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In the companion paper, "Aerodynamic Lift, Part 1: The Science,"[1] I described the key features of lifting flows. The objective of the present paper is to explain those features and the cause-and-effect relationships between them in a manner consistent with the laws of physics.

Most of the qualitative explanations of aerodynamic lift that have been put forward by others have followed either of two main approaches: Bernoulli-based explanations as given by J. D. Anderson,[2] and downward-turning explanations based on Newton's second and third laws, as advocated by Smith,[3] Waltham,[4] and D. Anderson and Eberhardt.[5] Eastlake[6] and others have argued that both approaches are basically correct and that either can be satisfactory. Weltner[7,8] and Babinsky[9] put forward explanations based on streamline curvature that are closely related to the simpler downward-turning explanations.

The explanation presented here is motivated by the observation that neither the Bernoulli approach by itself nor the downward-turning or streamline curvature approach by itself adequately explains all of the essential cause-and-effect relationships in a lifting flow, and that a satisfactory explanation requires elements of both and must deal in more detail with what the flow actually does. This new explanation is similar to the one given in my book,[10] but with enhancements that I hope make it clearer.

The simple, high-level explanation in terms of Newton's laws

The airfoil shape and angle of attack work together so that the airfoil exerts a net downward force on the air as it flows past. As a result of this downward force, some air is accelerated and thus deflected downward, as can be seen in the general downward curvature of the streamlines in the mid portion of Fig. 3 of the companion paper.[1] Of course the downward acceleration happens in accordance with *Newton's second law.* To produce this downward turning, the airfoil surfaces, especially in the rear portion, must slope generally downward from front to back. This requires a positive angle of attack and/or camber (overall curvature of the airfoil, so that the upper surface is more convex than the lower surface). Finally, according to *Newton's third law*, the air must push back against the airfoil with an equal and opposite (upward) force, which is the lift.

Explaining how the moving air is able to push back involves subtle cause-and-effect relationships, as we'll see below. So for a simple explanation, especially for young audiences, this is a good place to stop. Adding a simple statement quantifying the downward momentum imparted to the flow should be avoided, for reasons explained in the last section of the companion paper.

How the lift and the flow details are tied together in a set of mutual interactions

As the flow is forced to follow the predominantly downward-sloping surfaces of the airfoil, a set of mutual interactions is established between the lift force, the pressure field, and the velocity field. This is not a linear sequence of one-way cause-and-effect relationships; the relationships are all reciprocal. Nor are the relationships ordered in time; in a steady flow they are all simultaneous.

The general form of the pressure field is such that the most significant pressure differences are confined to a region whose extent is limited both vertically and horizontally (see Fig. 4 of the companion paper). Thus a major part of what we'll be seeking to explain is how pressure differences in both the vertical and horizontal directions are sustained.

At the overall flowfield level, the lift force and the pressure field support each other in a mutual interaction: The pressure field exerts the upward lift force on the airfoil, and at the same time the existence of the pressure field is a result of the equal-and-opposite downward force exerted by the airfoil on the air. The relationship is reciprocal, consistent with the reciprocity between action and reaction inherent in Newton's third law.

To visualize how the pressure field comes about, imagine a block of some uniform solid material resting on a table, and imagine pressing downward on the block with your thumb. The force you exert produces a smoothly varying non-uniform pressure field inside the solid material as illustrated in Fig. 1, similar to the pressure field in the air beneath a lifting airfoil (the part of the pattern below the airfoil in Fig. 2). The pressure fields in the two cases are similar in that they both result from applied forces, and they follow grossly similar spreading patterns. Of course the response of the material to the pressure field is different in the two cases. Within the solid block, internal shear stresses arise that counter the non-uniform pressure and hold the material stationary, with only a small static deformation. In the case of the flow around the airfoil, the air moves and deforms, and the pressure field is sustained in a mutual interaction between the pressure and the speed and direction of the flow. And because the airfoil is completely surrounded by flowing air, it generates a pressure field that includes reduced pressure above as well as increased pressure below.

So the existence and general form of the pressure field result from an interaction with the lift force itself. But the details are of course contingent upon what happens throughout the flowfield. The detailed distribution of pressure in the field is determined in a mutual interaction between the pressure field and the velocity field at the local level, at locations off the surface of the airfoil. The non-uniform pressure exerts forces

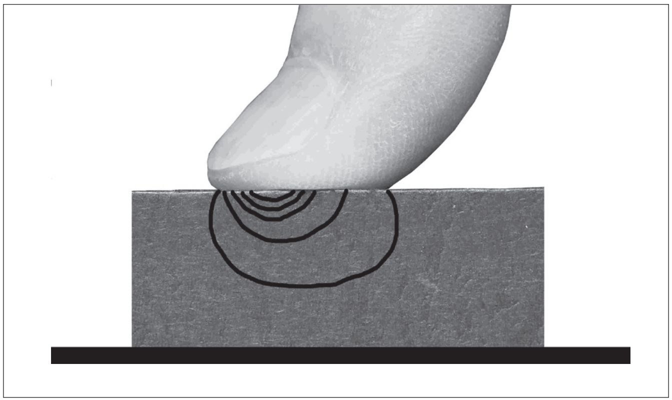


Fig. 1. General character of the pressure field inside a block of solid material, resulting from a downward force applied over a limited area of the top. Note the general similarity to the lower part of the airfoil pressure field in Fig. 2.

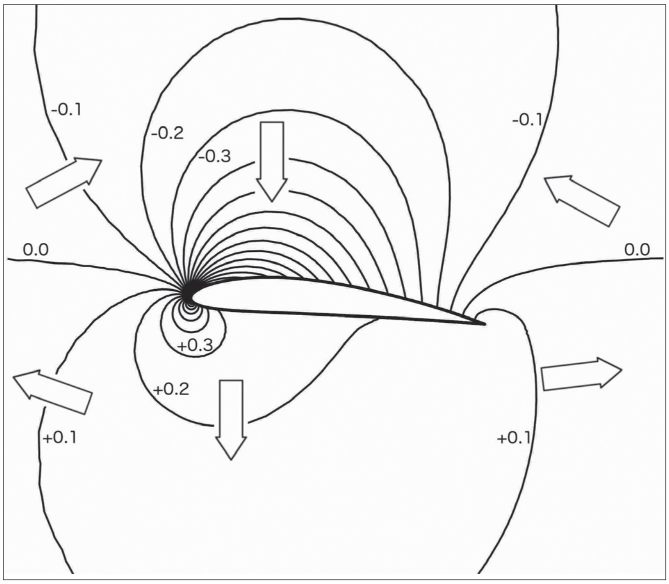


Fig. 2. The pressure field from Fig. 4 of the companion paper with block arrows added to indicate typical directions (but not magnitudes) of the pressure forces on the air, and the resulting accelerations, in different parts of the field.

on the air in directions perpendicular to the isobars, from higher pressure toward lower pressure. The block arrows in Fig. 2 are placed so as to indicate typical directions these forces take in different parts of the field. Newton's second law tells us that these forces cause air to accelerate in the directions of the forces. Thus air above the airfoil is pushed and accelerated inward toward the area of lowest pressure, and air below the airfoil is pushed and accelerated outward from the area of highest pressure. This is acceleration in the vector sense and involves changes in both speed and direction.

Thus the changes in flow direction described in the companion paper result from accelerations produced by the pressure field. For example, the forces indicated by the vertical arrows in the mid portion of Fig. 2 produce the downward turning visible above and below the airfoil in Fig. 3 of the companion paper.[1] We noted earlier that to produce this downward turning, the airfoil itself must have a positive angle of attack and/or camber. But remember that only the flow at the surface itself is in actual contact with the airfoil, and that out in the field the forces that produce flow turning are exerted by the pressure field, not directly by the airfoil itself. This flow turning by the pressure field is a non-viscous effect, with no significant contribution from viscous forces. Thus it is misleading to attribute it to the "Coanda effect," as is done in some explanations, a point discussed in detail by Denker[11] and McLean.[12]

Also note that downward turning isn't the only flow turning taking place. The sloping arrows on the right and left in Fig. 2 indicate upward force components and upward turning, consistent with the upward curvature of the streamlines in front of the airfoil and behind (streamlines behind the airfoil are curved upward even though their slope is still downward).

Early in the history of modern aerodynamics, it was noted that a lifting wing must generate upwash as well as downwash, lest air accumulate and become increasingly compressed in the lower reaches of the atmosphere (Lanchester[13]). So the presence of the ground, no matter how far away, makes some upwash a necessity. Note, however, that the more direct cause of the upward turning we see in Fig. 3 of the companion paper is the local pressure field.

Likewise, the changes in flow speed described in the companion paper are consistent with the horizontal components of the forces indicated by the arrows on the right and left in Fig. 2. And the higher flow speed above the airfoil than below is consistent with Bernoulli's principle. The applicability of Bernoulli's principle was discussed in some detail in the companion paper.

Thus all of the changes in flow direction and speed outside the boundary layer are directly caused by forces exerted by the non-uniform pressure field, in keeping with our usual understanding of Newton's second law. But this cause-and-effect relationship is not one way, because the non-uniform pressure depends on the air's motion. The relationship is thus reciprocal: Air flow accelerates in response to a pressure difference, and the pressure difference is sustained by the air's resistance to acceleration, i.e., its inertia. Thus generally inward accelerations serve to sustain the reduced pressures above the airfoil, and generally outward accelerations serve to sustain the increased pressures below. And upward accelerations play an essential role in sustaining the parts of the low- and high-pressure regions that protrude in front of the airfoil and behind.

To grasp the pressure-velocity interaction intuitively, it helps to note that a pressure difference can exist only because the air acted on by the pressure difference is able to "push back" against the unbalanced pressure force. When a parcel of air is subjected to different pressures on opposing sides, the parcel's neighbors exert a net force on the parcel as illustrated in Fig. 3. According to Newton's third law, this force must be opposed by an equal-and-opposite "pushback" exerted by the parcel on its neighbors. The "pushback" is provided by the inertia of the air in the parcel as it is accelerated by the pres-

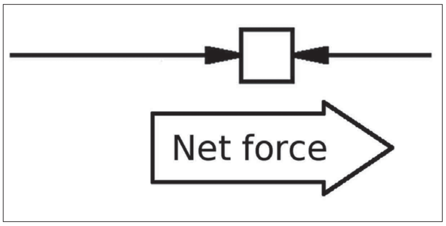


Fig. 3. Example of how a pressure difference exerts a net force on a fluid parcel. In this case, higher pressure on the left results in a net force to the right.

sure difference, in accordance with Newton's second law. This is why the mass of the air is important, and why lift depends on air density.

So the pressure field that exerts the lift force arises as part of a mutual interaction with the lift force itself and at the same time is sustained in a mutual interaction between the pressure and the vector velocity of the flow. Upward and downward deflections of the flow and different flow speeds above and below the airfoil are all essential parts of this interaction. The pressure differences follow naturally from Newton's second and third laws and from the fact that the flow along the surface is forced to follow the predominantly downward-sloping contours of the airfoil associated with angle of attack and/or camber. And of course the fact that the air has mass is crucial to the interaction.

How simpler explanations fall short

We've seen that lift is at least a 2D phenomenon, in the sense that it requires maintaining pressure differences in both the vertical and horizontal directions, and thus requires both turning of the flow and changes in flow speed. The key principle is Newton's second law in the vector sense as expressed in the Euler momentum equation for non-viscous flow.[14] The explanation given above could thus be called a "vector-Newton" or "Euler" explanation. Simpler explanations generally fall short by trying to explain lift in terms of only flow turning (Newton) or flow speed (Bernoulli), which amounts to trying to explain a 2D phenomenon in 1D terms. And depending on the details, they have other shortcomings as well.

• *Downward-turning explanations*

Explanations based on downward turning usually go as follows: Newton's second law tells us that to deflect the flow downward, the airfoil must push downward on the air. Then Newton's third law tells us that the air must push upward on the airfoil with an equal-and-opposite force, and thus there is lift.

This explanation is correct as far as it goes, but is incomplete. First, it doesn't mention the pressure field and thus doesn't explain how the airfoil can impart downward turning to a much deeper swath of the flow than it actually touches. And it omits the fact that upward turning is also taking place. Furthermore, it doesn't explain how the pressure differences in the horizontal direction are sustained. That is, it leaves out the Bernoulli part of the interaction.

• *Explanations based on flow curvature*

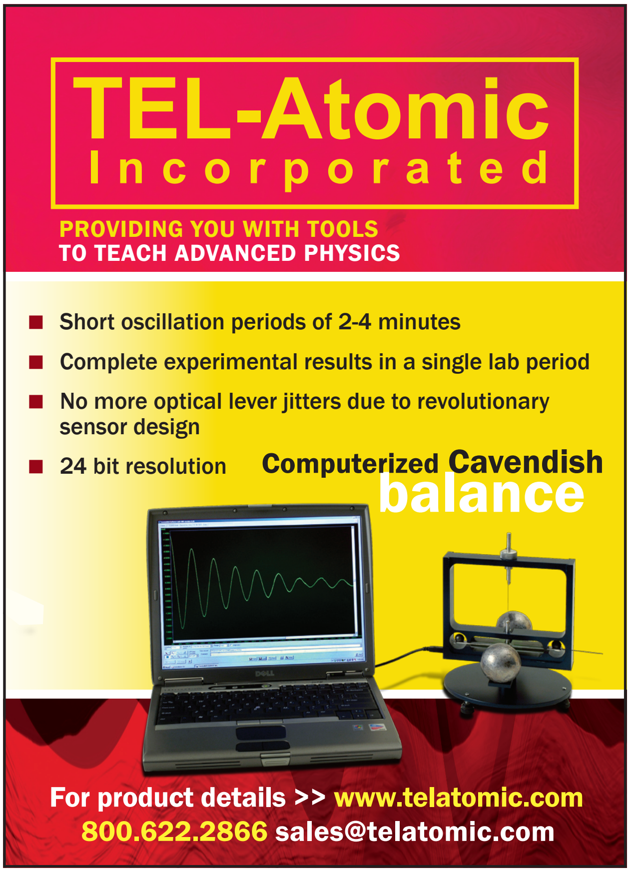
The explanations given by Weltner[7,8] and Babinsky[9] call attention to the downward curvature of the streamlines in the field, due to airfoil shape and angle of attack, and to the cross-stream pressure gradient that must accompany the flow curvature, according to Newton's second law. The pressure gradients above and below the airfoil lead to a pressure difference between the upper and lower surfaces and thus to lift.

These explanations improve on the simple downward-turning explanations by explaining that it's the pressure gradient that imparts downward turning to a deep swath of flow, but they don't mention the upward turning. Furthermore, they don't explicitly point out that the cause-and-effect relationship between pressure and velocity is reciprocal, and they imply that the Bernoulli part of the interaction is peripheral rather than a crucial part of the picture.

• *Bernoulli-based explanations*

Explanations based on Bernoulli start by arguing that the flow over the upper surface is sped up, either because the path length over the upper surface is longer and must be traversed in equal transit time, or because of an "obstacle," "hump," or "Venturi" effect. Because of the higher speed, the pressure over the upper surface must be lower, according to Bernoulli's principle, and thus there is lift.

Explanations of this type don't correctly explain what



causes the flow to speed up. The longer-path-length explanation is simply wrong. No difference in path length is needed, and even when there is a difference, it is typically much too small to explain the observed speed difference (Craig[15]). This is because the assumption of equal transit time is wrong, as can clearly be seen in Fig. 4 of Babinski[9] and in other flow visualizations. The "obstacle," "hump," or "Venturi" explanations typically invoke conservation of mass combined with "pinching" or "necking down" of the flow over the upper surface, but they don't provide a convincing physical explanation for the pinching. In general, explanations of the Bernoulli-only type imply that a speed difference can arise from causes other than a pressure difference, and that the speed difference then leads to a pressure difference, by Bernoulli's principle. This implied one-way causation is a misconception. The real relationship between pressure and flow speed is reciprocal. Finally, Bernoulli-only explanations don't explain how the pressure differences in the vertical direction are sustained. That is, they leave out the flow-turning part of the interaction.

Conclusions

The simplest explanation of lift, appropriate for young audiences, is based on Newton's second and third laws: The airfoil exerts a net force downward on the air as it flows past, and the air exerts a net force upward on the airfoil. Some air is deflected downward in the process.

To go beyond the simplest level requires a satisfactory explanation for how the air pushes back. This should include the following elements that are typically left out of simpler explanations:

- A lifting airfoil affects the *velocity field* and *pressure field* over a wide area.
- The pressure differences that exert the lift force on the surface arise as part of the overall pressure field.
- The pressure field is a direct result of an applied force, much as it would be in the case of a force applied to a block of solid material, and it is at the same time contingent upon accelerations of the fluid in the flowfield.
- The key cause-and-effect relationships, 1) between the lift force and the pressure field and 2) between the pressure field and the velocity field, are reciprocal.
- Pressure differences must be sustained in both the vertical and horizontal directions, and both turning of the flow and differences in flow speed consistent with Bernoulli's principle are therefore required. An explanation based on downward turning alone or on Bernoulli alone is incomplete.
- Both upward and downward turning play necessary roles in sustaining the pressure field.

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