Wind tunnel Aerodinamical Measurements*

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The aim of this project was to understand the fundamental aerodynamics' principles within an engineering approach. Wind forces acting over bodies are usually defined in terms of the aerodynamic - lift and drag - coefficients, which can be easily measured in a wind tunnel. Aerodynamic coefficients measured in models are representative as long as they are obtained in the same flow regime than the body under study. Flow regimes are characterized by the Reynolds' number, *Re*[a]. Most of the bodies of engineering interest move in a turbulent regime at a very high *Re*. Thus, wind tunnel measurements must ensure a high enough *Re* value to be representative. We determined the coefficients by different experimental methods, in order to compare them and reveal their limitations. Finally, the aerodynamic efficiency of the different studied bodies is compared.

I. INTRODUCTION

Planes are able to fly thanks to the difference between the pressures above and below their wings. The basic principle is that air must flow over and under the airfoil and, depending on its shape, in order to fulfill Navier-Stokes equations - the fundamental conservation equations for motion of viscous fluid substances - air exerts a net force on the shaped airfoil. For a basic introduction for aerodynamics see for example [1]

Such force can be represented as the sum of two perpendicular forces. The one which is parallel to the motion's direction is called *drag* whereas the perpendicular to it is called *lift*. In aerodynamics, *drag* represents the resistance exerted by the fluid to the movement of the object and *lift* could be understood as the force which helps flying compensating the weight - aircrafts - or increases the adherence by producing downforce - cars -.

Both *lift* and *drag* depend on the object shape. The main factor is the effective area that both forces "see". Due to their perpendicular nature, these areas are different, allowing us to either increase or decrease the forces as desired. Here, it is of high interest the role played by the *angle of attack, AoA*, defined as the angle between the airfoil's chord and the direction of motion. It is really relevant because *lift* increases proportionally to *AoA* until a limit value where it drops dramatically. This limit is called *critical angle of attack* or *stall angle* and its is deeply recommended to work with *AoA* well below it in order to increase safety of the flight.

However, there are other undesired sources of losses which affect flight efficiency, mainly turbulence. Turbulence is a mechanism which transforms mechanical energy into heat. Macroscopically turbulence is described as chaotic property changes such as low momentum diffusion, high momentum convection, and rapid variation of pressure and flow velocity in space and time. The aerodynamic design tries to maximize the aerodynamic efficiency and reduce losses such as turbulence. Thus the shape of aerodynamic bodies must be carefully designed and, furthermore, the interest to reduce turbulence production explains the absence of sharp angles in aerodynamic designs.

To sum up, these are the basic aerodynamic properties studied in this project. The procedure taken in this article is firstly to explain the experimental design and then show the results obtained followed by a discussion.

II. EXPERIMENTAL

Measurements were performed in an Eiffel type[2] open wind tunnel[3]. The test section has a length of 60 cm and a cross-section of 40x40cm^2. The wind flow is created by a turbine moved by an AC motor which works in a frequency range between 0Hz and 50Hz. The maximum wind velocity in the test section, at a supply frequency of 50Hz, is around 33 m/s. All experiments done at a fixed velocity, were performed at a supply frequency of 30Hz.

The wind tunnel is provided of a AFA3 TQEquipment three-component balance. The model can be fitted to the balance axis, and three force gauges allow us to determine the *lift*, *drag* and *pitch* produced by the air flow on the test model.

The features of the studied test models are:

a. Wing-shaped model. Wingspan: 300 mm. Chord: 150 mm. Weigth: 2 kg. This airfoil has horizontal symmetry. It is provided with 20 pressure sensitive probes along its chord, on both upper and lower surfaces, numbered and set to fixed positions in order to enable the user obtain pressure information.

b. Cylinder. Nominal diametre: 63.5 mm. Nominal length: 300 mm. Weigth: 1 kg. There is a single hole for pressure data acquisition at the cylinder center.

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* Done to an airfoil, a cilinder and two cars. Test of the turbulences.

[a] The Reynolds' number is defined as the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.

c. Cars. Front effective surface of BMW: $41.5cm^2$ and Front effective surface of Porsche: $32.5cm^2$. Two different car models were studied to compare their aerodynamic behaviour. To make the measurements, cars were placed on a platform connected to the balance system, whose aerodynamic response was previously known. Each different car model was studied with the windows open and closed and the results were compared.

Two different anemometers were used:

d. Pitot static traverse tube. Instrument used to measure fluid flow velocity at a fixed point of the space, through the measurement of static and dynamic pressures. Its spatial resolution is 0.01mm.

e. Hot-wire anemometer. This instrument is more accurate than the pitot tube. It has a very thin wire, made of tungsten, that is heated with an electric current. Air flowing around it has a cooling effect, so through the temperature of the wire the speed of the air can be determined. As the resistance of the metal depends on its temperature, the voltage detected between wire ends can be easily related to the air velocity.

III. RESULTS.

A. Wing-shaped model

a. Lift and drag coefficients. The *lift* and *drag* forces were measured for each angle of attach at increasing turbine rotation frequencies. Then *lift* and *drag* coefficients were calculated as

$$C_L = \frac{d\frac{F_L}{S}}{dP_D} \tag{1}$$

$$C_D = \frac{d\frac{F_D}{S}}{dP_D} \tag{2}$$

where F_L and F_D are the *lift* and *drag* forces, S is the surface of the airfoil and P_D the dynamical pressure, obtained from the Pitot probe.

The obtained results are shown in Table I and plotted in Figure 1.

AoA	C_D	C_L
0°	0.045	0.070
2°	0.048	0.149
5°	0.058	0.332
10°	0.090	0.611
15°	0.193	0.709
20°	0.325	0.716
25°	0.411	0.703
30°	0.466	0.675

TABLE I. Table of *lift* and *drag* coefficients .

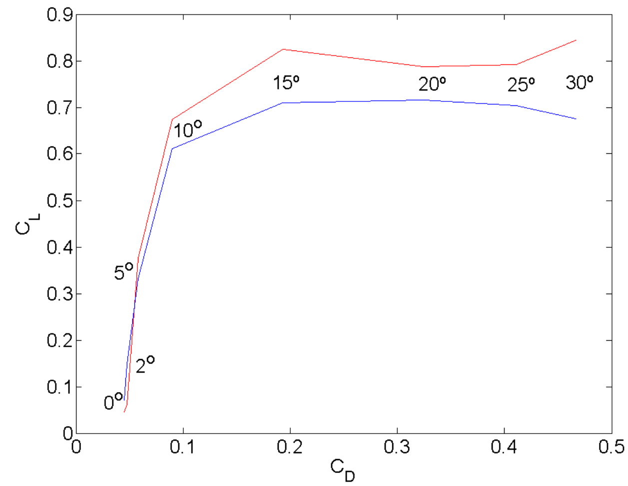

FIG. 1. Drag Polar of the airfoil. The blue line refers to the coefficients got using eq. (1) and (2) and the red one refers to the coefficients obtained with eq. (5).

b. Pressure map. A pressure map was measured and pressures are integrated along the wing-shaped chord in order to know the total pressure for each AoA using eq.(3) and eq.(4):

$$P_i = \int_0^L Pi(x)dx \tag{3}$$

$$P_T = P_{inf} - P_{sup} \tag{4}$$

Note that with the total pressures, one can calculate the *lift* coefficient per AoA again using eq. (5):

$$C_L = \frac{|P_T|}{LP_d} \tag{5}$$

where L is the chord length. The result of using eq.(5) is plotted also in Fig. (1) with a red line.

B. Cylinder

a. Drag coefficient. Using the same procedure than for the wing-shaped model, the drag coefficient is calculated for different velocities using eq.(2) taking as a reference surface the front surface of the cylinder (S). For the case of the cylinder, the *drag* coefficient is 0.833.

b. Pressure map. Rotating the cylinder, the pressure map was measured and it is shown in Figure (2).

From this data we can compute the *drag* coefficient using the following equation:

$$C_D = \frac{P_X}{2RL} \tag{6}$$

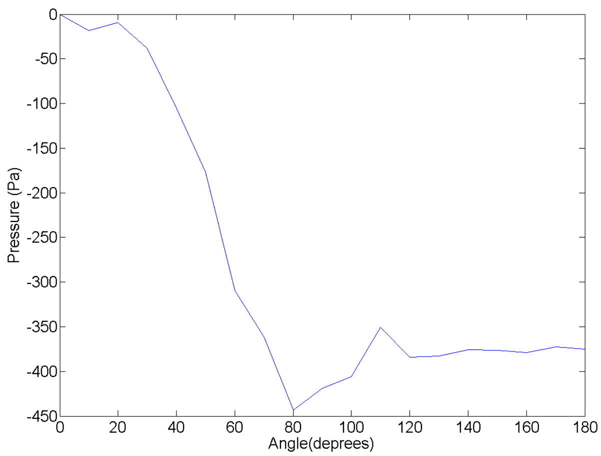

FIG. 2. Pressure measured in the center of the cylinder at different angles. Pressure is referenced to atmospheric pressure, that's why all values are negative.

where P_X is the sum of pressures in X-axis, R is the nominal radius of the cylinder and L is the nominal length. Using this method, the *drag* coefficient is 0.632 whereas with eq. (2) the result is 0.833.

C. Cars

Drag and *lift* coefficients have been measured for two different car models. Each model has been studied with the windows open and closed in order to compare the aerodynamic efficiency. In Table (II) the obtained results are shown.

$Coefficients$	BMW	$Porsche$
$C_{opendrag}$	1.233	0.948
$C_{openlift}$	0.139	0.082
$C_{closedrag}$	1.036	0.912
$C_{closelift}$	0.194	0.255

TABLE II. Table of *drag* and *lift* coefficients of the cars.

Figure (3) and Figure (4) show the linear regression used to compute the *drag* and *lift* coefficients; the uncertainties in each measure are represented. Coefficients with the open and closed windows can be easily compared in these graphs.

D. Turbulence

When the wind collides with the fixed cylinder, it has to change its direction in order to advance. This change of direction, related to the drag resistance of the cylinder, implies a variation in the wind velocity and pressure around the cylinder. If this change is abrupt, turbulences might appear.

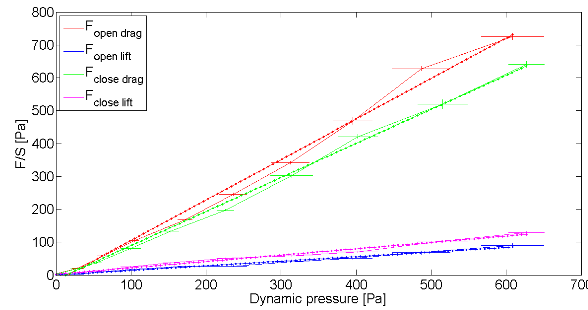

FIG. 3. Calculation of BMW coefficients.

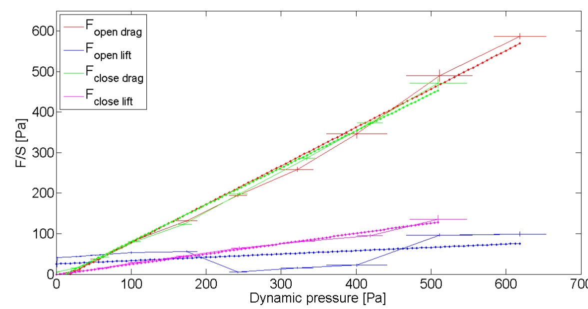

FIG. 4. Calculation of Porsche coefficients.

The velocity of the wind after the cylinder has been measured with two different instruments with their own advantages and limitations. The obtained results are plotted in Figure (5) for pitot tube and in Figure (6) for the hot wire anemometer.

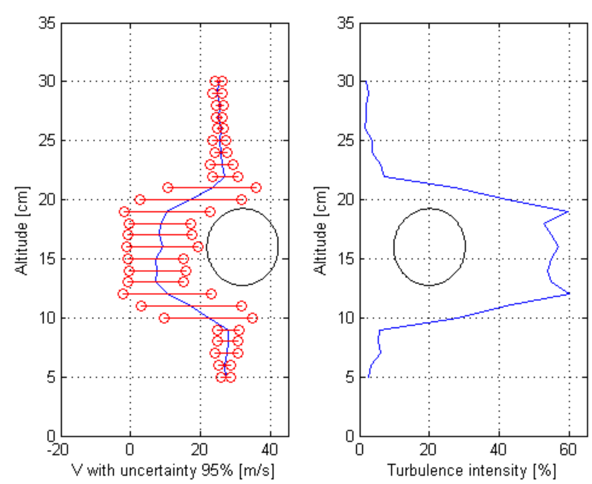

FIG. 5. Velocity and turbulence intensity measured with the hot wire anemometer

This change of velocity relates to the drag force of the cylinder that can be calculated through the difference of

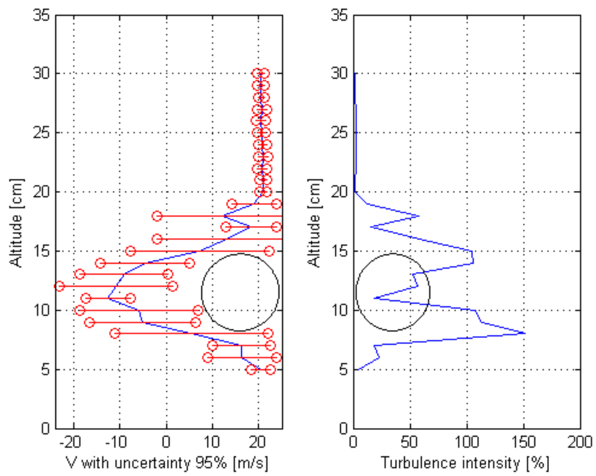

FIG. 6. Velocity and turbulence intensity measured with the Pitot's tube

linear moment per unit time of the wind with eq.(7):

$$F_D = \dot{P}_o - \dot{P}_f \tag{7}$$

where $\dot{P}_o$ and $\dot{P}_f$ are the linear moments per unit time of the wind before and after the cylinder.

The obtained values for each measurement instrument are shown in Table (III):

$Instrument$	$Dragforce(N)$
$Pitot$	21.8
$Hotwire$	25.5

TABLE III. Drag force for each instrument

IV. DISCUSSION AND CONCLUSIONS

a. Wing-shaped. First of all, as it can be seen in the Figure (1), for small AoA , the *drag* coefficient grows slower than the *lift* one. On the contrary, for large AoA, the *drag* coefficient grows quicker than the *lift* one. Moreover, the *lift* coefficient starts to decrease when an AoA of 20 degrees is reached, this is the *critical angle of attack*. That is an important issue of airplanes, as they can't fly with angle of attack higher than the critical angle because the lift decreases dramatically.

b. Cylinder. Notice that in Figure (2) there is a minimum at roughly 90 degrees because, indicating that at this point the tangential speed is maximum.

c. Cars. As expected the *drag* coefficients with open windows are higher than with closed windows in both car models. The cause is easy to understand, when the windows are open, the aerodynamics of the cars becomes worst, some extra turbulence is produced and then the *drag* coefficient increases. On the other hand, *lift* coefficients have a completely different behavior, they have higher values with the closed windows than if they are open.

In car design it is interesting to reduce *drag* and *lift* coefficients in order to have a lower air resistance and a higher traction onto the way. Also in the daily use of cars is important to reduce *drag* coefficient because a lower *drag* coefficient reduces the energy consumption.

d. Turbulence. As expected, both measurement instruments have their own advantages and drawbacks. Pitot tube's measure changes with the direction of the wind, giving information about possible turbulences or vortices, as it can be seen with the negative values of the velocity after the cylinder. However, the turbulence intensity obtained with this instrument is not completely reliable because the dispersion of the values is not only due to the turbulences but also to the pitot tube's limitations. The hot wire anemometer is more accurate than the pitot tube, resulting in more reliable measurements for laminar flow regime. However, due to the measurement technique, it cannot distinguish the direction of the wind causing some troubles if the wire is placed in a vortex in a turbulent flow.

Consequently, both instruments are able to qualitatively measure the turbulence phenomenon. Nevertheless, when it comes to a quantitative measure, both instruments give different results. These results are of the same order of magnitude though, as can be seen in Table (III).

ACKNOWLEDGMENTS

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[1] Fundamentals of Aerodynamics, 5th Edition, John D. Anderson Jr., ISBN: 978-0073398105, McGraw-Hill, 2007.

[2] Low-Speed Wind Tunnel Testing, 3rd Edition, Jewel B. Barlow, William H. Rae, Alan Pope, ISBN: 978-0471557746, Wiley, 1999.

[3] Wind tunnel of Escola d'Enginyeria de Telecomunicaci i Aeronutica, Campus del Baix Llobregat, Castelldefels, Catalunya