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Flying with the right principles at hand: An interactive lab to understand the physical origin of lift

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Summary. — A set of simple laboratory experiments aimed to understand the physical origin of lift is presented. The experiments are realized with simple materials and the use of multimedia reference sources (movies, computer simulations, flow visualizations) is extensively applied in order to put forward otherwise complex fluid dynamical concepts. Emphasis is put in the individuation and correction of commonly found misconceptions or wrong principles regarding, in particular, the concept of pressure, the role of viscosity, the flow behavior around an airfoil, the domain of applicability of fluid dynamical principles, the role of flow curvature in attaining lift and the dynamical mechanisms at the basis of flight.

PACS `01.50.-i` – Educational aids.
PACS `01.50.F-` – Audio and visual aids.

1. – The rights and wrongs of the physical explanation of lift at an elementary level

More than a hundred years have passed since the first flight in the history of humanity and there is still a "debate" about what is the most correct explanation of the physical origin of lift. There is certainly no doubt this is not a problem for aeronautical engineers who everyday design and test new aircrafts using the right principles and the right mathematical and physical tools. However, the problem of portraying a correct though accessible account of this complex subject to the student (high-school or undergraduate level) in possess of a much lighter educational baggage, or even to the layman, is another story. Several misconceptions are implicitly conveyed, wrong (and experimentally falsified) principles are invoked and the risk of getting a confused picture of the problem remains.

Lift can be easily explained using Newton's dynamics principles, provided a correct comprehension of fluid (in this case, air) behavior in its interaction with a solid boundary is achieved. To generate lift we need air speed (relative to the aircraft) which is attained through propulsion, wings, and downwards air's deviation (downwash). To deviate air

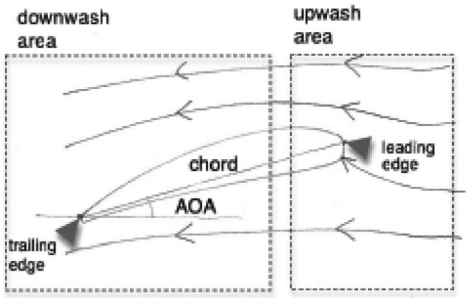

Fig. 1. – Basic parts and fluid movements around an airfoil.

downwards a force must be acting on it. The reaction force to the "bending" force on the fluid, air, is precisely lift which acts on the wing and keeps the aircraft airborne (Anderson and Eberhardt 2009). Simple Newtonian reasoning.

A closer look to this line of reasoning reveals that the origin of the fluid's bending around the airfoil needs to be investigated. What makes the fluid in contact with the wing bend? Here arise the many misunderstandings and wrong statements of the so called "simplified" explanations of lift in terms of the famous Bernoulli's principle. This notoriously wrong account of the origin of lift goes as follows: a) airfoils need to be curved (false) b) air flow separates at the wing's leading edge (see fig. 1) and travels above and below the wing to rejoin at the trailing edge in an equal time lapse (false: this is the so-called "equal transit time principle" which is experimentally falsified). Because of the previous assertions, in order to follow the equal transit time principle, air "needs" to accelerate on top of the wing to catch up with air travelling under it. As Bernoulli's principle states, higher air speed means lower pressure on top of the wing, resulting in the desired upwards net force, *i.e.* lift. The problem is that to achieve this simple explanation two wrong statements are made, Bernoulli's principle is not properly applied and the invoked pressure, transverse to the flow, cutting through several streamlines and responsible of the resultant lift is not the pressure which Bernoulli's principle discuss (which is the static pressure along a streamline) and which may well not relate to the same "constant" in the famous equation for every streamline in the flow (Prandtl 1952).

To begin with, let us remind that Bernoulli's principle applies to an inviscid (zero viscosity) and incompressible flow. While incompressibility is a good approximation for subsonic flow, air is not inviscid. No real fluid is. Fortunately (as it simplifies enormously the calculations), for many applications the hypothesis of an inviscid fluid can be applied. However, the conditions under which this simplifying hypothesis can be done are not discussed neither in the "simplified" explanation with Bernoulli. The truth is that if the air were not viscous, lift could not be attained at all, since viscosity is the only mechanism (together with pressure) by which a fluid can interact with a solid boundary, sticking to it due to the so called no-slip condition. This fact, experimentally verified, asserts that at the solid-fluid boundary the relative velocity of the fluid and the solid surface is zero, *i.e.*, the fluid "sticks" to the surface, slowing down the flow and generating asubstrate where the flow speed grows from zero (at the surface) to the outside flow speed (see fig. 2). This substrate, called boundary layer, is actually very thin for the flow conditions of an aircraft (relative wind-wing speed, air density and wing dimensions) but it is enough to constrain the flow to adhere to the wing and follow its

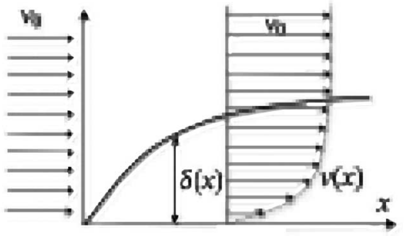

Fig. 2. – Velocity distribution $v(x)$ along the developing boundary layer of a fluid sticking to a solid surface. Its free velocity is v_0.

profile, inducing the downwards air deviation which ultimately explains lift. Outside the boundary layer, where viscosity plays a fundamental role, the fluid can be considered inviscid and there Bernoulli's principle can be correctly applied.

This represents the boundary layer hypothesis, introduced by Ludwig Prandtl in 1903 (Anderson 2005) and which marked the beginning of a new era in the history of fluid dynamics and aerodynamics in particular. It is the boundary layer to force air to follow the wing profile, as it generates a favorable pressure gradient (lower pressure) in the flow direction. And this is why air accelerates. As we know from simple experience, air tends to travel from areas of higher pressure to areas of lower pressure and in doing so it accelerates, as atmospheric circulation demonstrates, for instance. The "simple" explanation of lift using Bernoulli neglects the only thing which is needed for air to accelerate, *i.e.* viscosity.

Emphasizing this is the main scope of this laboratory proposal. For once the role of viscosity is properly taken into account, the simplifying approximations of non viscous flow outside the boundary layer can be done, but a proper understanding of the fluid dynamical mechanisms at the core of the lift have been correctly put forward. Now, we know that air accelerates over the top of a wing because air is slowed down by the boundary layer formation which generates a favourable pressure gradient in the flow direction. But this is not enough. To attain lift we still need asymmetry in the flow and this can be achieved only if the wing and the wind meet at a certain angle, the angle of attack (AOA). This is the angle between the wind's direction and the chord of the wing (see fig. 1), the geometrical line that connects its leading and trailing edges. A symmetric wing with no AOA will not develop lift as the flow encounters and leaves the wing in the same direction. The AOA is necessary for it forces the air to up wash at the leading edge and then downwash at the trailing edge (see again fig. 1), inducing flow curvature. Curving means accelerating, as we know, and since air is sticking to the surface (no-slip condition) a centripetal force is actually acting on the air which is constrained to bend down following the wing profile. This centripetal force generates a pressure gradient (this time acting in the transverse direction) following Euler's equation which in its simplest form can be written as (Faber 2001) $\partial P/\partial r = \rho v2/r$, where P is pressure, r is distance from the center of curvature, v is the flow speed and ρ is density.

Hence, when air encounters a wing with a given AOA, two things happen: air bends and accelerates (both things because viscosity is acting between the air and the wing surface!). Then, the transverse pressure gradient forces air downwards, generating downwash: the reaction to the flow curvature is lift. Flow curvature implies associated forces. Can we measure them easily in the laboratory? The answer is yes. The typical levitating

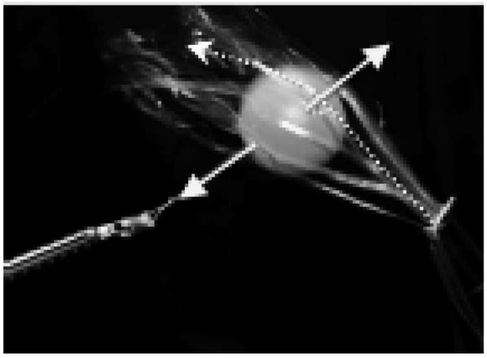

Fig. 3. – A levitating ball is pulled back into the air jet as shown by the scale because of the reaction force to the bending fluid (Coanda effect).

ball experiment on an air jet is paradigmatic of what we have just discussed. Needless to say this fascinating experiment is also typically *bending fluid (Coanda effect)* explained using Bernoulli's principle (Cohen and Horvath 2003) while its simple explanation relies in viscosity (air sticking to the ball's surface), flow curvature (easily visualized using a few cotton threads, see fig. 3) and the corresponding force (easily measurable with a spring scale). It should be remarked, of course, that airplanes do not fly in air jets but are fully embedded by the flow, but this simple experiment is extremely useful to put forward the intimate relation between flow curvature and lifting forces. The levitating ball experiment is a simple example of Coanda effect([1]), the tendency of a fluid jet to adhere to the surface (curved or not) over which it flows (López-Arias, Gratton e Oss, 2009), and it deserves a better physical treatment at an elementary level as it is used in several applications, from heating and cooling devices, to thrust reversal in jet engines or boundary layer control in airfoils (Gerhab and Eastlake 1991) to name just a few. The conclusion is that in order to build a coherent and accessible account of the physical origin of lift, we need to put forward and demonstrate experimentally:

a) The role of viscosity and the no-slip condition (Experiment 1).

b) The Coanda effect as a paradigm of flow interaction with a solid surface, measuring the force associated to the flow curvature (Experiment 2).

c) The measurement of the reaction force to downwash using a simple surface or an airfoil (Experiment 3).

2. – The experiments

2˙1. *Experiment 1: The way fluids behave. Viscosity and the "no-slip" condition.* – Real fluids are viscous. We can walk because of the friction between our shoes and the floor. Similarly, airplanes can fly thanks to air's viscosity (fluid's internal friction). When a fluid flows over a solid surface, a thin layer of fluid (the so called boundary

([1]) After Henri Coanda (1886-1972), romanian aeronautical engineer who discovered this, up to then unknown effect, by serendipity during the test flight of the first jet airplane (Coanda 1) designed by Coanda himself.

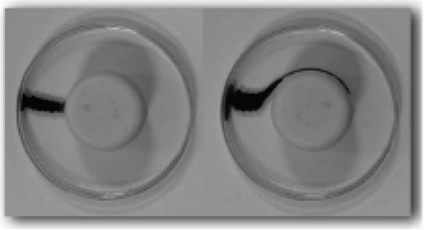

Fig. 4. – A cylinder is rotated while partly submerged in a thin layer of a glycerine. A strip of black ink makes clear the no-slip condition close to the cylinder surface.

layer) sticks to the surface (the so called no-slip condition). In it the relative speed of the surface and the fluid is zero (fig. 4). The boundary layer modifies fluid's flow by viscous stress. Air sticks to the wings of an airplane, modifying its own trajectory and generating "downwash" (air is pushed downwards). An airplane could never fly in an inviscid fluid.

2·2. *Experiment 2: Bending fluids. The Coanda effect*. – A jet of fluid (liquid or gaseous) will stick to a curved surface and follow its profile. At the origin of the fluid's bending lays viscosity and the no-slip condition at the solid-fluid boundary. An equal and opposite reaction to the force that bends the fluid acts on the cylinder (fig. 5). Air is a fluid. Momentum exchange between air and a surface takes place through shear stress and viscosity.

2·3. *Experiment 3: Changing air direction: downwash and the lift force*. – Under appropriate conditions any solid surface will divert a flux of air. The amount of diverted air ("downwash") is directly related to the generated lifting force on the surface. Airplanes and helicopters divert air down for generating the needed lifting force to remain airborne (fig. 6). Such a force corresponds to the added contribution of the pressure field *along* the airfoil surface. Pressure gradient *along* an airfoil determines air's speed in the flow direction.

A very simple set of experiments made with simple materials and the use of multimedia visual aids (Multimedia Fluid Mechanics 2008) can help to build a simple though correct understanding of the physical origin of lift. In the way new concepts of fluid dynamics

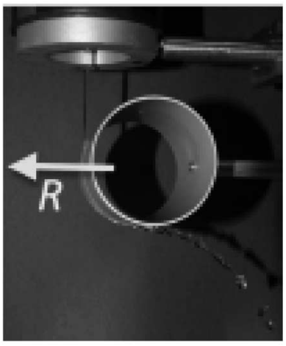

Fig. 5. – Coanda effect of water on a solid cylinder.

Fig. 6. – The double scale experiment: lower weight on the right (lift) higher weight on the left (downwash).

can be introduced which may enlarge the interest of students in an otherwise complex subject which nevertheless has an extremely wide spectra of applications in almost any branch of science. The use of virtual flight simulation software (Try to fly 2009) can help to increase students interest and comprehension of the practical aspects of flight at the light of the new acquired concepts.

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