Understanding wing lift

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Abstract

The conventional explanation of aerodynamic lift based on Bernoulli's equation is one of the most common mistakes in presentations to school students and is found in children's science books. The fallacies in this explanation together with an alternative explanation for aerofoil lift have already been presented in an excellent article by Babinsky (2003 *Phys. Educ.* **38** 497–503). However, in Babinsky's explanation, the air friction forces are ignored and the flow-field curvature introduced by the aerofoil shape is understood intuitively. In this article, a simple analysis of the lift with friction forces incorporated is presented to give a more precise qualitative explanation.

Introduction

How do aeroplane wings work? How does the shape of an aerofoil affect its lift? These questions are argued in many school classrooms, but the correct answer is still the cause of controversy. This controversy is related to the misleading 'aerofoil shape' explanation, which relies on Bernoulli's equation, made popular by widespread use in children's science books, magazine articles and pilot's textbooks. On the other hand, explanations to the general public based upon circulation, curvature of streamlines or Newton's laws are scant.

In spite of student interest, the topic of aerodynamic lift is often not fully explored by teachers and this may be due to the fact that the popular explanation is not convincing and/or not related to Newton's mechanics. Some of the most popular explanations rely on the arguments based on Bernoulli's equation. Frequently the generation of lift is wrongly justified by the 'path length' explanation, based on the different distances around the upper and lower surfaces of the aerofoil, and by the 'equal time' argument based on air particles travelling along the upper surface reaching the trailing edge at the same time as those travelling along the lower surface [1, 2]. Thus, since the path along the upper surface is longer, the air on the upper surface must flow faster than the air below for both parts to reach the trailing edge at the same time.

In this article, we will propose an alternative physical explanation based on Newton's third law (action/reaction), viscosity and Coanda effect.

Alternative explanation for aerofoil lift

All fluids show internal friction (viscosity). In many cases, the forces due to viscosity are so small in comparison with forces due to inertia, that neglecting the viscosity may seem justified as a first approximation. However, a closer examination shows that in the interior of the fluid, we can treat the fluid as inviscid, but care must be taken when considering the layers of the
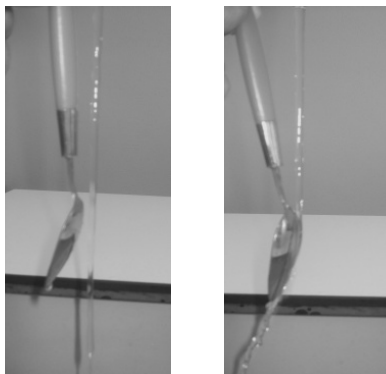
Figure 1. Flowing water adhesion along a curved spoon surface.

Figure 2. Distribution of the velocity gradient into the boundary layer.

Figure 3. Air layers radially accelerated.

fluid in the immediate vicinity of solid bodies. Experiments show that fluids like water and air never slide on a surface but remain attached to it. This phenomenon is due to the viscosity of fluids and to the resultant intermolecular forces between the fluids and solid molecules with a consequent fluid adhesion to the flow surface.

Let us consider, as an example, the flowing water adhesion effect along the back of a spoon, as shown in figure 1.

If fluid flow is laminar the water follows the spoon curvature profile. This effect is known as the Coanda effect [2]. As shown in figure 1, the changing fluid flow direction is produced by the aforementioned forces resulting in a force applied to the moving water by the surface of the spoon and, according to Newton's third law, this action requires a simultaneous reaction force exerted by the fluid on the spoon. Something very similar occurs when air is flowing along a wing. When an aeroplane is flying the air is pulled downward, which creates a pressure difference across the wing, in turn, increasing the tangential velocity of the incoming air. This fact demonstrates that the faster motion of the air at the upper surface occurs as a consequence (and not as a cause) of the lower pressure.

The transition from the velocity of the body to that of the stream in such a case takes place in a thin layer of the fluid, whose thickness decreases as velocity increases and as viscosity decreases. Thus, the viscosity creates a layer where the velocity parallel to the surface of the aerofoil diminishes as it reaches the surface. However, this layer of rapid change in tangential velocity around
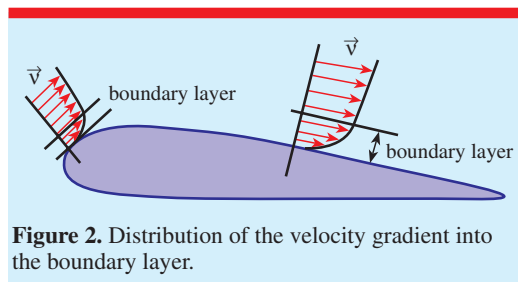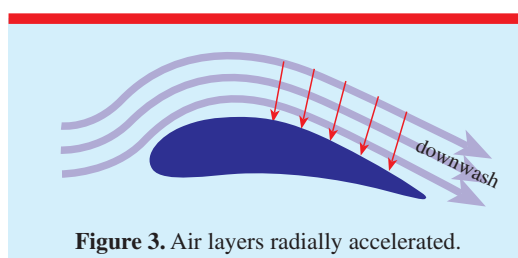
the aerofoil gets thicker as we follow it from the leading edge to the trailing edge, as sketched in figure 2. This is known as the 'boundary layer'.

Thus, the air viscosity, Coanda effect and aerofoil contours are responsible for changing air flow direction, accelerating down the air molecules around the aerofoil. This phenomenon occurs longitudinally in layers from the aerofoil surface where the velocity is zero (is at rest relative to it), to inviscid outer stream fluid flow (figure 2). At this point, the flow velocity is no longer affected by the interaction with the aerofoil surface.

Inside the boundary layer, the effect of the fluid viscosity progressively decreases the closer we get to its outer frontier. Beyond that frontier, it is safe to consider the flow to have no viscosity and that the air stream is in laminar flow. This variation of viscosity induces a decrease of air velocity inside the boundary layer from its outer frontier to the aerofoil surface.

Now, consider the upper surface of an 'ordinary' aerofoil with a smooth curvature to ensure no flow separation (see figure 3). The air flow near the aerofoil follows the geometrical shape of the upper surface generating a pressure gradient and acceleration, both perpendicular to the streamlines and directed to the centre of the flow trajectory. The air molecules are accelerated downwards in a kind of 'suction' that extends along the convex surface of the aerofoil as far as the trailing edge. Due to the gradient of the pressure the upper aerofoil profile streamlines are

pulled down to keep up with the boundary layer, following the upper aerofoil shape as sketched in figure 3. Hence the static pressure decreases in the direction of the streamline's centre of curvature [1].

The pressure gradient may also be explained by air flux inertia. To follow the contours of the aerofoil, the air needs to be accelerated in the direction of the streamline's centre of curvature. Following this line of argument, the upper surface of the aerofoil will pull down the air layer in contact with its surface and consequently drag the adjacent air layers creating a centripetal force. According to Newton's third law, a symmetrical force is applied to the aerofoil and consequently a zone of low pressure is created close to the upper surface. Thus, a pressure gradient is established which ensures that the flow follows the shape of the surface.

From the centripetal force per unit of volume, F_c, give by

$$F_c = \rho \frac{v^2}{r}, \qquad (1)$$

we infer that an increase in the value of the fluid density (ρ) as well as an increase in the air linear velocity (v) relative to the wing and/or a decrease in the radius of curvature (r) of the air trajectory will cause an increase in the centripetal force.

The lower surface of the aerofoil also contributes to the lift, both through the creation of radial acceleration of the flow as a result of the profile curvature (see figure 4) and by the air deflection at the lower surface of the aerofoil, especially during positive angles of attack. Air deflection and pressure are linked. We cannot have one without the other.

The shape of an 'ordinary' aerofoil is also important to the generation of the centripetal force and the consequent pressure gradient. Figure 4 shows a representative distribution of the pressure gradient around the aerofoil surface. The arrows are oriented in the direction of high pressure. The signs + and − represent the profile zone with high and low pressure, respectively.

At the upper surface, fluid particles travelling along convex curved streamlines are responsible for the creation of a favourable lift force. Because such particles are changing direction there must exist a centripetal force acting normal to the direction of motion. The centripetal force
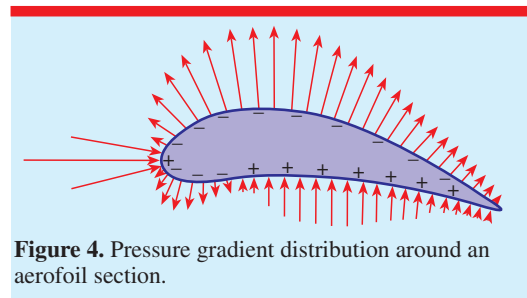

Figure 4. Pressure gradient distribution around an aerofoil section.

generates a pressure gradient, which ensures the flow follows the shape of the surface. Thus the geometry of the aerofoil profile together with the friction force and Coanda effect are the primary causes of the streamline velocity distribution around an aerofoil.

At the lower surface, the wing has initially a short convex profile that becomes concave after the inflection point. At the convex profile an opposite force to the positive lift direction is produced. Nevertheless, this force is overcome by the favourable lift effect resulting from the flow over the concave profile region.

In front of the aerofoil, the pressure increase is due to the frontal incidence of the air, contributing to the drag (figure 4).

The angle of attack may have an important effect on the aerodynamic lift as a wing is rotated relative to the airstream. For positive angles, the air molecules collide into the wing's lower surface and this effect results in a positive contribution to the lift. This is the reason why lift also exists in aeroplanes with symmetrical and flat wings, where the lift associated with the wing geometry is null. Therefore, in wings with 'ordinary' curvature, lift occurs even with small negative angles of attack. This happens because the contribution of the air's centripetal acceleration to the lift overcomes the opposite contribution of the air's incidence with the upper surface of the wing. This explains the 'flying upside down' situation [3]. Normally, the gap of angles with favourable lift varies approximately between −10° and +20°. Outside this interval, the air stream does not follow the surface profile homogeneously, thus creating turbulence.

In summary, lift occurs when flow is shifted downwards.

Conclusion

In this article we present a simplified explanation of aerodynamic lift without resorting to the misleading approximation of the Bernoulli equation, in opposition to the popular lift explanation. These popular theories are partially correct and they sound logical. However, the incorrect use of presuppositions generates misconceptions that cannot be easily refuted.

Our explanation is appropriate for school students. This explanation is based on the generation of a gradient of pressures around the aerofoil, as a consequence of the centripetal force created by the air viscosity, the Coanda effect and wing shape.

Acknowledgment

References

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