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Aerodynamic Lift, Part 1: The Science

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Every so often an article appears in the popular press pointing to the apparent confusion surrounding the topic of aerodynamic lift and alleging that even the "experts" don't fully understand it.[1] This makes attention-grabbing copy, but it overstates the case. Actually, the science of lift is not in dispute. It is well understood in terms of a quantitative mathematical theory that is based on established laws of physics, produces accurate predictions, and has been agreed on by the science and engineering communities since the early 20th century. Confusion arises only in connection with explaining lift in qualitative terms.

In this paper I start with a description of the basic physics represented by the mathematical theory, which leads to a discussion of why qualitative explanations of fluid flows are difficult in general. I then describe the key known features of lifting flows without trying to explain or justify them. Finally, I discuss two lifting-flow issues that have been treated in questionable fashion in other papers in the physics education literature: the applicability of Bernoulli's principle and the vertical momentum imparted to the air by a lifting wing. All of this sets the stage for the companion paper, "Aerodynamic Lift, Part 2: A Comprehensive Physical Explanation."[2]

Mathematical theory provides accurate predictions but not intuitive explanations

The mathematical theory treats air as if it were a continuous material, or continuum, an approach justified by experimental observations and by derivation from the kinetic theory of gases. Conservation of mass, Newton's second law, and conservation of energy are expressed as a set of *equations of motion* for a continuum fluid. In the vector equation that enforces Newton's second law, forces internal to the fluid are represented in the physically correct manner, such that Newton's third law is also satisfied throughout the flowfield. When the effects of turbulence in the boundary layer and wake of a body are included through an empirical turbulence model, the full equation set is referred to as the *Reynolds-averaged Navier-Stokes (RANS) equations*. If viscosity and turbulence are ignored, we have the *Euler equations,* and with some further restrictions we have classical *potential-flow* theory. All of these versions of the equations[3] involve vector calculus and partial differential equations (PDEs) and aren't fit topics for introductory physics courses, let alone for the general public.

Predicting the flow around a particular body requires solving the equations of motion with the body shape imposed as a constraint, thus determining a distribution of vector velocity consistent with the body shape and a distribution of pressure that together satisfy the equations everywhere in the flowfield. Until about 50 years ago only the potential-flow equation could be solved, but today the full RANS equations are routinely solved by the computer-based methods of *computational fluid dynamics* (CFD). Under the usual conditions of airplane flight, CFD predictions of the integrated forces and flowfield details in wing and airfoil flows agree well with experimental measurements and are quite useful in engineering practice. And simple CFD codes such as Wind Tunnel by Algorizk (www.algorizk.com) can be useful as teaching tools, showing students how the forces and the details of the flow depend on the airfoil shape and the flow conditions.

So the theory provides us with equations that accurately represent the physics, and CFD solutions to the equations can tell us *what* happens in a lifting flow. But neither the basic equations nor the CFD solutions provide us with an intuitive physical explanation for how lift actually comes about. Correctly explaining lift qualitatively isn't easy, for reasons discussed below, and the explanations that are typically offered tend to oversimplify and can be misleading. Over the last 100 years or so, many different explanations have been put forward for various audiences, and the apparent incompatibilities among the different approaches has been a source of confusion and controversy. Earlier explanations are discussed further in the companion paper in the section "How Simpler Explanations Fall Short."[2]

The difficulty of explaining fluid flows qualitatively

As we saw above, continuum fluid flow is satisfactorily understood in a scientific sense, in that we have a well-established quantitative theory. But for our own intuitive understanding, and for sharing with young audiences, we would also like to have qualitative explanations that make the cause-and-effect relationships clear overall. Such explanations are difficult because fluid flows are typically much more complex than the motion of a simple rigid body. Flows of practical interest are generally non-uniform, with velocity and pressure varying from point to point throughout an extended flowfield. To comprehend non-uniform fluid motion, it helps to imagine the flowfield as being divided into a large number of *fluid parcels* separated from each other by imaginary boundaries that move with the flow.[4] Every parcel moves in coordination with its neighbors, and no gaps or overlaps form. Forces are exchanged only between parcels in contact with each other, and each parcel individually obeys the relevant physical laws, including Newton's second law. The direct physical interactions are thus local and relatively simple, but the ways in which these local interactions are manifested at the overall flowfield level tend to be complex. In understanding a non-uniform flow, we face the problem of following what happens to a large number of parcels in coordinated motion, in which each parcel moves and deforms in response to forces (mostly pressure) exerted on it by its neighbors, and in which the forces exchanged between neighboring parcels depend on the motions. We thus have difficulties on two levels: accounting for the aggregate behavior of a system with a large number of interacting "parts," and reciprocal cause-and-effect between the forces and the motions.

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An example of this reciprocal cause-and-effect is provided by *Bernoulli's principle*. Under certain conditions, according to Bernoulli, lower pressure means higher speed, and higher pressure means lower speed. When Bernoulli's equation is applied to two points that lie along the same streamline of a flowfield but have different velocities and pressures, the cause-and-effect relationship that it represents is inherently reciprocal: The pressure difference constitutes the net force that causes the velocity difference, in keeping with the way we usually understand Newton's second law, i.e., that a force causes an acceleration. But at the same time, the pressure difference is sustained by the fluid's acceleration between the two points and the fluid's inertia. This reciprocity of cause and effect is discussed in more detail in connection with Fig. 3 of the companion paper.

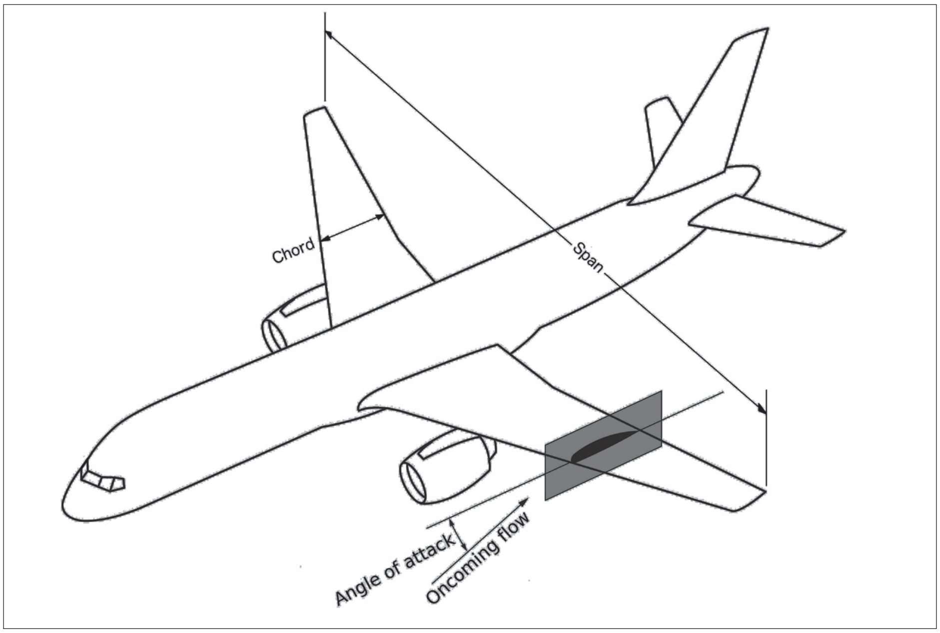

Fig. 1. Airfoil shape and angle of attack.

The quantitative theory doesn't sidestep any of this complexity; it handles it correctly, at the cost of having to solve a set of PDEs. On the other hand, we humans are limited in what we can correctly work out by mental effort alone. Predicting the details of a lifting flow, or even the existence of a lift force, requires determining the spatial distributions of vector velocity and pressure that satisfy Newton's second law everywhere in the flowfield simultaneously, something that can't be done reliably without computation. This means that a qualitative explanation must generally start with some a priori knowledge of what the flow does and that a realistic goal is to *describe* and *explain*, not to *predict* or *prove*.

In keeping with this, the explanation of lift in the companion paper takes the key features of the velocity and pressure fields around an airfoil to be known a priori, as described below in the present paper, and then explains how those features are related, consistent with the laws of physics. It doesn't claim to have predictive capability.

A description of the lift force

The flow around a wing is easiest to understand in the reference frame of the airplane, in which the wing appears stationary and the air appears to flow past. And most wings are of high enough *aspect ratio* (ratio of span to average chord, see Fig. 1) that the flow in cross sections is qualitatively the same as if the span were infinite, and the flow were two dimensional. So we'll deal with the details of the flow in 2D terms.

• *Pressure differences, airfoil shape, airspeed, and angle of attack*

When a wing produces lift, the flowing air reacts to the presence of the wing by reducing the pressure on the wing's upper surface and increasing the pressure on the lower surface. The increased pressure on the lower surface pushes up harder than the reduced pressure on the upper surface pushes down, and the net result is upward lift. Of course the upward force exerted by the air on the wing is accompanied by an equal-and-opposite downward force exerted by the wing on the air, in accordance with Newton's third law. The lift force depends on the wing's *airfoil* shape, which is just the shape of a cross section of the wing, as illustrated in Fig. 1. It also depends on the density of the air and the speed of the flow. To produce a pressure difference large enough to hold an airplane aloft, the air must flow past the wing with sufficient speed. The minimum airspeed at which a heavy airliner can maintain steady flight is well over 100 mph, and even a light general-aviation airplane has a minimum airspeed of about 50 mph. Lift also depends on the angle at which the airfoil is oriented relative to the oncoming flow, called the *angle of attack*. A positive angle of attack means that the *leading edge* (front) of the airfoil is positioned higher than the *trailing edge* (back), as illustrated in Fig. 1. Within an airfoil's usual operating range, lift increases with increasing angle of attack, so that by controlling its angle of attack, an airplane can control the amount of lift the wing generates, maintaining precisely the amount needed, depending on the situation.

The key features of lifting flows

From experimental observations and mathematical solutions amassed over decades of research, we know in considerable detail how lifting flows behave. In this section I describe the flow features that are essential to understanding lift, without trying to explain or justify them. This will constitute the a priori knowledge that the physical explanation given in the companion paper depends on.

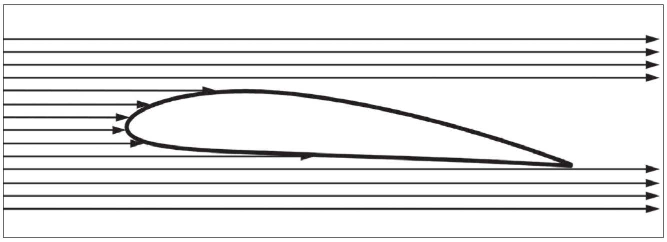

Fig. 2. Incorrect view of air molecules flying like a hail of bullets directly into an airfoil, as they would if they had no random motion and didn't collide with each other.

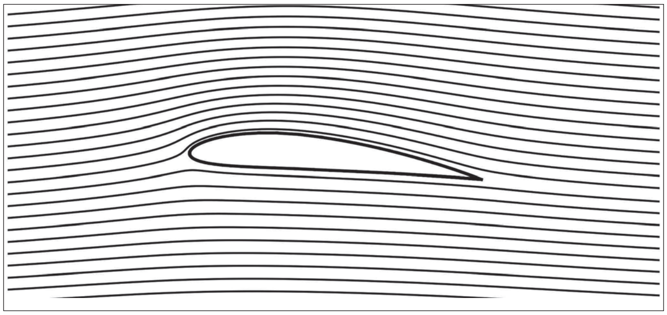

Fig. 3. Typical streamline pattern around a lifting airfoil, illustrating the spread-out nature of the continuum *velocity field*. From an XFOIL[5] solution for the flow around an NACA 4412 airfoil at 5° angle of attack.

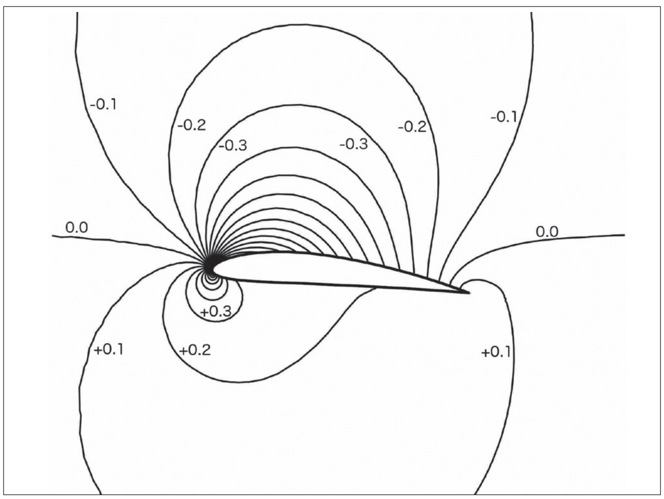

Fig. 4. The *pressure field* from the same flow solution as in Fig. 3, as illustrated by the pattern of *isobars* (contours of constant difference from ambient pressure). The contour interval is 0.1 in the *pressure coefficient* $(p - p_\infty)/0.5\rho V^2$, where p_∞ is the ambient pressure, ρ is the air density, and V is the airspeed.

• *Velocity and pressure are affected over a wide area, not just at the airfoil surface*

Air molecules fly in all directions in random thermal motion and travel an average of only about 70 nm between collisions with their neighbors. Because of the random motion and frequent collisions, molecules don't just fly directly into the airfoil like a hail of bullets as in Fig. 2. Instead, the air moves as if it were a continuous material that deforms and changes course to flow around the airfoil as illustrated by the streamline pattern in Fig. 3. As the flow close to the surface follows the contours of the airfoil, the direction and speed of the flow are affected over a wide area, in a spread-out pattern called a *velocity field.*

The changes in flow direction are easily seen in the streamline pattern in Fig. 3. Flow approaching in front of the airfoil is deflected upward. The flow passing above and below the airfoil is deflected downward, following the predominantly downward-sloping airfoil surfaces. Flow leaving behind the airfoil is deflected upward again, so that it eventually loses the downward velocity component it acquired previously. With regard to velocity magnitude, air entering the region above the airfoil is sped up, and air leaving is slowed back down. Air passing through the region below the airfoil sees the opposite: It slows down and then speeds back up. The higher speed above the airfoil is reflected in closer spacing of the streamlines there.

The pressure is also affected over a wide area, in a spread-out pattern of non-uniform pressure called a *pressure field*. When an airfoil produces lift, the reduced pressure above the airfoil is generally spread diffusely over an extended region, and the increased pressure below the airfoil is likewise diffusely spread out, as illustrated by the pattern of *isobars* (contours of constant pressure) in Fig. 4. The differences from ambient pressure tend to be largest on forward portions of the upper and lower surfaces and to die out gradually with distance from the airfoil. Of course the pressure differences that exert the lift force on the airfoil are just the part of this pressure field that contacts the airfoil surface. In popular explanations of lift, the pressure field tends not to be mentioned at all or is underemphasized. We'll see in the companion paper that it is crucial to a correct understanding of lifting flow.

• *Direct effects of viscosity and turbulence are confined to a thin boundary layer and wake*

When viewed as a continuum, the air very close to the airfoil surface flows parallel to the surface. But the molecules have vigorous thermal motion relative to the bulk flow and constantly bombard the surface from short distances away from their last collisions with other molecules. All real-world solid surfaces are rough on the scale of air molecules, so that molecules hitting the surface bounce off in random directions unrelated to their incoming directions. This results in the *no-slip condition,* in which the continuum velocity of the flow goes to practically zero at the surface, as if the air were adhering to the surface. As a result, the flowfield develops a natural two-part structure. A thin *viscous boundary layer* forms adjacent to the surface as shown in Fig. 5, where the flow speed increases from zero rapidly over a short distance from the surface.[6] Within the boundary layer the flow is subjected to strong shearing action and is affected by viscous and/or turbulent shear stresses. The boundary layer can be laminar (smooth and ordered) over some front portion of the airfoil, but it generally transitions to turbulent well before it reaches the trailing edge.[6] The retarded flow in the boundary layers leaving the trailing edge feeds into a *turbulent wake* downstream, which gradually grows thicker as the momen-

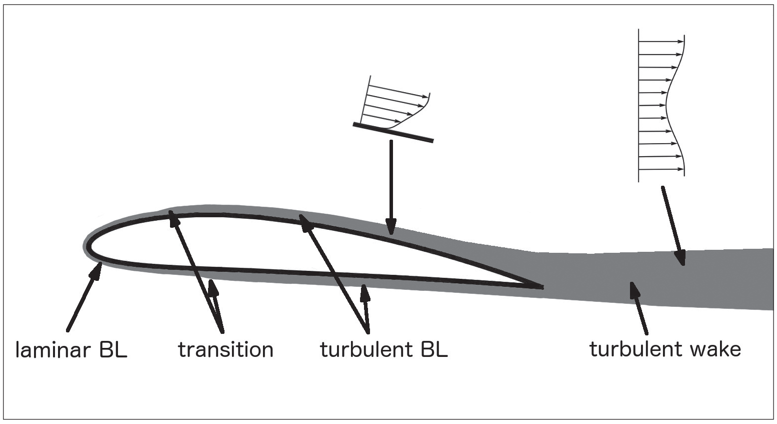

Fig. 5. Development of the viscous boundary layer (BL) and turbulent wake of an airfoil, illustrated by the shaded area. Thickness is exaggerated for clarity. Actual thickness of the boundary layer on the forward portion of the airfoil is too small to see at this scale.

tum deficit diffuses outward and the velocity deficit grows "shallower." If the airfoil has a sharp trailing edge, and the angle of attack is not too high, the flow naturally follows both the lower surface and the upper surface all the way to the trailing edge, as it does in Fig. 3, a situation called "attached flow." Note that the boundary layer and wake are the only part of the field where viscous and/or turbulent forces are significant and that in the rest of the field, called the *outer flow*, the flow behaves as if it were non-viscous. In attached-flow situations, the effects of the boundary layer and wake on the overall flow pattern are subtle and not readily visible in illustrations like Figs. 3 and 4.

The applicability of Bernoulli's principle

Bernoulli's principle by itself doesn't provide a satisfactory explanation of lift, as we'll see in the companion paper, but that doesn't mean that the principle isn't valid in an airfoil flow. Derivations of the usual form of *Bernoulli's equation* assume a flow that is steady, non-viscous, and incompressible (constant density). In the flow around an airfoil, the flow outside the boundary layer and wake (the *outer flow*) behaves as if it were non-viscous. So under steady conditions in the reference frame of the airfoil, at airspeeds that aren't too high, Bernoulli's equation applies in the outer flow, both along streamlines and from streamline to streamline.

Some authors in the physics education literature have asserted that Bernoulli isn't applicable to airfoil flows, but these claims aren't consistent with the science. For example, Huebner and Jagannathan[7] asserted that the assumption of incompressible (constant density) flow is a serious limitation. Actually, the assumption of constant density is quite accurate as long as the local flow speed is less than about 30% of the speed of sound (local Mach number < 0.3). And the compressible-flow counterpart to Bernoulli's equation[8] is accurate for any speed from zero to supersonic. The basic qualitative relationship (Bernoulli's principle) applies across the whole speed range.

Freier[9] raised a different issue, asserting that in a lifting flow the "Bernoulli constant" varies from streamline to streamline, invalidating any simple connection between lift and Bernoulli. But Freier's derivation went astray with a sign error in the cross-stream momentum equation, and his conclusion is contradicted by the following simple argument: In steady flow around an airfoil, every streamline can be traced far upstream to where the velocity and pressure approach uniform values, so that a single Bernoulli constant applies everywhere outside the boundary layer and wake.

Finally, Anderson and Eberhardt[10] argued that Bernoulli is not applicable because a wing has drag and thus does mechanical work and imparts energy to the air as it passes through, violating one of the assumptions in the derivation of Bernoulli. It's true that a wing adds energy to the air in the reference frame of the air mass. But the flow in that reference frame is unsteady (varying with time), and Bernoulli wouldn't apply anyway, even if no work were being done. Anderson and Eberhardt's argument doesn't work in the reference frame we usually use in studying lifting flow. That is the reference frame fixed to the wing, in which the flow is steady and the wing is not moving, so that no work is done by the wing and no energy is imparted to the air. In the wing reference frame, Bernoulli applies quite accurately in the steady flow outside the boundary layer and wake.

The complexity of quantifying the downward momentum imparted to the flow

Smith,[11] Waltham,[12] and a review committee in *The Physics Teacher*[13] have advocated augmenting a simple downward-turning explanation of lift by including the quantitative statement that the time rate of change of momentum of the air downwards is equal to the lift, via Newton's second law. This sounds straightforward, but actually it's an oversimplification that's true only for a particular choice as to what is meant by "the air." Applying Newton's second law to a lifting flow isn't as simple as the statement implies. First, it requires identifying the body of air to be included in the calculation, by defining a *control volume*[14] surrounding the airfoil. Second, defining the vertical momentum of the air within the chosen volume requires integration, given that the velocity is non-uniform. Finally, the calculation must account for the total (net) force acting on the body of air, including not just the downward force exerted by the airfoil, but also the upward force exerted by the pressure field at the control volume's outer boundary, given that the pressure along the bottom of the control volume is generally higher than the pressure along the top (see isobar pattern of Fig. 4). The simple momentum statement is true only if the net force acting on the air is equal to the force exerted by the airfoil, and for that to be true the outer-boundary pressure force must be zero. One might expect that this would happen if the top and bottom boundaries are moved far enough away, so that the pressure difference vanishes. But it's not that simple. For the integrated pressure force to vanish, not only must the pressure difference vanish,

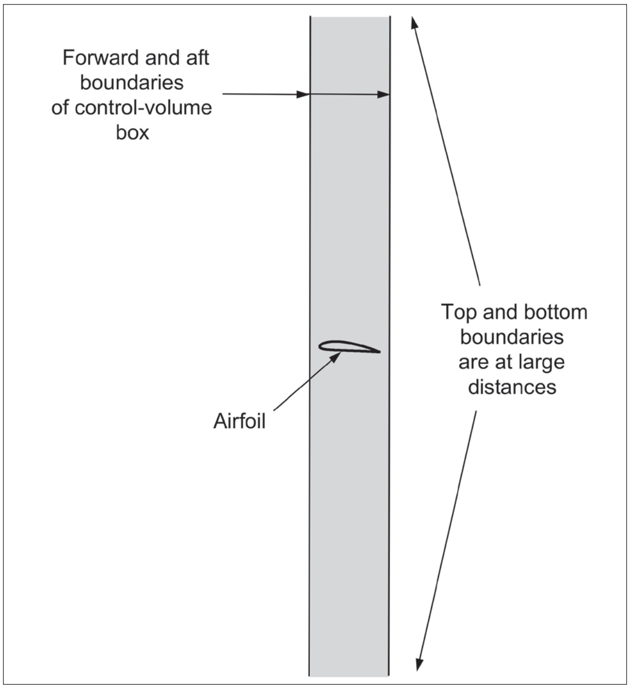

Fig. 6. Illustration of a tall-sliver control volume, which is the only way of defining a body of air for which the time rate of change of momentum of the air downward has been shown to be equal to the lift.

but the horizontal dimension of the box must remain finite. Thus the pressure force vanishes only for a control volume in the form of a tall vertical sliver as illustrated in Fig. 6, in the limit as the height goes to infinity while the width is held finite. For a control volume of any other shape such that the width grows large along with the height, the outer-boundary pressure force offsets some or all of the force exerted by the airfoil, and the simple momentum statement is false, as explained by Lissaman[15] and McLean.[16]

Thus the pressure field complicates the issue, and the simple momentum statement is misleading unless it's accompanied by the discussion given above. For elementary physics students it's probably best to avoid these complexities and simply not to make a quantitative statement about the momentum imparted.

Conclusions

Aerodynamic lift is understood scientifically in terms of a quantitative mathematical theory that makes accurate predictions, generally through computation. Qualitative explanations, on the other hand, entail special difficulties owing to the inherent complexity of fluid flows in general, and as a result a realistic goal of qualitative explanations must be to describe and explain, not to predict.

We described the lifting force and the key features of lifting flows, without trying to explain or justify them. The explanation is left to the companion paper "Aerodynamic Lift, Part 2: A Comprehensive Physical Explanation."[2]

We also examined two issues that have occasioned confusion in the past and concluded that:

- In steady flow around an airfoil at low local Mach numbers, Bernoulli's equation is applicable outside the boundary layer and wake.
- Because the pressure field complicates the issue, quantitative statements regarding vertical momentum imparted to the air are problematic unless they specify what "air" they refer to.

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