Physics of Flight - reviewed

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1. Introduction

The explanation of the aerodynamic lift has a long history, but there is controversy regarding the fundamental physics and their relation to Newton's mechanics to date (Smith 1972, Fletcher 1975, Weltner 1987, Baumann/Schwaneberg 1994). This topic could be one of the most interesting and motivating in physics education. But the physics of flight nearly disappeared from the curriculum in schools and basic physics courses in most European countries. One reason, why teachers despite of students interest neglect this topic might be the fact that the conventional explanation of the aerodynamic lift based on Bernoulli's Law has serious drawbacks and is partly erroneous.

Niermann (1989) analysed German, American and English textbooks published within the last one hundred years investigating the explanations of aerodynamic lift. The main result is that explanations based on Bernoulli's law are dominating since the 1920s.

This situation is changing recently. A growing number of authors question the conventional explanation and replace it by an explanation based on fundamental mechanics (Weltner 1987, Anderson/Eberhard 2001). It is most remarkable that the famous textbook of Tipler (2007) gives in its last edition a correct and convincing explanation.

2. The conventional analysis of explanations based on Bernoulli's law

Basically, these explanations follow the same pattern.

Firstly, Bernoulli's law is stated. It says that there is a reverse relation between flow velocity and static pressure: If the flow velocity goes up the static pressure goes down and vice versa.

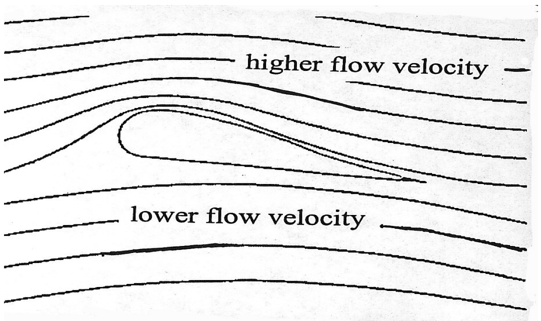

Figure 1: Airflow around an airfoil.

Secondly, streamlines of air passing an airfoil are demonstrated and analysed. (Figure 1.) It is stressed that the air at the upper side flows faster than the air at the lower side. Finally, Bernoulli's law is applied to the different flow velocities at the upper and lower side of the wing resulting in a lower pressure at the upper surface and a higher pressure at the lower surface. These pressure differences produce a force on the airfoil - the lift.

An analysis of the logical structure using a coherence diagram or concept map shows that this explanation is not complete. If different flow velocities are to cause different pressures a physical reason for the fact that the air flows faster at the upper side must be given, too. Three types of reasons can be found:

(i) Analysis of path lengths.

Referring to figure 1 it is argued: *The profile of a wing is such that the air has further to travel over the upper surface and hence has to flow faster to maintain streamline flow*.

A well known university textbooks says (Mansfield/Sullivan 1998): "*If air is streaming from the left against the airfoil or if the airfoil moves in air at rest to the left the air will be separated. Since the path length along the upper side of the airfoil exceeds the path length along the lower side the velocity of the air at the upper side must exceed the velocity at the lower side.*""

These arguments are based on a tacit hypothesis: Air that is adjacent before the separation by the airfoil has to meet again behind the airfoil.

Smith (Smith 1972) pointed out that there is no law or rule in physics to require adjacent air before the separation to meet behind the airfoil again after separation. Adjacent air before the separation indeed does not meet behind airfoil. Figure 2 shows experimental evidence of air streaming along an airfoil. Smoke tracer mark the streamlines.

The figure shows at the leading edge adjacent air before the separation. The figure shows at the trailing edge that the air that passed along the upper surface travelled even further creating a shift between the upper and lower air. This disapproves the arguments based on differences in path length.

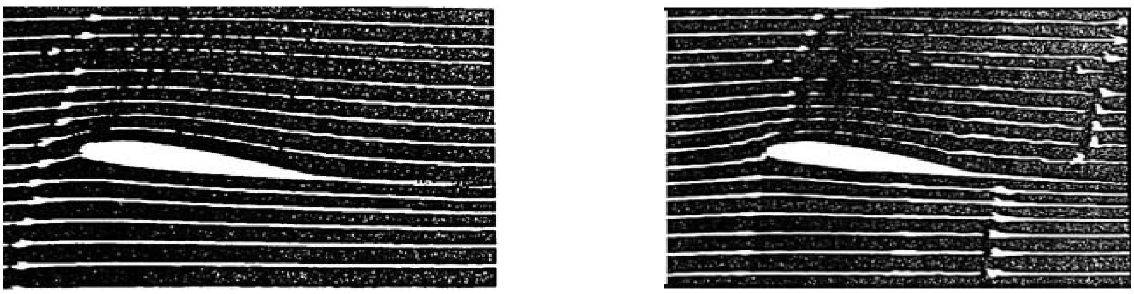

Figure 2: Streamlines around a profile

(ii) Using the concept of circulation.

In this type of reasoning the velocity distribution is explained using the concept of circulation. It starts from the description of a potential flow around the airfoil. Next, a circulation flow is superimposed in such a way that the stationary flow around the airfoil is obtained. The circulation must be such that the flow is even at the trailing edge. By this procedure a flow of the air is achieved which can be used to calculate the velocity distribution and hence the pressure distribution.

The concept of circulation is a sophisticated mathematical discription of the velocity distribution but not the cause of the latter.

(iii) Some textbooks give reasons without substantial meaning (like Cutnell 1998): *"Because of the shape of the wing the air travels faster over the curved upper surface than it does over the flatter lower surface"*. This type of reasoning makes the geometry of the profile responsible for the behaviour of the streamlines without giving a physical cause why and how the streaming velocities are influenced by the airfoil.

This leaves the fundamental question open: How to generate the velocity distribution around an airfoil.

3. A general view - Aerodynamic lifting force as reaction force while air is accelerated downwards by the airplane

For simplicity reasons we first discuss the lift by the rotor of a helicopter or the propulsion force of a propeller or a jet. In both cases an air stream is generated and air is accelerated. To accelerate air a force must be exerted on the air and the reaction force acts on the rotor or the propeller. Quantitatively this force equals the change of momentum of the air stream: $F = \dot{m} \cdot v$.

Basically, the same physics apply to the airfoil. The airfoil acts as a slightly curved plane moved horizontally with a small angle of attack. It accelerates air initially at rest downwards.

This vertical acceleration of air can be demonstrated by a simple but convincing experiment. Firstly we construct an indicator of air movements (see Figure 3). At one end of a thin wood lath we fix a piece of cardboard in a horizontal position, this may be half of a postcard. At the other end we fix a counterweight. Now the indicator is suspended. Thus the cardboard may move freely to follow movements of the surrounding air.

If an airfoil is moved horizontally beneath or above the cardboard it will swing downwards indicating a vertical movement of the air. This movement depends on the angle of attack. If this angle is increased the vertical movement increases as well. This holds for the velocity too. An airfoil to suit our needs is produced by forming cardboard into the shape of an airfoil and gluing the trailing edge together (see Figure 3).

Before starting the experiment the indicator must be at rest. This requires a closed room without students moving and windows and doors shut. The airfoil must be moved strictly horizontal starting from some distance in front of the indicator. Thus this experiment can be used to demonstrate quantitatively the impact of angle of attack and of the velocity on the downward movement and consequently on the lifting force.

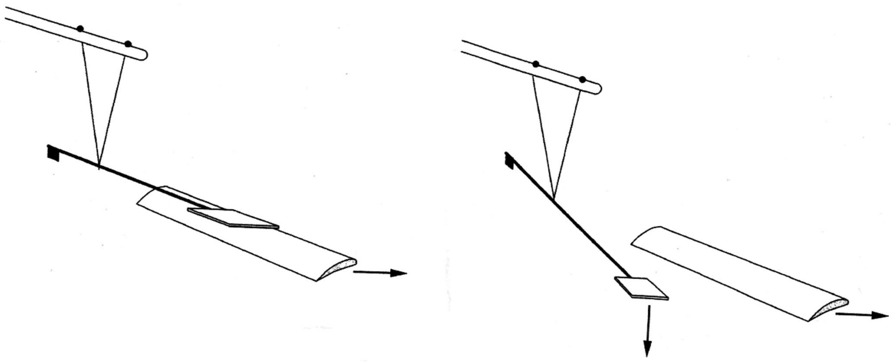

Figure 3: Indicator of air movement. Left: Position of cardboard before and while passing of the airfoil. Right: Vertical movement of the cardboard indicating vertical movement of the air induced by the airfoil. Wood lath: Cross section about 5 mm x 5 mm, length about 1 m. Airfoil about 15 cm x 60 cm.

Viewed from the aircraft the airfoil deflects the horizontal flow of the air downwards. This vertical motion is called downwash and can be observed easily. A thread of wool must be glued to the trailing edge of an airfoil. If positioned in the air stream of a blower or fan the direction of the thread follows the direction of the trailing edge indicating the direction of the air stream behind the airfoil. If the angle of attack is varied the direction of the thread varies too. This demonstrates that the direction of the airflow near the airfoil can be manipulated by the position of the airfoil itself. An airfoil may be produced by cardboard glued together. To accelerate air downwards the plane has to applicate a force on the air. Some important relations can easily be derived from the vertical flow of momentum caused by the airfoil.

Lift and angle of attack: The airflow near the airfoil follows the geometrical shape of the latter's surface. The air stream is deflected downwards approximately proportional to the angle of attack. Consequently the lift is approximately proportional to the angle of attack too. This holds for angles of attack between -10° and 15°. With an exceeding angle of attack the air stream ceases to follow the surface homogenously creating turbulence. In aviation this process is called 'stall'.

It should be noted that the trailing edge of a strongly curved profile - used for aircrafts with low velocities - points downward. Even if the angle of attack is zero the air behind the airfoil has a vertical velocity component. Consequently the airfoil produces lift.

Velocity and lift: The geometry of the streaming flow remains the same if the velocity is doubled. Two factors double:

- The mass of air deflected downwards per unit of time.
- The vertical component of the streaming velocity.

Combining the effects the lift is to increase four times if the streaming velocity is doubled.

Lift and air density: The reaction forces are proportional to the accelerated mass and therefore proportional to the density of the air. At an altitude of 12.000 m density and air pressure are approximately a quarter of their standards at sea level. Consequently the lift is reduced to a quarter as well. Doubling the velocity can compensate this loss. Thus long distance aircrafts fly in heights of about 10 000 km.

4. The one-dimensional Euler-Equation and the generation of pressure

This passage gives a theoretical explanation why higher screaming velocity is an effect of lower pressure and why it never can generate lower pressure. On the other hand, it will be shown that lower pressure can be generated if the streaming low is forced to be curved. The calculations may be skipped by readers not fond of mathematical derivations.

To understand the origin of the pressure distribution along the surface of an airfoil in detail we must refer to the Euler equations. Those describe the relation between pressure gradients and acceleration of incompressible fluids without friction. Euler applied Newton's laws to the motion of fluids. We refer to the most simple form - the one-dimensional Euler equation - which holds for stationary flow confined by streamlines (Tuckenbrodt/Schichtling 1967). Gravitational effects are excluded. We assume a cubical volume. (Figure 4.) For the mass Δm confined in the volume the basic equation is:

$$F = \Delta m a.$$

We analyse separately *tangential acceleration*, figure 4, and *normal acceleration*, figure 5.

4.1. A tangential acceleration

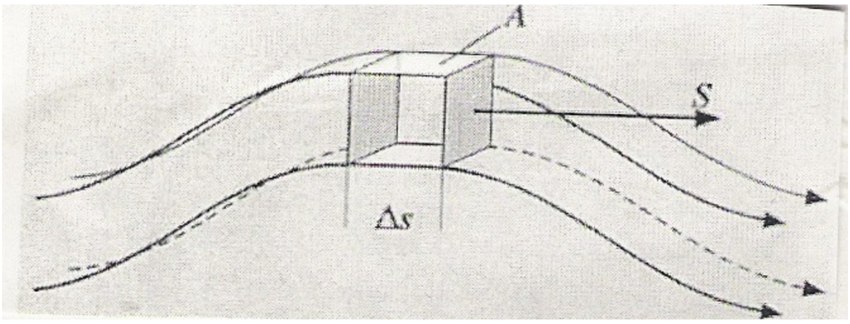

Figure 4: Tangential acceleration of a volume within curves stream lines.

A tangential acceleration in s-direction is the result of a force. A force in s-direction occurs when the pressure acting at the faces A at the back is higher than the pressure in front: It must be stressed that an acceleration in s-direction is caused by a decrease of pressure in s-direction.

$$F = \Delta m \cdot \ddot{s} = -\mathrm{A}\frac{\delta p}{\delta s} \cdot \Delta s.$$

Inserting the mass $\Delta m = \rho A \Delta m$ and $\ddot{s} = \frac{dv}{dt}$ we get

$$\rho \frac{dv}{dt} = -\frac{dp}{ds}.$$

This equation is transformed to

$$\int_1^2 \rho \cdot dv \frac{ds}{dt} = -\int_1^2 dp.$$

Solving the definite integral we arrive at the Bernoulli equation:

$$\frac{\rho}{2}\left(v_2^2 - v_1^2\right) = p_1 - p_2 .$$

4.2. Normal acceleration

(See figure 5). A *normal acceleration* within curved streamlines needs a higher pressure at the outer lateral face than at the inner lateral face.

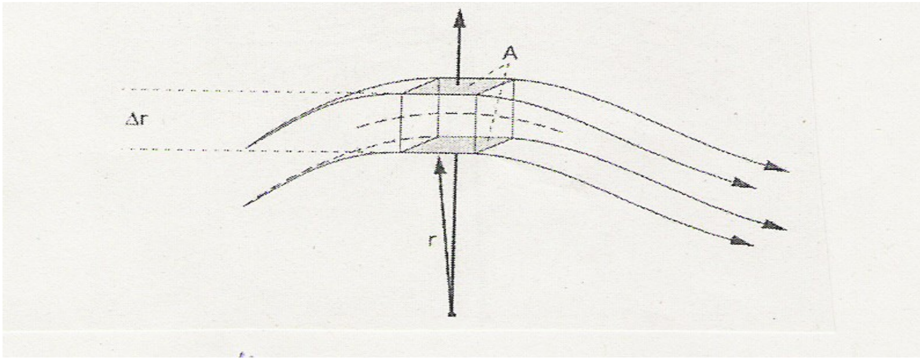

Figure 5: Normal acceleration of a volume element within curved streamlines.

According to figure 5: $F = -\mathrm{A}\frac{dp}{dz} \cdot \Delta z = \Delta m \cdot \ddot{z}$.

Inserting the mass of the volume $\Delta m = \rho\Delta \cdot \Delta z$ we arrive at

$$\frac{dp}{dz} = -\rho \cdot \ddot{z} .$$

The acceleration in direction of the centre of curvature is well known. It is the centripetal acceleration of a circular motion.

$\ddot{z} = -\rho\frac{v^2}{R}$ (R = radius of curvature, v = streaming velocity).

Finally we obtain

$$\frac{dp}{dz} = p\frac{v^2}{R} .$$

Curved streamlines within a flow are related to pressure gradients. Unfortunately this equation cannot be integrated directly. The integration requires the knowledge of the total flow field.

Nonetheless, the analysis of normal acceleration of air serves as an explanation for the generation of regions with lower or higher pressure for the flow around an airfoil.

We refer to the stationary flow near an airfoil. The streaming air passing the airfoil cannot penetrate the surface and is forced to move on streamlines that surround the airfoil and follow its geometrical shape. Close to the airfoil the flow is forced to approximate the latter's geometry. This is due to the Coanda effect. The motion near the airfoil is a forced motion determined by the shape of the airfoil and the latter's position in relation to the direction of the flow (angle of attack).

At the upper surface of the airfoil the acceleration is directed to the centre of curvature, i.e. mainly downwards. The necessary pressure gradient is created by a slight 'removal' of the air from the surface reducing the pressure and creating a pressure gradient in the vertical direction. Thus a pressure gradient is established which ensures that the flow follows the shape of the surface. Colloquially one might say that the pressure gradient is created by the centrifugal force of the air flowing around the surface. From the curvature of the streamlines the pressure gradients and consequently the distribution of pressure of the surface of an airfoil may be derived.

At the upper surface the pressure going outward must grow. Since we have normal pressure in a greater distance we have lower pressure at the surface.

Furthermore a consequence of the lower pressure at the upper surface is the positive tangential acceleration of the incoming air. The problem of how to explain the faster motion of the air at the upper surface is now solved. It is the lower pressure that makes the air accelerate and flow faster.

5. Notes on the origin of the conventional explanation

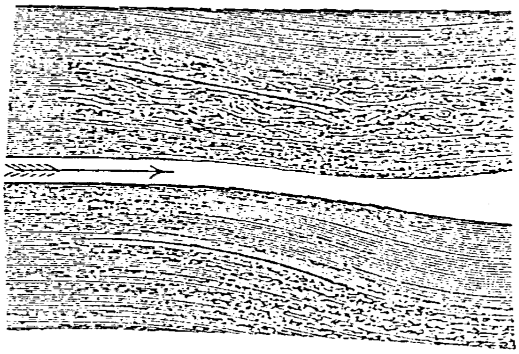

Figure 6: Deflection of airflow by an even plane and a curved plane.

More than a hundred years ago Otto Lilienthal (Lilienthal 1889) explained the aero dynamical lift correctly and clearly. He compared a curved plane with a flat plane. He referred to figure 6 and wrote: "*The air passing the planes is accelerated downwards in both cases. The air below has to go down and the air passing the upper side has to fill the space above. The deflection of the air stream downwards happens abruptly at the front edge of an even plane. This gives rise to turbulence and vortices. It is different with the curved plane. The airflow passing the front edge will be deflected gradually from its horizontal direction and led downward. The flow gains a horizontal velocity component without any sudden impact. It is clear that only the curved plane - provided its direction at the front edge parallels the original direction of the flow - will divert the air stream downwards with less turbulence in a direction which is given by the tangent at the trailing edge of the plane. The vertical momentum of the air stream makes for the upward force acting on the airfoil.*"

The explanation based on the relation between aerodynamic lift and the acceleration of a downward air flow prevailed in textbooks in this simple form until 1920 without having been elaborated further. By approximately the year 1920, when aviation gained much interest in science and public, the explanation based on Bernoulli's law appeared and displaced the explanation based on reaction forces.

In any case it was necessary that the explanation of lift using Bernoulli's law had to be complemented by giving a cause for the higher streaming velocity of the wing's upper surface.

Thus the origin of the erroneous path length reasoning may be found in a diagram given by Prandtl (1921), figure 7.

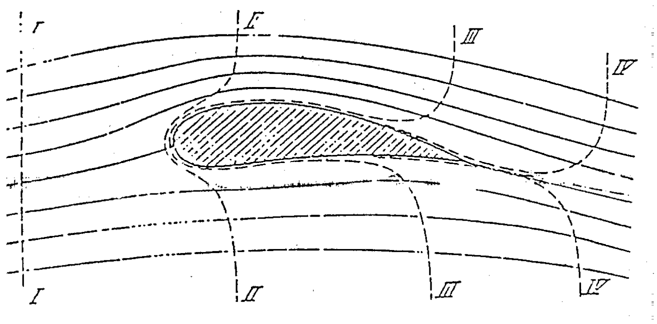

Figure 7: Position of originally adjacent air particles during the flow around a profile at consecutive times I, II, III, IV.

Dotted lines connect air volumes originally adjacent. With this diagram Prandtl tried to show that air at the inner layers stick to the surface. In respect to one point this diagram is not correct. It indicates that the volumes remain at the same vertical position and it indicates that originally adjacent air meets again at the end of the airfoil. This diagram misses the phase shift shown in figure 2, which seems not to have been observed by Prandtl at that time.

Diagrams of this type might have misled scholars to the hypothesis that adjacent air has to meet again after passing the airfoil.

6. The flow and the system of vortices

Regarding the total flow of a streaming around an airfoil we have to add details. If the airfoil generates low pressure at its upper side and high pressure at its lower side this causes lateral movements rotating to the ends of the wing. Below the wing air moves outwards and above the wing air moves inwards. Beyond the ends of the airfoil air moves even upwards. Thus a system of vortices is generated in figure 8.

Figure 8: System of vortices behind an airfoil

The vortices behind the wing are directed clockwise at one side and counter clockwise at the other side. The system of vortices is of a remarkable stability and moves downward as a whole.

Literature

Anderson, David, Scott Eberhard (2001): *Understanding Flight*, Mac Graw Hill

Baumann, R., R. Schwaneberg (1994): *Interpretation of Bernoulli's Equation*, in: The Physics Teacher, New York, Vol. 32, Nov. 1994, pp. 478 - 488

Cutnell, Johnson (1998): *Physics*, Chichester /New York
Fletcher, N.H. (1975): Mechanics of Flight, in: Physics Education , 1975, S. 385-389
Lilienthal, Otto (1889): *Der Vogelflug als Grundlage der Fliegekunst. Ein Beitrag zur Systematik der Flugtechnik*, Berlin
Mansfield, M., O. Sullivan (1998): *Understanding Physics*, Chichester/ New York
Niermann, K. (1989): *Darstellung der Aerodynamik in Schulphysikbüchern*, Alsbach/Bergstraße
Smith; N. F. (1972): *Bernoulli and Newton and Fluid Mechanics*, in: The Physics Teacher, New York, 1972, 10, S. 451-455
Prandtl, L. (1921): *Applications of modern Hydrodynamics to Aeronautics*, in: NASA Report, 1921, 116, pp. 161-182
Tipler, Paul, Gene Mosses (2007): *Physics for Scientists and Engineers*, 7th Edition
Tuckenbrodt, E., H. Schlichting (1967): *Aerodynamik des Flugzeuges. Grundlagen as der Strömungsmechanik Aerodynamik des Tragflügels* (Teil I), Berlin/Heidelberg/New York
Weltner, Klaus (1987): *A comparison of explanations of aerodynamical lifting force*, in: American Journal of Physics, 1987, Vol. 55, No. 1, pp. 50-54
Weltner, Klaus (1990): *Aerodynamic Lifting Force*, in: The Physics Teacher, New York, 1990, No. 2, Vol. 28, pp. 78-82

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