

Take out a pencil, please. Here is a short quiz. The sole question is multiple choice.

The production of lift by an airfoil is described correctly and accurately by:

A. Bernoulli's Law
B. Newton's Law(s)
C. This article
D. All of the above.

I believe that the answer is D. A and B are certainly true. You will have to judge C.

As a career aerodynamicist, I am pleased to see flying machines discussed in physics classes. Their power in captivating the imagination and motivating students is significant. As an occasional reader of and contributor to *TPT*,[1] however, I am dismayed to read articles delving into the details of why Bernoulli's law is at fault in explaining how airfoils generate lift and why Newton's laws need to be used instead. Aerodynamics as taught to aeronautical engineers does not find any controversy in this issue. Both approaches are right in all situations. Which approach should be employed is merely a matter of which is more convenient to use given the type of data available to characterize a particular flow pattern. The inability of one model or the other to explain lift production is really a problem of using a version of these laws that is oversimplified. In other words, a message worth emphasizing in physics classes is that too many simplifying assumptions might ruin the accuracy of a theoretical model that is fundamentally a correct choice and really should work just fine.

Before we can look precisely at lift production, we need to delve into some definitions of basic concepts and terminology. Please note right up front that this is an aerodynamicist's view. Other technical fields that are heavily involved with fluid flow sometimes have terminology traditions that are a little different, partic-


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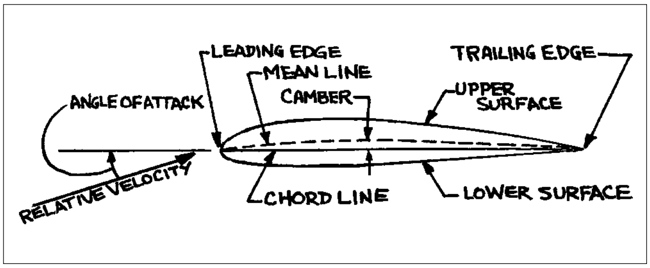

Fig. 1. Airfoil terminology.

ularly those focusing on pumping liquids through pipes.

Airfoil Terminology

Referring to Fig. 1, let's start with airfoil terminology. The farthest forward point on the airfoil shape is called the *leading edge,* while the farthest aft point is called the *trailing edge*. A straight line from leading edge to trailing edge is called the *chord*. The curved line defining the top half of the airfoil is called the *upper surface*, and the bottom half is called the *lower surface*. A curved line midway between upper and lower surface is called the *mean line*, referring to arithmetic mean of the upper and lower surface vertical-position (measured perpendicular to the chord) coordinates. Some texts call it the *mean camber line*, but mean line seems like a more precise term to me. The greatest vertical distance between the mean line and the chord line is called *camber* and is usually a few percent of the length of the chord. The nose-up or nose-down attitude of the airfoil is described by angle of attack, which is the angle between the chord line and the direction of the air movement relative to the airfoil (relative velocity vector).

The definition of lift and drag forces includes a fine point relating to force direction that might slip unnoticed through verbal discussions but becomes critical when solving equations. There is a single resultant force acting on an airfoil. However, it can be resolved into components with respect to any convenient coordinate system. Aerodynamicists are usually interested in what are known as *wind axes*, meaning axes oriented with the relative velocity vector, also known as relative wind. *Lift* is the force component perpendicular to the relative wind, and *drag* is the force component parallel to the relative wind. Lift and drag vectors are often sketched as perpendicular and parallel to the chord of the airfoil, which is generally not quite right. And lift and drag are even more frequently sketched as perpendicular and parallel to the ground, which is correct only if one presumes that the wing is flying level and thus is not correct if the wing/airplane is climbing or descending.

Fluid Flow

With terminology squared away, we move on to the basic physical principles governing fluid flow. Analysis of fluid flow is typically presented to engineering students in terms of three fundamental principles: conservation of mass, conservation of momentum, and conservation of energy. Newton's name seldom comes up, except to encourage student ownership of these principles by reminding the class that certain segments of them, particularly conservation of linear momentum, are what they probably called Newton's laws in physics class.

The equations that represent these principles can be expressed in two ways. High school students are probably not prepared to absorb this point, but college students might find it interesting. The three laws can be expressed as a set of simultaneous differential equations or integral equations. The differential approach is most useful if one intends to describe the fluid behavior at a specific location, or at many locations in the process of mapping out the details of the flow field. This is where Bernoulli's law is most frequently brought into the picture. This is also the foundation of most computer programs such as FoilSim.[2] The integral approach, which sometimes becomes recognizable as Newton's laws, concentrates on the larger-scale phenomena of what changes in momentum and energy occurred in a region of the flow, and what forces had to be exerted on the flow to make those changes occur. This model is dramatically simpler for certain types of problems like thrust produced by a jet engine because the complex details of the behavior of the flow inside the engine do not appear in the equations. Both approaches are equally valid and equally correct, a concept that is central to the conclusion of this article.

Conservation of Energy

First consider conservation of energy, since this is where Bernoulli's law shows up. (Here's a possible injection point for interdisciplinary/historical content. Have your students research Bernoulli's background. Bernoulli is actually three guys, a real family affair.) A *streamline* is the path a particle follows as it moves through a flow field. Visualize a time-lapse photo of car headlights moving along a highway at night. The light streaks are streamlines. The total energy of a fluid "particle" or infinitesimally small volume of fluid is constant as it travels along a streamline if no external work is done on it. This is generally true for external flows like air flowing around an airfoil. In contrast, for internal flows like flow pumped through pipes or flow through the inside of that jet engine, the total energy might not be constant. In either case energy can be shifted back and forth between kinetic energy and potential energy as the particle moves.

The measurable characteristic that quantifies total energy is called *total pressure*, P_T, which is measured with a Pitot tube, also known simply as a total pressure tube. This type of pressure instrument is nothing more than a tube with the open end facing directly upstream so that it "catches" the moving air. (Another interesting spot for some interdisciplinary/historical content. Have students look up Henri Pitot and see what he was doing when he devised this instrument. He was measuring water flow around bridge pilings in the Seine River in Paris, and proved that the accepted flow theory of the time was seriously in error.) If you do external work on a fluid, like putting it through a pump, you raise its total pressure. If you make the fluid do external work, like having it turn a windmill, you reduce its total pressure.

Potential energy is quantified by static pressure, P_S. Static pressure is the pressure component that is not influenced by the direction of movement. Some references say that if you simply say "pressure" that "static pressure" is clearly implied. I have found that this shorthand causes confusion and thus I never use it. In concept it is measured by drilling a measurement hole in a surface that is parallel to the velocity vector. In a wind tunnel, this is trivially easy. One simply drills a hole in the wall of the tunnel. On an airplane in flight, it can be tricky because of interference of the flow around several nearby parts of the airplane, but a hole in the side of the fuselage is still the usual solution.

Another alternate terminology issue may arise here. As previously mentioned, a pump raises the total pressure of the fluid. In flows contained by walls such as pipes, the energy addition also raises the static pressure. And static pressure in a pipe is easier to measure than total pressure, so there is a tradition of describing work done on the fluid as an increase in static pressure. In external flows like flow over airfoils, the energy addition process is fundamentally different. Work done on this flow usually appears in the form of an increase in velocity, like you feel when standing in front of a fan, and thus static pressure is not representative of external work. Again, this article is the aerodynamicist's view.

Kinetic energy is quantified by dynamic pressure, which is the product of fluid density and velocity squared, $\frac{1}{2}\rho V^2$. Comparing it to $\frac{1}{2}mv^2$, dynamic pressure is clearly the familiar definition of kinetic energy divided by fluid volume. Since it occurs over and over in aerodynamic discussions, it is usually abbreviated as q.

In low-speed air flow, below about 300–350 mph, the equation form of the conservation of energy principle is also known as Bernoulli's law. Readers may have seen this equation written with a third term on the right side of the equation that contains the height of the fluid. In discussions treating liquid flow such as pressure on dams or in water towers, this third term can be very important. But in gas flow it is always negligibly small. So, we have Bernoulli's law for incompressible (low-speed) gas flow:

$$P_T = \text{constant} = P_S + \tfrac{1}{2}\rho V^2 = P_S + q.$$

As an airplane flies through the atmosphere, the atmospheric pressure is the static pressure, and total pressure is higher than atmospheric pressure by an amount equal to the dynamic pressure. This pressure rise is what the car/motorcycle/boat-racing community tends to call "ram pressure." When a model is being tested in a wind tunnel, the fundamental situation is different. The atmospheric pressure surrounding the tunnel is generally close to the total pressure inside the tunnel, and as the air accelerates into the test section of the tunnel, the static pressure drops below atmospheric pressure, again by an amount equal to the dynamic pressure. In either case, as the streamlines deflect to go around a body shape like a wing, the total pressure is constant as the fluid moves along a streamline and its static pressure changes as the local velocity changes. That local static pressure becomes the surface pressure on the body shape, which generates forces on the body. Note that local static pressure is no longer the same as the freestream static pressure at a modest distance away from the body shape where the flow that has not been diverted by the body shape.

Conservation of Momentum

Now let's move on to conservation of momentum: the force exerted on a fluid equals the time rate of change (derivative with respect to time) of its linear momentum. If you exert a force on something, you change its momentum. If you don't exert a force on something, its momentum stays unchanged or is conserved. This is Newton's laws, if you choose to call it that. When an airfoil is producing lift, that force does in fact change the vertical component of the airflow's linear momentum, and the drag force changes the horizontal component of the airflow's linear momentum. When the air is moving slowly enough that its density does not change appreciably, the gist of the term *in-*

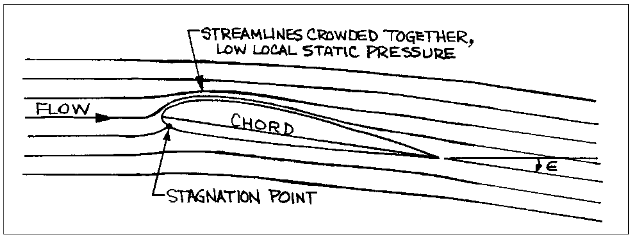

Fig. 2. Streamlines around the NACA 2412 airfoil.

compressible flow, then the momentum changes are measurable as local flow velocity changes. Measuring drag by measuring the velocity loss within the wake of the airfoil is easily done because it is occurring over a relatively small region of the flow field. This is a standard wind-tunnel experiment that my classes do every semester. Measuring lift by measuring the increase in downward vertical velocity in the flow coming off the trailing edge of the airfoil is conceptually possible. This downward velocity is definitely there and is known as *downwash*. I have never heard of anyone actually measuring it with sufficient precision to calculate lift, not because it is physically unsound but because it is not a practical experiment. It is not practical because the downwash is distributed over the entire flow field downstream of the trailing edge, and it would thus be very difficult to measure enough data points to integrate the distribution accurately. (A gorgeous photo of this phenomenon caused by a jet flying through a cloud layer is downloadable from Ref. 3.) However, the flow's downward deflection angle called *downwash angle*, ϵ, is routinely calculated in aerodynamics texts because it has a large effect on the flow over the tail of the airplane. Downwash angle is easily estimated as approximately half the angle of attack. It is shown somewhat exaggerated in Figs. 2, 4, and 5 to make it easier to visualize.

In the interest of generalization, it is appropriate to recognize that the isolated wing is not the only type of flow-field geometry. When there are other surfaces nearby, such as walls in flow through ducts or the ground, those other surfaces can and do change the momentum of the flow as well. Consider the similar cases of low pressure causing a car's convertible top to bulge upward or the low pressure on the roof of a house in a hurricane that can lift the entire roof off the house in one piece. There is definitely lift being produced in these situations, but without net downwash. How can that be? Upward lift on the roof causes a downward momentum change, but it is almost immediately canceled by the upward momentum change associated with the downward force on the ground. This must be so because once the air has passed the obstacle and the local flow-pattern variations settle out, the flow cannot end up anything except parallel to the ground. That is, the stabilized flow cannot penetrate the ground, so there cannot be any velocity component perpendicular to the ground.

Conservation of Mass

And last but not least, the conservation of mass: the amount of mass per second flowing between streamlines remains constant. The effect of squeezing streamlines together as they divert around the front of an airfoil shape is that the velocity must increase to keep the mass flow constant since the area between the streamlines has become smaller. After the flow has passed the thickest part of the airfoil and the streamlines begin to spread out as they approach the trailing edge, the velocity decreases. Exercising the conservation-of-mass principle is what you do when you put your thumb over the open end of a garden hose to make the water squirt out faster. Smaller area means faster velocity. This HAS TO BE INCLUDED with Bernoulli's law when explaining lift for it to really make sense.

Now we can finally get down to the detailed explanation of how lift is generated! First, let's pause for a moment to point out the flaw in an old description that is still sometimes used, the "equal-time-of-passage" concept. In this concept the relation between air speed and static pressure expressed as Bernoulli's law is usually stated correctly. But do you remember hearing that troubling business about the particles moving over the curved top surface having to go faster than the particles that went underneath, because they have a longer path to travel but must still get there at the same time? This is simply not true. It does not happen. The fact is that the particles that went the long route over the top go so much faster due to streamline squeezing that they get to the trailing edge before the ones that took the shortcut underneath. I have demonstrated this in a water tunnel many times using intermittently pulsed hydrogen bubbles to make the flow visible. And FoilSim can easily be made to show the result of theoretical calculations that verify the same thing.

Lift

The proper explanation of lift generation is a bit more complex, but we now have the background to appreciate it. Shown in Fig. 2 is a plot of an airfoil with a nearly flat bottom surface, the NACA 2412. Most single-engine Cessna aircraft have used this airfoil since the 1940s, which almost certainly makes it the most widely used airfoil in the world. The equal-time-of-passage picture of lift-producing flow patterns leads to the seemingly logical yet incorrect conclusion that this airfoil could not produce upward lift when it is inverted. I have the very similar flat-bottom NACA 4412 airfoil on my own aerobatic aircraft, and I routinely fly it upside down. I can assure the readers that lift by an inverted airfoil does work. The question then is what key factor has been left out of the simplified picture. The missing item is called the *stagnation point*, the small region near the leading edge at which the local velocity stagnates or is brought to a standstill against the airfoil surface. It is literally the point at which the flow field splits. Flow above the stagnation point flows along the upper surface, and flow below the stagnation point flows along the lower surface. Critical to this picture is that for a cambered airfoil the stagnation point is not right at the leading edge. It is a little below the leading edge, displaced a couple percent of the chord length aft of the leading edge on the lower surface of the airfoil. The result is that the split flow field is interacting with an effective surface shape that is not nearly as simple as the airfoil shape drawn at zero angle of attack.

The precise position of the stagnation point is determined by the magnitude of the circulation. The circulation concept, which comes up in yet a third way of calculating lift, is that if one were to remove the uniformly distributed freestream velocity from the curving flow around a lifting airfoil, what would remain is a rotating, roughly elliptical flow pattern that moves clockwise around the airfoil given the direction of flow drawn in the figures in this article. This rotating flow is called *circulation*. Its existence is not intuitively easy to accept, but I have seen it nicely photographed by a camera moving exactly with the freestream flow. The strength of the circulation is directly proportional to

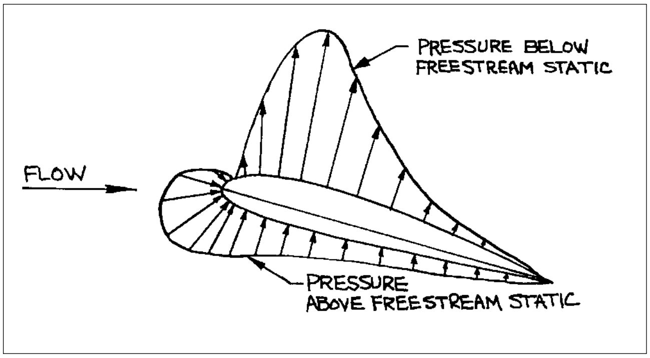

Fig. 3. Surface pressure.

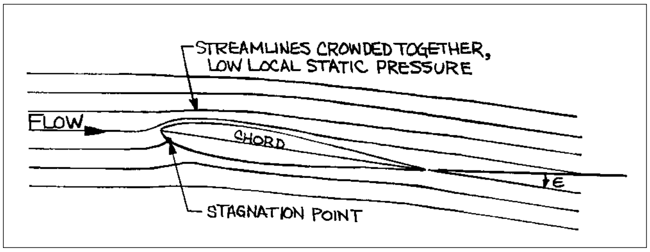

Fig. 4. Symmetric airfoil at positive angle of attack.

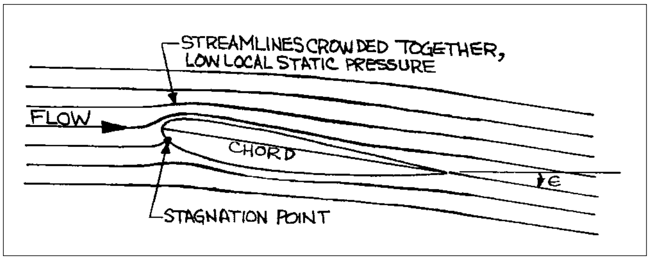

Fig. 5. Inverted NACA 2412 airfoil.

the magnitude of the lift force, known as the Kutta-Joukowski law. This fact is the basis of Prandtl's lifting line theory, the other lift calculation process previously mentioned. There is also a boundary condition called the Kutta condition, which specifies that there must be a rear stagnation point that remains exactly at the trailing edge of the airfoil. These two facts taken together are the physical requirement that causes the front stagnation point to move farther and farther aft along the lower surface as the angle of attack is increased.

The streamlines are squeezed together as the flow diverts around the nose of the airfoil, increasing the local velocity in accordance with the conservation of mass. The velocity increase decreases the local static pressure, which is also the surface pressure on the airfoil, in accordance with Bernoulli's law which you recall is the conservation of energy. Then aft of the thickest part of the airfoil shape the streamlines spread back out. The flow slows down, and the local static pressure goes back up. This happens to some extent on both the upper and lower surface of the airfoil, but it is much more pronounced on the forward portion of the upper surface, so the upper surface gets the credit for being the primary lift producer.

Once this concept is clear, then it is also clear that the surface pressure distribution will vary along the chord length of the airfoil, as illustrated in Fig. 3. Note that FoilSim will display either the pressure distribution or the local velocity distribution very nicely. This pressure distribution is also dramatically different at different angles of attack. Yet the equal-time-of-passage discussion of how Bernoulli's law relates to lift ignores the pressure variation along the chord. This implies to many readers that pressure is constant, another reason the oversimplified presentation fails to explain logically some aerodynamic details. The resultant force is determined by integrating the surface-pressure distribution over the surface area of the airfoil. The integration process might be more detailed than a high school class is prepared for. But measuring and integrating the pressure distribution is another standard experiment in my wind-tunnel testing course, which is predominately junior-level engineering students. And it does produce accurate answers.

Because of the stagnation-point position, the typical cambered airfoil needs to be oriented 2 or 3° nose down, at negative angle of attack, to get it to produce zero lift. The stagnation point is also not right at the leading edge of a symmetric airfoil, one without camber, when the airfoil is at nonzero angle of attack and is producing lift. This is shown in Fig. 4. This answers the apparent mystery of how a symmetric airfoil can produce lift. As far as the flowing air molecules know, the airfoil is not a symmetric shape. This is also true of a flat plate at non-zero angle of attack. On these shapes as well, as angle of attack increases, the stagnation point moves further aft along the lower surface.

And imagine also this same phenomenon when the airfoil is upside down. As you can see readily in Fig. 5, the streamlines illustrate that the flow over the original bottom surface, which is now the top surface, is definitely not encountering a flat surface when the airfoil is set at a modest angle of attack. There is lots of curvature near the leading edge of what is now the top surface, causing the inverted airfoil to produce upward lift. The disadvantage of using the airfoil shape in this orientation is that the shape is now poor for lift production, so the angle of attack must be significantly higher than that required to produce the same lift when it is right-side up. The result is that drag is high and aerodynamic efficiency (usually expressed as the ratio of lift to drag) thus is low. But the lift production is definitely there.

Bernoulli and/or Newton

So, where has this modestly complex verbal trip taken us? Here's my mental picture. Two things are happening simultaneously as an airfoil produces lift. If we take the flow-field detail perspective, we use the conservation of mass and conservation of energy, Bernoulli's law, to describe a streamline-squeezing pattern that produces low pressure on the airfoil surface, resulting in an upward force on the airfoil. In the larger-scale perspective, as long as there are no other flow-altering surfaces nearby, the forces on the airfoil are acting on the moving fluid and changing its momentum in accordance with the conservation-of-linear-momentum principle, Newton's laws. Both pictures can be expressed as mathematical models that correctly calculate the forces being generated. Which one is preferable depends only on which one is simpler to use with the data available. Neither is inherently more accurate or more correct.

I would like to conclude with a plea to teachers to emphasize whichever model works more conveniently in their scenario, without stating or even implying that the other is wrong. I always explain lift in terms of Bernoulli's law and have felt comfortable that it made sense to audiences at many different levels. I carefully reviewed several oft quoted references[4-7] in the physics-teaching literature and do not feel that any of them describe a shortcoming of Bernoulli's law that is technically correct. Besides that, Bernoulli's law is one of the foundations of fluid physics and is the source of some of my favorite aerodynamic-toy demonstrations. However, I readily agree that Newton's laws may be a simpler description as long as one does not need to evaluate the details of the flow field. My hat's off to those of you who are accepting the Herculean challenge of finding a way to describe complex physical principles in sufficiently simple terms to hit home with students whose attention spans may be pretty short and who may not be prepared to follow an explanation that uses calculus. But Bernoulli is an icon of aerodynamics and deserves to be so. There is no need for controversy.

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3. "Beginner's Guide to Aerodynamics," a publication of NASA Lewis (now NASA Glen) available on the web at http://www.grc.nasa.gov/www/K-12/airplane/bga.html. An incredible resource for teaching materials, even to downloadable slides for illustrating lectures. Also examines the three most common incorrect explanations of lift.
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- Hubert Smith, *The Illustrated Guide to Aerodynamics,* 2nd ed. (Tab Books, 1992). An excellent basic book written by a close friend of mine and longtime teacher at Penn State.
- John Anderson, *Introduction to Flight*, 2nd ed. (McGraw-Hill, 1985). More technical in presentation than Smith's. The author is widely recognized as the best textbook writer in the aerodynamics field and has written several other books.
- Ira Abbott and Albert von Doenhoff, *Theory of Wing Sections* (Dover Publications, 1959). Old, but considered the bible of airfoil theory. Much of it is the same as NACA (National Advisory Committee for Aeronautics, the predecessor of NASA) Technical Report 824, which is available at http://naca.larc.nasa.gov/.