Up to the Skies

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Abstract

The paper first deals with the origin of aerodynamic lift and offers two possible non-traditional explanations of its existence. Both interpretations use only Newton's laws of motion and work without Bernoulli's equation. The simplicity of the argumentation allows them to be used in upper secondary school as well.

The following text describes the flight of birds, the importance of flapping wings, and the V-flight formation. In describing the flight of insects, the causes of the differences between small and large flyers are commented on, and the main mechanisms that increase the lift force of small flyers above the value usual for larger birds and aircrafts are explained.

The Appendix highlights some of the difficulties in interpreting Bernoulli's equation.

Introduction

From time immemorial, man has longed to imitate birds and fly. The mythological story about Daedalus and Icarus is well known, as well as a number of naive medieval reflections and perhaps even attempts to fly using one's own strength. However, it was first necessary to achieve certain technological progress in order to be able not only catch up with the birds but to overcome them significantly.

In this paper, we will first focus on a basic physics description of the interaction of a flying object with the air, and then we will notice some peculiarities of bird and insect flights.

A flying or floating object must solve two basic problems in order to ensure its movement:

1) Compensation of gravity by a force that points vertically upwards and which we call the lift force.

2) Gain a horizontal force for forward motion, thus horizontal acceleration and overcome aerodynamic drag.

When moving on land, the situation is simple and both necessary forces are naturally provided by the support of a solid base. However, the flyer or swimmer has nothing but fluid in their surroundings, and therefore both forces must come only from interacting with that fluid.

Buoyant and Lift Force

In principle, there are two basic ways to gain an upwards force in a fluid:

1) Buoyancy

The buoyant force is described by the well-known Archimedes' law

$$F = V \rho g$$

where the individual symbols have their traditional meaning. However, only swimmers moving in water can be satisfied with buoyancy. The buoyant force in air under normal conditions reaches only about a thousandth of the value needed for the flight of any animal, and no living organism is able to fly independently using Archimedes' law. Only human products, balloons and airships can do this by compensating for low air density is using a large volume of the light flying object.

2) Lift (force)

Unlike buoyancy, lift requires a fluid flowing around the object, i.e. the mutual movement of the flyer and the surrounding air. A standard example used to interpret the lift is the asymmetrical aerofoil.

Figure 1 is a copy from the Mechanics for Gymnasiums textbook [1].

The interpretation of the lift is usually part of fluid mechanics in textbook texts, and Bernoulli's equation is used in the argumentation:

$$\frac{1}{2}\rho v^2 + p = konst$$

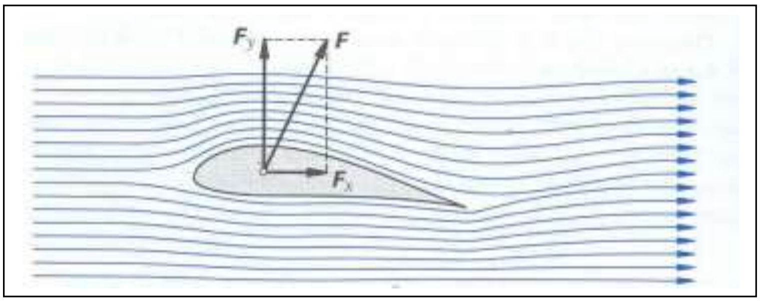

Figure 1. The usual illustration of the flow around the wing. The streamlines are incorrectly drawn here, see the text.

The air above the wing moves at a higher velocity than under the wing, so there is smaller pressure above the wing and the difference in compressive forces on the lower and upper surface of the wing gives the resulting lift (and drag) force.

This argument is basically fine, the problem is how to justify the different air velocities under and above the wing. Today, only exceptionally, but still, we can find two basic explanations, both incorrect[1].

a) Theory of equal transit-time

Due to the asymmetry of the aerofoil, the air above the upper surface is faster than the flow around the lower surface because the path length over the upper surface is longer.

This interpretation assumes that air molecules must fly over and under the wing in the same amount of time. But there is no reason at all for this assumption and it is completely indefensible. In fact, the air above the wing actually flies faster, but much faster than the equal transit-time theory predicts, see for example [2]. The absurdity of this argument also results from the fact that in this way it would not be possible to explain, for example, the actual lift on a flat inclined plate.

[1] Bernoulli's equation is sometimes misinterpreted and some popular flowing fluid experiments are misinterpreted. The reader can find a more detailed comment in the appendix at the end of this text.

b) Theory of constricted cross-sectional area

Above the wing, the streamlines are condensed, which looks like the flow situation in a constrictive tube, where the higher velocity in the narrower part can be easily explained using the continuity equation; see Figure 2.

Here in the place of denser streamlines we can indeed expect a higher velocity, but the constricted "tube" is not bounded from above and the change in velocity cannot be determined from the continuity equation. Moreover, as in the previous case, the lift on a flat inclined plate cannot be explained in this way, where, on the contrary, above the plate, the cross-sectional area along the plate increases, which according to the continuity equation would mean a decrease in velocity (and an increase in pressure).

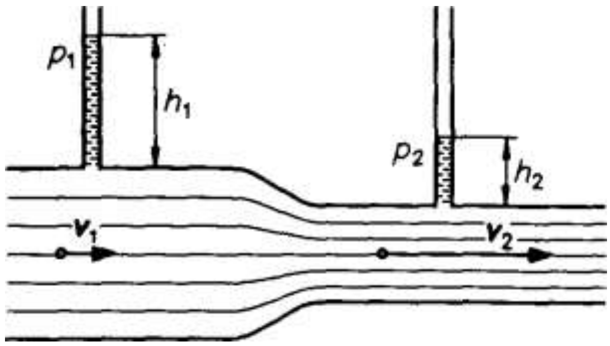

Figure 2. Illustration of the continuity equation and Bernoulli's equation.

In the following, we will offer two different ways explaining the lift on the aerofoil, which are very simple, argumentatively straightforward, and indisputable. Surprisingly, however, none of them use Bernoulli's equation.

The basis of both interpretations is a fact that is usually neglected in upper secondary school textbooks: When it flows around the aerofoil, the air streamlines turn downwards, see Figure 3, or experimental confirmation [3].

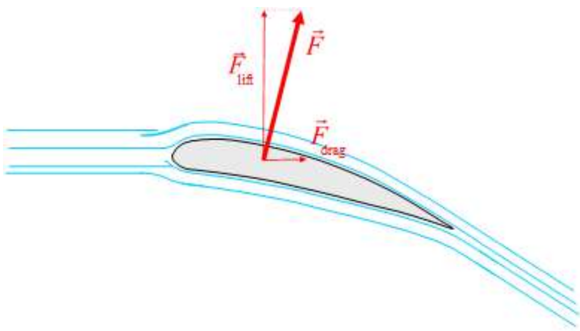

Figure 3. Behind the wing streamlines turn downwards.

Thus, in Figure 1, the streamlines are drawn incorrectly, and it is really paradoxical that what is absolutely crucial for the existence of lift is completely ignored in the basic textbooks.

A) Turning of streamlines and centripetal force

Consider a fluid flowing in a curved tube, of constant cross-sectional area; see Figure 4. The imagined volume element moves along a circular trajectory and must therefore be affected by a centripetal force. However, the source of the force is only the surrounding fluid and the centripetal force will have the correct direction only if the pressure increases from the centre.

When flowing around the aerofoil, the streamlines above and below the wing turn in the same direction. Thus, in both cases, the pressure increases upward (and backward). Imagine that we approach the aerofoil from below. We start at the point of atmospheric pressure, and as we approach the wing, the pressure increases. There must therefore be an overpressure under the wing. Similarly, when moving away from the upper surface of the wing, the pressure increases, but at a greater distance, the pressure is atmospheric. There must therefore be an underpressure above the wing. The difference in pressure below and above the wing is the cause of the existence of the lift force.

B) Turning of streamlines and Newton's third law

The second way is even simpler. If the wing turns the air streamlines downward, it must exert a downward force on the air. So according to the action-reaction law, the air acts on the wing with the opposite force, i.e. upward.

For the existence of aerodynamic lift, it is essential that the wing, or another object, deflects the airflow downward. In other words, anything that deflects the airflow downward or simply "blows" the air downward, has lift. We all take this for granted in the helicopter's main rotor, and it is exactly the same with the wings of birds or airplanes.

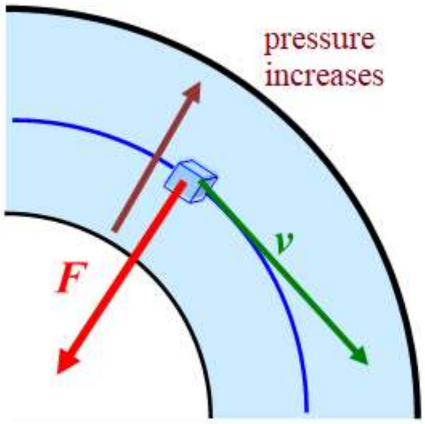

Figure 4. Fluid in a curved tube.

It remains to answer the question: "And why does the wing actually deflect the airflow down?" At a non-zero angle of attack of a wing, or even a flat plate, it is clear that the air flowing under the wing is forced to twist the direction of its movement downward. But above the wing it is not clear; the streamlines could continue horizontally after reaching the highest point. The fact that the streamlines follow the arched upper surface of the wing is the so-called Coandă effect, see for example [4]. Due to its viscosity, the flowing air column entrains the molecules of the surrounding air. If air flows over a solid surface, it creates an underpressure by this drifting and the airstream is sucked towards the surface by the underpressure. If the surface is arched, the flowing air tries to follow the surface, which deflects the direction of its movement as it happens above the wing.

Force for forward movement

Airplanes are provided with forward force by propellers or jet engines. A bird/glider (sailplane) has only wings with which to gain not only lift, but also the forward force. The resultant force of the lift and drag forces points vertically backward during horizontal flight. To keep horizontal flight at a constant velocity, the resultant force must be directed vertically upward or even tilted forward (e.g. to overcome the aerodynamic drag of the plane/bird). The easiest way to do this is to tilt the whole Figure 3. We get the situation in Figure 5. In reality, this means that the flyer with a tilted wing permanently falls slightly obliquely down. And this is how a very long flight can be performed. It is necessary to fall in relation to the air, and in rising air jets such a fall may be horizontal or even ascending in relation to the ground.

Another way is wings flapping – the most common way of flight of a bird. A flap down is actually a short fall with a tilted wing. By suitable setting of the angle of attack, it is possible to obtain the forward component of the force even when the wing moves upwards.

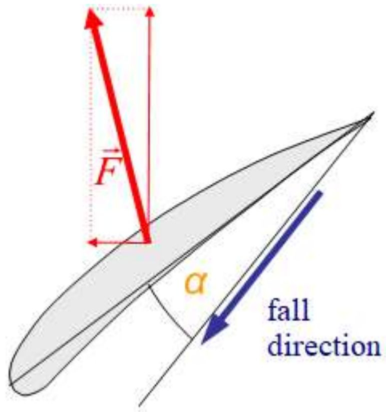

Figure 5. Tilted situation form figure 3.

Induced vortex and V-flight formation

It is known that migratory birds during long flights utilize the so-called V-formation. They use the so-called induced vortices, which arise at the ends of the wings. The cause of these vortices is simple. There is overpressure under the wing and underpressure above. The air spontaneously flows from places with larger pressure to lower pressure points, so at the ends of the wings the vortex from the bottom of the wing rotates upwards according to Fig. 6. Outside the wing there is an area where the air rises up in the vortex and another, flying bird settles into that position. The rising air jet thus makes it easier for the rear bird to fly.

Figure 6. Formation of induced vortex. Taken from [5].

It is stated that the flight in the V-formation extends the flying range by up to 70 %. It is interesting that the flight in the V-formation also helps the bird that flies in front. An impressive depiction of induced vortices can be found in [6].

The so-called induced resistance is associated with the formation of an induced vortex, which increases the overall aerodynamic drag in flight. The rear bird in the V-formation suppresses the vortex of the front bird and thus reduces its flight resistance.

Induced resistance is a significant undesirable phenomenon even in aircraft flight. The designers suppress its effect for example, by bending the wing tips, so-called winglets, see Figure 7.

Figure 7. Winglets at the tips of wings.

Long feathers on the wingtips, which bend upwards in air pressure during flight, have a similar significance for large gliding birds, thus suppressing the induced vortex.

Flight of insects

The flight of insects is in many ways different from the flight of birds and cannot be explained by the lift theories used for birds and aircrafts. Even experimentally determined lift values on a real **static** insect wing give only about a third of the required value.

The flight of insects began to be studied in detail experimentally and theoretically only at the end of the last century and is still not fully understood. The conditions for insect flight differ in two key aspects:

1) **The insect is small** and the fluid flow does not remain similar when scaling. The character of the flow is given by the so-called Reynolds number *Re*, which is defined as

$$Re = \frac{Dv\rho}{\eta}$$

where *D* is the characteristic dimension (for example the size of the body that is being flowed around), v flow velocity, ρ density and η dynamic viscosity.

Thus, a reduction of the dimensions or flow velocity has a similar effect as an increase in the viscosity of the fluid.

2) **The insect flaps its wings quickly during a relatively slow flight**. For example, a bee flying at 2.5 m/s flaps its wings at frequency 250 Hz. Thus, during one flap period, it travels 1 cm. This means that when the wing returns to some position, it returns to the place where the air is still stirred by the previous flap. In addition, with the rapid movement of the wings, the flow is highly non-stationary, which brings new effects. On the other hand, the flow around the wing of a bird or an airplane can be considered stationary, and these flyers still fly through the "fresh" air.

A detailed explanation of insect flight physics can be found, for example, in [7].

During the flight of insects, three important mechanisms have been identified that change the lift and have no analogy for larger flyers.

A) Non-detachment of the vortex from the leading edge (Delayed stall vortex)

As the angle of attack increases, the lift increases significantly at first, but the resistance increases only slightly. At a certain angle of attack, the streamlines no longer follow the upper arched surface of the wing and detach, creating a vortex. Lift drops highly and resistance increases. For large wings, this effect occurs at relatively small angles, about 10º – 15º, and for example, for aircraft, the separation of streamlines is a state of emergency.

The insect is able to fly with much larger angles of attack, up to 45º, and thus gains greater lift. With a very short flap of the wings, the emerging vortex does not have enough time to break away from wings and the air in it still turns in the right direction above the wing, which maintains the necessary lift.

B) Lift as a consequence of rotation

When flapping the wings "back and forth", it is necessary to turn the wing somewhere near the amplitude, so that even when moving back, the wing has a suitable angle of attack. Experimental measurements on an enlarged wing model, which flapped in an oil – a higher viscosity environment show that the lift is highly dependent on the phase shift between flapping and rotating the wings. If the wings rotate in advance of the flap, so that at the beginning of the return movement the rotation of the wing is practically completed, the resulting lift increases. Conversely, with a delayed rotation, the lift decreases. By a small change in the timing of the phase shift, a significant change in lift can be achieved, which gives the insect an opportunity to manoeuvre very well.

C) The use of energy of the previous vortex

Due to their fast flapping, the wings return to the place of the vortices created by the previous flap. The airflow between the vortices uplifts the wing, thus contributing to greater lift.

All three mechanisms are shown in Figure 8.

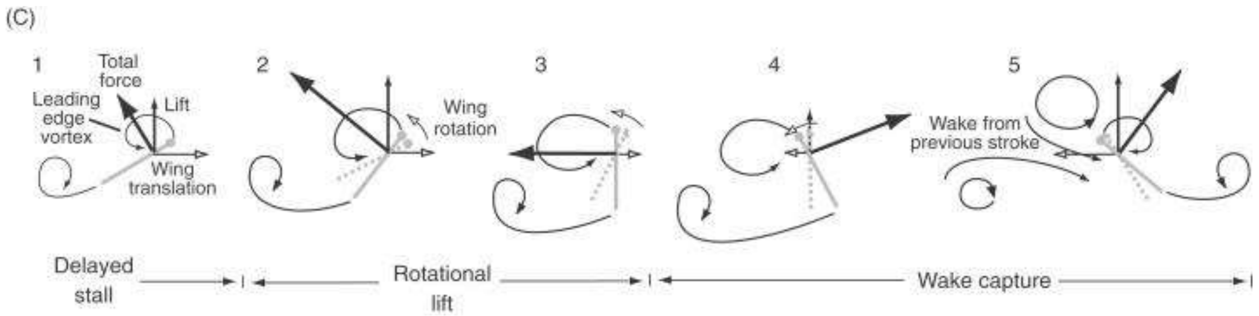

Figure 8. Illustration of the three main mechanisms for increasing the lift: 1 Non-detachment of leading and trailing edge vortices (Delayed stall vortex), 2 Change of lift caused by the rotation of the wing (Rotational lift), 3 Uplifting of the wing from the previous flap (Wake capture). Taken from [8].

The smallest flyers

For the smallest flyers – insects with a wingspan of the order of tenths of a millimetre – the situation is completely different. For very small Reynolds numbers, the drag coefficient increases sharply, while the lift coefficient remains essentially constant; see Figure [9]. It is therefore more advantageous to use drag force instead of lift. The movement of the wings of these flyers resembles rowing, when moving down the wing is set flat, while when moving back, the surface of the wing is tangent to velocity. For this mode of flight, the wing does not need to form an aerodynamic surface similar to the membranous wings of larger insect species. The wings are formed by tassels or cilia, which gave the name to the order of Thysanoptera (Thrips) or the family of Mymaridae (commonly known as fairy flies or fairy wasps). A comparison of the way insects fly with different Reynolds wings can be found, for example, in [9].

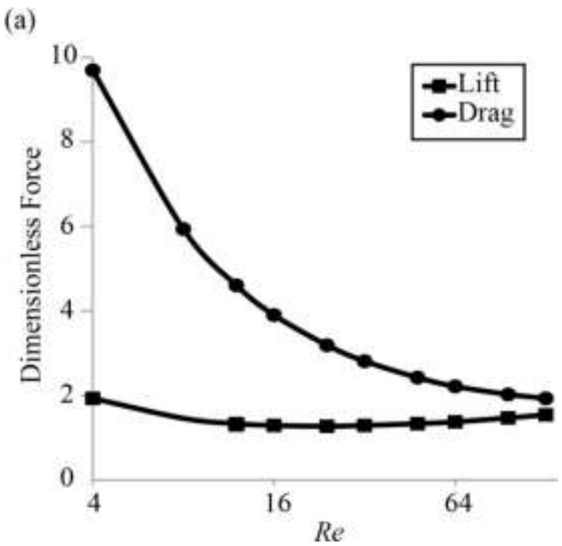

Figure 9. Dependence of the lift force and drag force on Reynolds number. Taken from [10].

Conclusions

Aerodynamics and its application in living nature and technology are an interesting and attractive topic that can bring the teaching of physics closer to real life. It turns out that the formation of lift on the aerofoil can be explained only on the basis of Newton's laws of motion and there is no need for the usual argumentation using Bernoulli's equation. The interpretation is completely straightforward and indisputable, free of weaknesses that can be found in the standard textbook procedure.

The dynamics of a viscous fluid is a very difficult part of physics, yet some of its consequences in describing the flight of birds, insects and even the smallest flyers can be simplified to the upper secondary school level.

Appendix: Bernoulli's equation and its application

A simple consequence of Bernoulli's equation is that there is lower pressure in places with higher flow velocities. However, this conclusion does not hold in general and it cannot be said that there is always lower pressure in a place with a higher flow velocity. The statement is valid only if we consider the situation on a single streamline or if the compared streamlines have the same initial conditions.

If we interpret the Bernoulli's equation as the law of conservation of mechanical energy for an incompressible fluid, we can only use it if the energy is actually conserved. Unfortunately, this is not always respected, and we can often find cases where popular and well-known experiments with flowing fluid are explained incorrectly.

As an example, we will explain an experiment with a ball levitating in a rising airstream (in English texts, this experiment is called the "Bernoulli ball").

Interpretations often argue with Bernoulli's equation that there is a higher pressure in the surrounding still air than in the airstream. When deviating from the air flow, the ball is returned to the low pressure place by the surrounding higher pressure; see Figure 10.

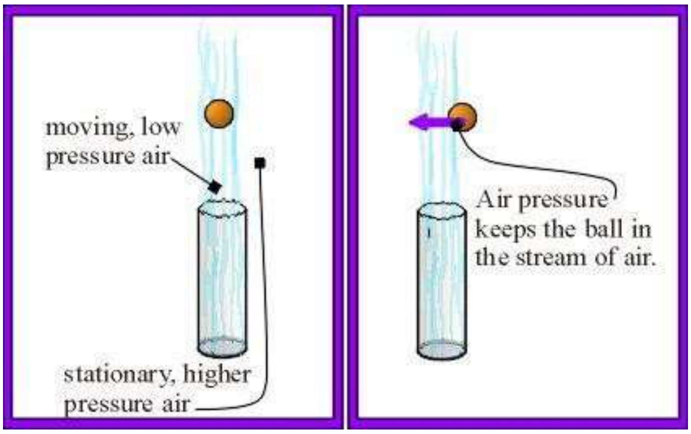

Figure 10. Illustration of a misinterpretation of a levitating ball. Taken from [11].

Here, however, we cannot compare the state of the surrounding still air with the state of the flowing air.

The airflow has been accelerated by the blower and its total energy (per unit volume) is higher than the energy of the surrounding air. In fact, the pressure inside the airstream is the same as in the surrounding environment, which can be very easily verified by a simple experiment with a U-tube.

For a correct explanation, it is necessary to consider the asymmetry of the flow around the ball, which occurs with a relatively narrow beam of flowing air; see Figure 11. We will comment on the situation in the middle of Figure 11.

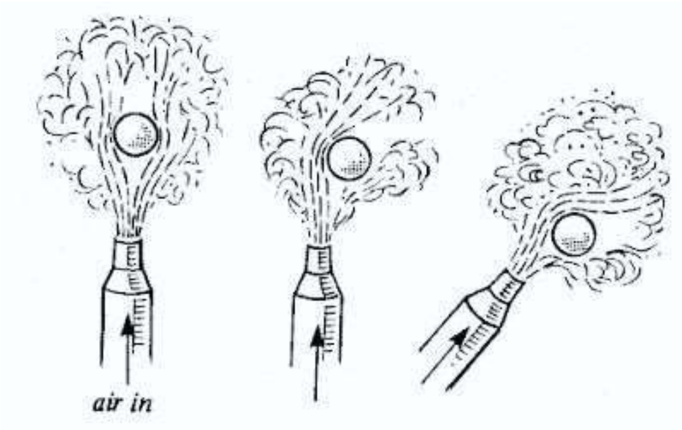

Figure 11. To the interpretation of a levitating ball. Taken from [12].

As the ball deviates from the airstream, the air flows around asymmetrically. On the side where the airstream hits the ball more tangentially, then on the left, thanks to the Coandă effect, the streamlines manage to follow the curved surface of the ball for a longer time, which ultimately leads to a deflection of the airstream to the right. The ball, by its presence, deflected the airflow to the right; it exerted a force on the air to the right. According to the action-reaction law, the air exerts a force on the ball to the left, which returns the ball to the airstream. We would argue similarly in the case of a sloping airstream, in Figure 11 on the right.

References

[1] Bednařík M. a kol., *Mechanika pro gymnázia* [Mechanics for gymnasiums], Prometheus Praha, 1993.
[2] https://www.youtube.com/watch?v=iwA-pD96vxI.
[3] https://www.youtube.com/watch?v=6UlsArvbTeo.
[4] https://www.youtube.com/watch?v=AvLwqRCbGKY.
[5] https://www.boldmethod.com/blog/lists/2017/02/5-factors-that-affect-vortex-strength/
[6] https://www.youtube.com/watch?v=22wcTz4VMJg (from 2:20).
[7] Sane S.: *The aerodynamics of insect flight*, Journal of Experimental Biology 206, 4191-4208, 2004, available from https://www.researchgate.net/publication/9037046_The_aerodynamics_of_insect_flight/link/572f5f1d08aee022975b691f/download.
[8] https://doi.org/10.1016/B978-0-12-374144-8.00109-0.
[9] https://www.youtube.com/watch?v=nXOd0mE0s3c.
[10] Santhanakrishnan A. et al., *Flow Structure and Force Generation on Flapping Wings at Low Reynolds Numbers Relevant to the Flight of Tiny Insects*, Fluids, *3*(3), 45, 2018
[11] https://demos.smu.ca/index.php/demos/fluid-mechanics/94-bernoulli-floating-ball
[12] https://sites.google.com/site/hsa2013ana96/my-pbl-project