WIND TUNNEL EXPERIMENTS TO TEACH PHYSICS

S. Le Clainche[1], M. Schlapkohl[2], V. Theofilis[1], H. Wei[1], J.A. Tendero[1], Q. Liu[1], J.M. Pérez[1]

[1] Universidad Politécnica de Madrid (SPAIN)
[2] Deutsche Schule Madrid (SPAIN)

Abstract

Innovative teaching experimental activities for secondary school students have been developed in order to introduce some aerodynamic concepts, with the aim of making science subjects such as mathematics and physics more attractive. Post-graduate students of Universidad Politécnica de Madrid (UPM) and teachers of Deutsche Schule Madrid (DSM) have constructed a small wind tunnel. The main goal has been to provide a tool for secondary school students to become familiar with the scientific method developing curiosity, imagination, initiative, critical thinking and problem-solving skills. Students of DSM have performed wind tunnel experiments, resulting in a successful and amusing experience. The students were able to relate the experimental results obtained with the physic principle of flight, previously explained in class. Evaluations reveal that both, the teacher and the students, considered the experience as interesting and helpful to lead with teaching physics, mathematics and engineering sciences. The teacher observed the strong motivation factor developed for the students to continue learning engineering sciences. Some of the students expressed that this experience had changed their prejudices about physics and mathematics, based only on theoretical approaches.

Keywords: innovation, wind tunnel experiments, principle of flight, fluid dynamics for secondary school.

1 INTRODUCTION AND MOTIVATION

The modern European school is trying to develop a new system of teaching activities suitable for children to get used to mathematics and physics sciences. This leads to show the children the link between the theoretical concepts that they usually learn in the school with some of the physics principles behind the most relevant technological advances, i.e.: the principle of flight.

The principle of flight is a concept linked to fluid dynamics. The high complexity in the background of physics and mathematics behind the fluid dynamics science makes this topic difficult to understand for primary and secondary school students. Therefore, teaching this subject seems far from the possibilities of the teacher. This aspect, leads to develop new teaching activities that make possible the connection between the complex sciences and the possible interests and capabilities of the students and teachers.

Following this idea, Inholland University has designed a small wind tunnel supported by the European project Fly High 518156-LLP-1-2011-1-ATCOMENIUS-CMP. The main goal is to make accessible to secondary school students some of the tools normally related with post-graduate students and the scientific field. In addition, the possibility of doing experiments related to fluid dynamics brings the opportunity of teaching complex physics in an entertaining and practical way.

Universidad Politécnica de Madrid (UPM) and Deutsche Schule Madrid (DSM) collaborated in the construction of the tunnel. Secondary school students from DSM carried out the experimental measurements. The present article describes the experience of the teachers and students gained in the construction and application of the wind tunnel. The article is organized as follows: first, it shows the main theory explained by the teacher in class that describes the physical principles of flight, second it describes the steps followed in the construction of the wind tunnel, finally it shows the main results and comments of the teacher and the students about the experience of applying the wind tunnel as a tool to learn physics.

2 THEORY: THE PRINCIPLE OF FLIGHT

The principle of flight is based on fluid dynamics, a branch of the physics that deals the science of fluids in motion. This complex discipline includes aerodynamics, which study the air and gases in motion, and hydrodynamics, which study the liquids in motion. The equations describing the motion of fluids are the Navier-Stokes (NS) equations, a set of differential equations whose foundational axioms are the conservation laws: conservation of mass, conservation of momentum and conservation of energy. The high complexity of these equations lies on the need of an extensive knowledge in mathematics and physics to understand them. However, if special assumptions are considered, such as steady laminar incompressible flow, the NS equations can be simplified giving rise to the possibility of explaining the principle of flight to secondary school students.

2.1 Introduction to fluid dynamics. Basic concepts

As it was previously mentioned, fluid dynamics studies the science of fluids in motion. A fluid is a substance that is continuously deformed under an applied shear stress. Some examples of fluids are the air and the water. Fluids can be characterized by their temperature, density and viscosity.

Fluid dynamics studies the fluid in motion (flow) surrounding a certain body, for example the wing profile of a plane, a cylinder or a car. In similar conditions, the performance of the flow surrounding these three bodies will be different in each case. Thus the flow behavior depends, not only on the fluid characteristics, but also on the shape of the selected body. Additionally, it is possible to change the flow performance increasing/decreasing the flow velocity.

The flow performance can be classified as laminar, turbulent and transitional:

- *Laminar flow* occurs when there is no interaction between the flow layers, i.e.: when the fluid flows in parallel layers. We can find laminar flow in the case of the water dropping from the tap, or in a waterfall, before the water drops. Laminar flow is associated with low velocity and high viscosity flow.
- *Turbulent flow* occurs when the flow layers are strongly mixed and the flow is not parallel anymore. We can find turbulent flow in a waterfall, when the flow interacts with the ground. Turbulent flow is associated with high velocity and low viscosity flow.
- *Transitional flow* occurs in the transition from laminar to turbulent flow.

Figure 1 shows the differences between laminar and turbulent flow.

Figure 1: Laminar and turbulent flow in a waterfall.

2.2 Forces on the airplane

Based on the Newton’s laws 'to every action there is an equal and opposite reaction', it is possible to distinguish difference forces, in equilibrium, interacting simultaneously in the airplane at level flight. These are: thrust, drag, weight and lift (see Figure 2). The point of equilibrium of the forces corresponds to the center of gravity of the plane.

The thrust moves the airplane in the direction of motion. This force is also known as propulsion and is obtained by propellers or jet engines. The drag is the force opposite to the thrust that slows the aircraft. This force is generated by the friction and by the differences in air pressure. The weight is the force generated by the gravity and is a function of the mass of the body. Finally, the lift is the force that occurs in opposite direction to the weight that holds the airplane in air.

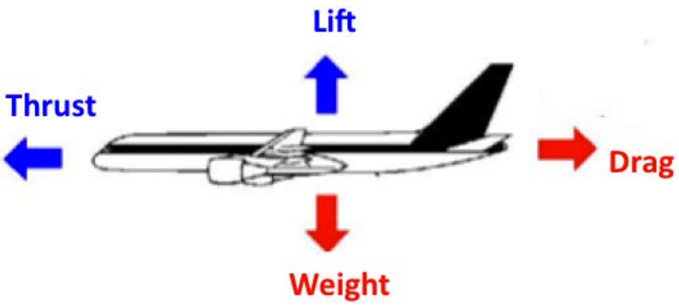

Figure 2: Forces acting on the airplane at level flight.

2.2.1 Lift force, Drag force and angle of attack

The effect of flying is the consequence of the rise of the lift and drag forces. Variations on these forces depend on the flow conditions (flow density, viscosity and velocity), the body shape (body surface) and the angle of attack. This angle measures the inclination of the body respect to the incoming flow (see Figure 4).

In aerodynamic bodies, the lift increases with the angle of attack (AoA) of the body up to the 'stall' conditions (maximum value of lift). Then, if we keep increasing the AoA, the lift starts to decrease. At a certain point, this effect may lead to critical conditions in the airplane and the pilot could lose its control. The lift also increases with the flow velocity.

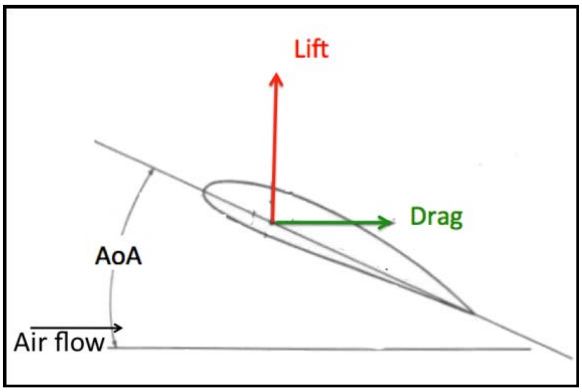

Figure 4: Angle of attack measured in the aircraft.

In Figure 4, the flow interacts with the body and is divided in two parts surrounding the wing profile (upper and lower sides). As seen, the upper length of the wing is bigger than the lower one, so the flow goes through a longer distance. Consequently, in order to the flow particles arrive at the same time to the same position (conservation of mass), the flow velocity needs to be higher in the upper sideof the wing than in the lower side.

Additionally, due to the conservation of momentum law, the total pressure, which is the sum of static and dynamic pressures, must be constant (Bernouilli's principle). On the one hand, the dynamic pressure increases with the velocity. On the other hand, the static pressure generates the force. Since the total pressure must keep constant, when the velocity increases (the dynamic pressure increases), the static pressure decreases.

As consequence of the conservation laws, the static pressure is lower in the upper side on the wing than in the lower side. These forces balance, represented in Figure 4 as lift force, produces the effect of flying (take off of the air plane). Finally, the forces interacting at level flight are in equilibrium.

3 METHODOLOGY: WIND TUNNEL, EXPERIMENTAL TECHNIQUES AND TEST MODELS

In this section it is explained the performance of the construction of the wind tunnel, the experimental techniques used and the test models that has been selected. On the one hand, the wind tunnel was designed to be constructed by people not specialized in this kind of work. Therefore, teachers or (post) graduate students can easily construct it. On the other hand, teachers of the DSM school have designed most of the experimental techniques used. So, the materials employed are not very sophisticated, making the wind tunnel experiments accessible to all. Finally, the test models selected were made using a 3D printer, o directly bought on a toyshop.

3.1 Wind tunnel construction

One of the main tools used in aerodynamic research is the wind tunnel. A wind tunnel consists on a tubular passage in which the air is moved by a powerful fan that leads to study the flow past solid objects using different experimental techniques.

UPM and DSM collaborated in the construction of a small wind tunnel, designed by InHolland University. The tunnel is an open tunnel of 1.5 meters long. It is composed by three pieces: the metal diffuser, the test section, of 15 x 15 x 40 cm, and the contraction (see Figure 5). The diffuser is joined to a fan. The fan sucks the air upstream the contraction, so the air goes through the wind tunnel. If we introduce a body in the test section when the fan is connected, it is possible to study the air motion around such body (aerodynamics).

InHolland University provided a set of wood pieces, defining the test section and the contraction, and the design of the diffuser. A company made the metal diffuser.

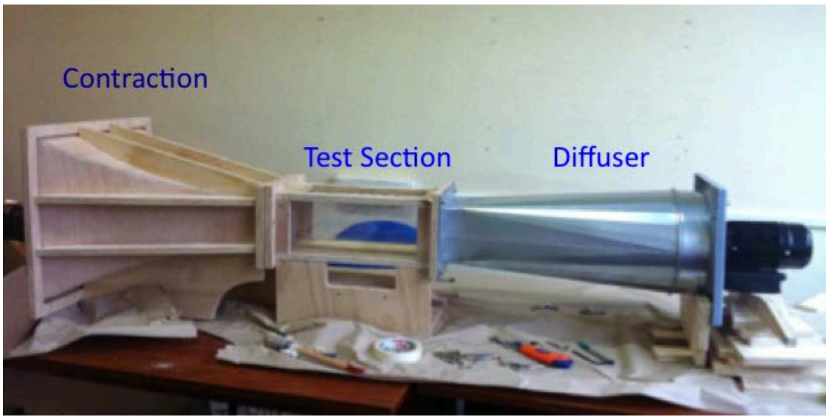

Figure 5: wind tunnel.

The fan and the controller (to control the wind velocity) were acquired in a company specialized in industrial fan. The chosen fan was the AXIAL 2-250M 45, with a diameter of 250 mm, a flow of 3.010 m^3/h and power 0.25 kW.

In the test section it was necessary to add a lid for the upper part in order to manage to change the test model. The material used for the windows of the test section was methacrylate. The assembly between the windows and the wooden frames was carried out with two screws. Figure 6 a) shows the test section in detail. Figure 6 b) shows the assembly of the methacrylate window and the wooden frame.

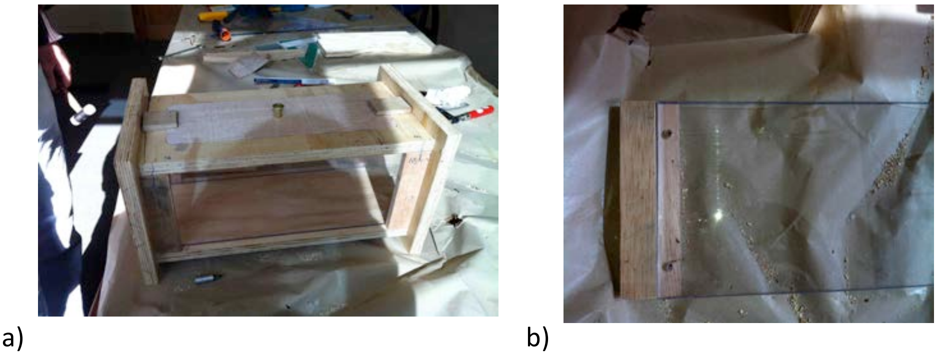
a) b)

Figure 6: test section: a) general view, b) window.

The wooden pieces were put together to make the contraction. In order to avoid strong discontinuities, the wooden frames were previously polished and painted. Finally, all the parts of the tunnel were assembled using silicone and screws.

3.2 Experimental devices

Once the wind tunnel was constructed, different techniques were used to perform the experiments in the wind tunnel: flow visualizations and velocity, temperature and pressure measurements using electronic cells. All the experimental setup has been made with materials not very sophisticated, cheap and accessible to all.

3.2.1 Flow visualizations

The set up of these experimental techniques was carried out in the DSM school. Flow visualizations were performed using tufts, smoke dispersion and laser reflection. The flow motion was recorded with a video camera.

- *Tufts*: The material used for the tufts was wool thread. The location of the wool threads was upstream the test section.
- *Smoke dispersion*: It was possible to generate smoke streams by means of burning incense upstream the wind tunnel, close to the contraction. A fog machine was also used.
- *Laser reflection*: Two laser pointers, with two different colors, were used to perform the flow visualizations. The laser beam was spread using two optical lenses. To perform the experiments, the light was turned off and the video camera recorded the fluid laser reflections on smoke stream.

3.2.2 Electronic cells

InHolland University provided an electronic kit suitable to measure pressure, temperature and forces. They also provided a detailed manual with the electronic devices that were composing the kit. So in case that any device fails, it is possible to easily create your homemade electronic kit.

The kit contained specific electronic cells, useful to measure atmospheric pressure, atmospheric temperature, differential pressure and forces. The balance measurements were carried out by two gauges, which measured the forces in two perpendicular directions. These two forces correspond to the lift and drag forces of the test body.

The electronic kit was connected to the PC. Phyton software was previously installed in order to detect the experimental cells. Additionally, InHolland University provided a Visual Basic program to perform the experimental measurements.

3.3 Test model

The experiments were performed to study the flow around a wing profile (NACA0015), a cylinder and a car model. The wing profile and the cylinder were designed using a CAD program and built with a 3D printer. The car model was acquired in a toyshop. Figure 7 shows the setup of the wing profile in the wind tunnel and the electronics devices.

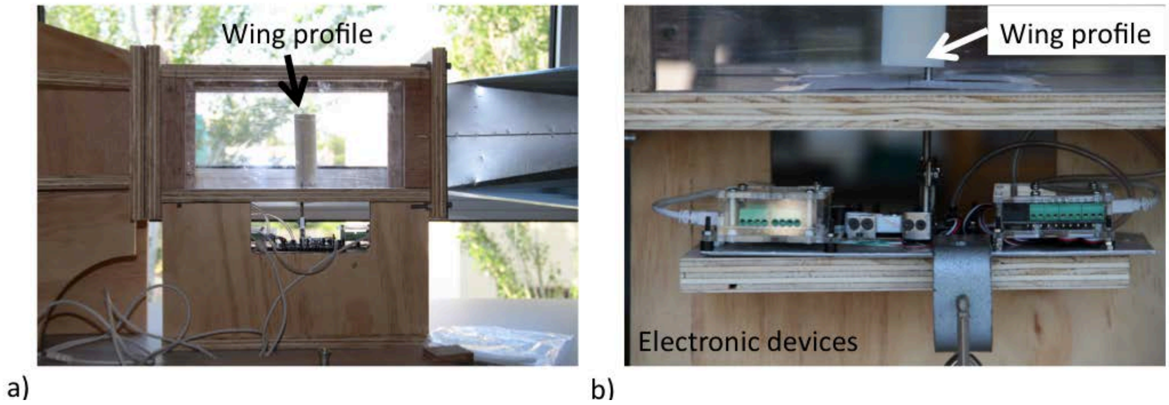

Figure 7: Wind tunnel setup. Wing profile and electronic devices.

4 APPLICATION: WIND TUNNEL EXPERIMENTS IN THE SECONDARY SCHOOL

Secondary school students performed experimental measurements in class under the supervision of their teacher. The students employed a total of 15 hours of the sciences class to perform these experiments. They consisted on flow visualizations and experimental measurements of flow velocity, pressure and forces. Additionally, with the aim of introducing to the youngest students in the scientific field, the teacher performed some flow visualizations in class for the youngest students of secondary school.

As first step, flow visualizations were performed to explain to the students the differences between laminar and turbulent flow and their relation with the flow viscosity and velocity. The students were able to visualize the flow streamlines using smoke visualizations, tufts and laser visualizations. Figure 8 shows some students doing the experiments in DSM school.

Figure 8: DSM school students doing wind tunnel experiments.

First, smoke visualizations were performed to study the flow around a car model. Figure 9 shows the evolution of the smoke *streamlines* (lines defining the trajectory followed by the flow particles) surrounding the car when the flow velocity is increased. It is possible to identify a transition from laminar to turbulent flow and the evolution of the *boundary layer* (the flow bordering the body, interface).

Figure 9: Smoke visualizations. From left to right: from low velocity to high velocity.

Secondly, the streamlines were also visualized in the flow surrounding a car using tufts. In Figure 10 it is possible to distinguish the differences between laminar and turbulent flow and the flow boundary layer.

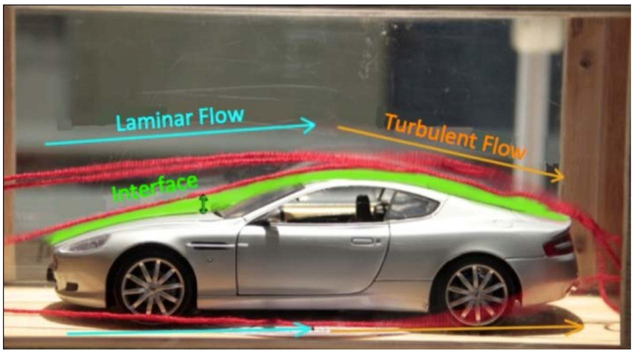

Figure 10: streamlines visualizations using tufts.

The same technique was used to study the flow around a cylinder. Figure 11 shows the streamlines evolution when the velocity is sequentially decreased. As seen, upstream the cylinder the flow is laminar and downstream the flow detaches the cylinder. When the velocity decreases, the flow detachment is modified. In the cases at lower values of velocity it is possible to see the streamlines reattachment downstream the body. The size of the eddies formed downstream the body is bigger at lower velocity values, so it is possible to visualize such eddies with the tufts.

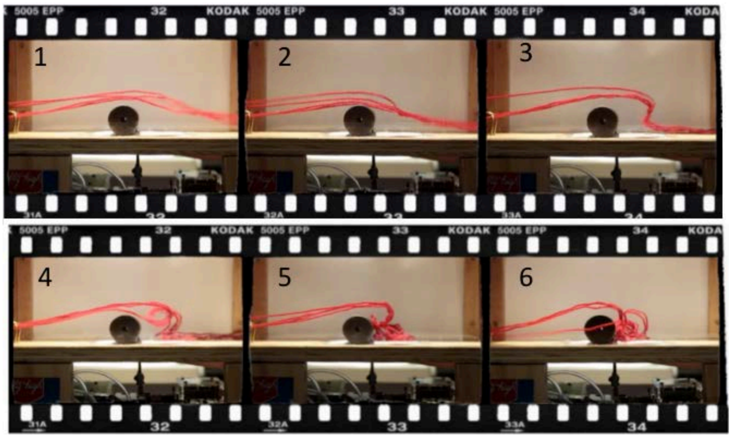

Figure 11: streamlines visualizations using tufts to study the flow around a cylinder. From 1 to 6: flow velocity is reduced from 11 m/s to 4.5 m/s.

Finally, two laser pointers were used to visualize the flow around a wing profile. To perform this experiment it was necessary to record the laser reflections on smoke stream. The smoke was generated using a fog machine. Figure 12 shows an example of this visualization. Depending on the motion of the laser reflection, it was possible to distinguish two different flow regions surrounding the body: laminar flow, upstream the profile, and turbulent flow, downstream the profile.

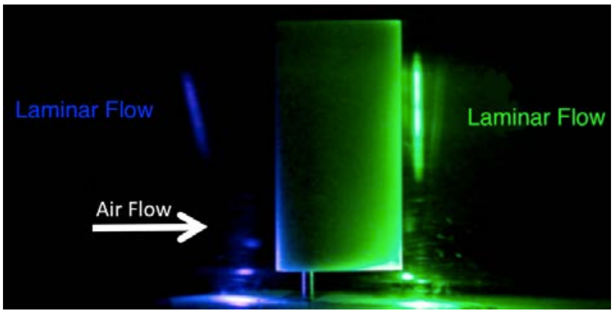

Figure 12: flow visualizations using laser pointers to study the flow around a wing profile.

Once the students were able to distinguish the differences between laminar and turbulent flow, the principles of flight were explained in class with the help of the wind tunnel measurements and the equations explained in Section 2. The experiments were performed to study the flow around a wing profile. The velocity, pressure and forces (lift, drag) were measured using the electronic devices.

First, the students studied the flow around a wing profile at different incoming flow velocities. They were able to relate the variations in velocity and pressure with the conservation laws. Secondly, they measured the lift and drag forces in the wing profile maintaining the velocity whilst varying the angle of attack. They observed the influence of the velocity, the pressure and the AoA over the lift force. They understood the principles of flight, the concept linked to stall conditions in the airfoil and the possible consequences of flying at very high angle of attack. As seen, the lift increases its value up to reach stall conditions (maximum value). Then, the lift decreases. Figure 13 shows the variation of lift coefficient with the angle of attack measured by the students.

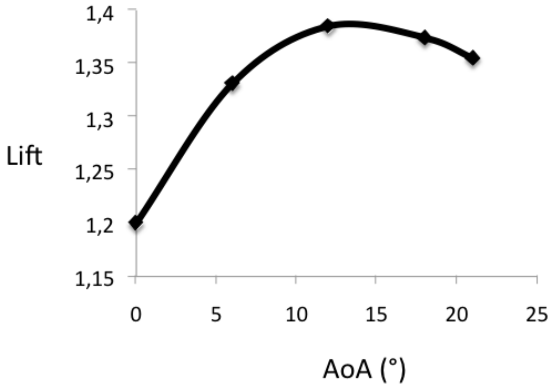

Figure 13: Lift as function of angle of attack in a wing profile.

It should be noted that all the experiments carried out by the students validate the theory. After doing the experiments, the students wrote a report explaining the results obtained and went a bit more in depth with the physical problem behind these experiments. The students learnt the methodology needed to follow their studies in the scientific field and were able to apply the theoretical concepts learnt in class to real problems.

Some videos containing additional material to the experiments showed in this article can be found in the following links:

- http://www.youtube.com/watch?v=hIP_Lz_EHvU
- http://www.youtube.com/watch?v=_HEDkQj-Yrk
- http://www.youtube.com/watch?v=j79m8S1K0cM

5 IMPROVEMENTS TEACHING PHYSICS: TEACHER AND STUDENTS

The main goal of doing wind tunnel experiments is to facilitate the meaningful and functional learning. The possibility of relating the theoretical concepts learnt in class with real practical problems leads to develop the ability of comparing and analyzing problems. The students also get closer to the scientific field, learning the need of being rigorous and systematic when it comes time to do an experiment. The inventiveness and the handmade ability are some of the skills that the students develop with the experimental setup.

After this experience, the teacher observed a strong motivation factor developed for the students to continue learning mathematics, physics and engineering sciences. He observed major attention and interaction in the subsequent physic classes. Some of the students argued that the experience had changed their mind about the math and physic subjects. These subjects were considered as annoying, tedious and even not useful for some of them.

Evaluations reveal that both, the teacher and the students, considered the experience as interesting and helpful to lead with sciences subjects. Providing a creative and interactive environment seems to be fruitful and positive to attract the students attention towards the engineering scientific field, to increase motivation in school, to open the mind of students and teachers and to develop new critical thinking and problem-solving skills.

ACKNOWLEDGEMENTS

Support of European project Fly High 518156-LLP-1-2011-1-ATCOMENIUS-CMP is gratefully acknowledged. Some of the experimental results were provided by the DSM students Diego Fernández, Alberto Huerta and Ignacio Quesada.

REFERENCES

[1] Tony Arts, Cem Asma, Patricia Corieri, Nicoletto De Pascale, Claudia Dobre, Tania Kirmse, Michel Riethmuller; How does an airplane fly? Basic principles Environmental and safety issues; ISBN 978-2-87516-01, von Karman Institute for Fluid Dynamics, 2010.

[2] Thomas F.; Fundamentals of Sailplane Design, College Park Press Maryland, 1999, ISBN 0-9669553-0-7.

[3] Fly High Teacher's Guide for Secondary Lower and Upper Level. July 2013.

[4] Air Cadets, the next generation. Flight. Volume 2: Principles of flight. ACP 33.