DESIGN AND PRELIMINARY TESTS OF A THREE-COMPONENT BALANCE FOR WIND TUNNEL

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Abstract. *The knowledge of the aerodynamic forces and moments on two-dimensional airfoil sections is extremely important for the design of airplane wings, turbomachine blades and other lifting surfaces. The flow around an airfoil depends mainly on its geometry, angle of attack and Reynolds number, as well as surface roughness and freestream turbulence. Because of all these effects, it is very difficult to calculate accurately the aerodynamic loads on an airfoil, even with the powerful computer and advanced numerical models available nowadays. Therefore, it is important to measure these loads accurately in a wind tunnel in order to have detailed information about the aerodynamic characteristics of a given profile. In this paper we present the design and preliminary tests of a three-component balance for low-speed wind tunnels. The balance is able to measure the lift and drag forces and the pitching moment that develop on an airfoil as a function of the angle of attack when this airfoil is placed in the test section of a wind tunnel. The aerodynamic loading is measured from the angular deflection of load cells instrumented with strain gages. The strain gage voltage output is input to a data acquisition system and processed on a specific software developed on a LabView platform to produce graphs of lift, drag and pitching moment coefficients as a function of the angle of attack. Preliminary tests on a four-digit NACA profile is carried out to evaluate the balance performance.*

Keywords*: balance, wind tunnel, airfoil, aerodynamic loads, experimental measurements.*

1. INTRODUCTION

The knowledge of the aerodynamic forces and moments on two-dimensional airfoil sections is extremely important for the design of airplane wings, turbomachine blades and other lifting surfaces. The flow around an airfoil depends on its geometry, angle of attack, Reynolds number, as well as other additional parameters such as surface roughness and freestream turbulence. Because of all these effects, the accurate calculation of the aerodynamic loads on an airfoil is very difficult, even with the powerful computer and advanced numerical methods available nowadays. Therefore, the development of new airfoils or the study of old airfoils operating under new conditions require that careful measurements of these loads be performed in a wind tunnel in order to have detailed information about the profile's aerodynamic characteristics.

There are at least four techniques to measure the mechanical loads on a body (Barlow *et al.*, 1999): (*i*) direct measurement of the forces using a balance; (*ii*) measurement the of the stresses on the body surface, i.e. pressure and shear stress, and subsequent integration over the surface; (*iii*) survey of the velocity profiles upstream and downstream of the body and of the pressure distributions on the upper and lower walls of a wind tunnel; (*iv*) experimental determination of the body motion under the action of the aerodynamic forces and computation of the forces from the equations of motion. In this paper we use the first approach to measure forces on a model aiming at developing a balance for low-speed (incompressible) wind tunnel. Specifically, we present a new concept for a three-component balance that is able to measure independently the lift and drag forces and the pitching moment in a nominally two-dimensional flow. The balance captures the angular deflection of load cells instrumented with strain gages as a response to the aerodynamic loads that develop on the airfoil model when placed in the tunnel test section. A data acquisition system hooked up to a computer collects data in the form of output voltage. The balance output is processed by a specific program, developed on the LabView platform, which produces graphs for the lift, drag and pitching moment coefficients as a function of the angle of attack. A prototype of the balance was constructed and preliminary tests were conducted for a NACA 0012 airfoil. The tests indicate that the balance is capable of producing accurate measurements of the aerodynamic forces and moment that develop on the body. In the next sections, the balance, the experiment and the preliminary results that we have obtained are described in detail, and the conclusions from this first study are discussed.

2. DESCRIPTION OF THE BALANCE

The balance is a measuring instrument designed to measure the aerodynamic loads on bodies immersed in (nominally) two-dimensional flows. Because of that, the complete device mounted in the wind tunnel consists of two deflection sets, one on each side of the test section. We define as a deflection set the complete assembly of beams (load cells) and the associated alluminum structure used for the measurement of each one of the three loads (drag, lift and moment), as shown in Figs. 1 and 2. Thus, each measuring system (lift, drag and moment) is the sum of two deflection sets exactly alike, except that only one set is instrumented. In other words, only one deflection set is instrumented with strain gages and with the angle-of-attack measuring module (described below). Both sets are mounted symmetrically facing each other, so as to avoid perturbing the two dimensionality of the wind-tunnel flow. The deflection sets are linked to each other by a rigid (and light) balsa-wood rod that goes through the test section and that is attached to model lying within the test section. Figures 1 and 2 show two views of the complete balance assembly, that is, the balance and the two deflection sets mounted in the test section of the wind tunnel, with an airfoil model also mounted in the test section as part of the entire assembly. The deflection set on the right is the instrumented one, which is connected to the data acquisition system and the computer during testing, whereas the deflection set on the left is the one that provides symmetrical model support during testing in the wind tunnel.

Figure 1. Skewed view of the general balance assembly in the wind tunnel.

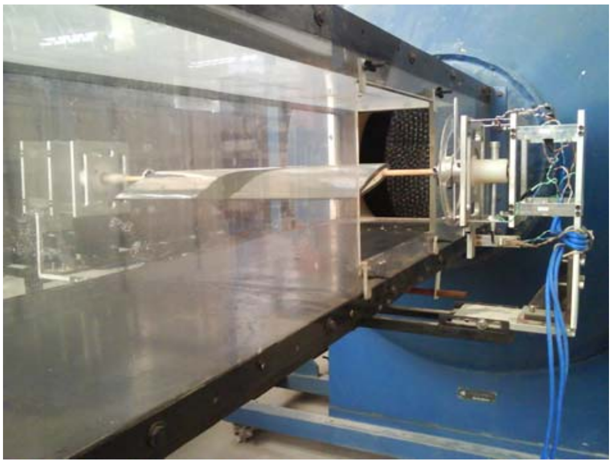

Figure 2. Front view of the general balance assembly in the wind tunnel.

The instrumented deflection set has three load components, one corresponding to the lift force, one to the drag force and another to the pitching moment. Each load component has a specific measuring system, all based on load cells that respond to a bending moment. The lift and drag measuring systems are each composed of four load cells mounted in parallel, whereas the moment component is composed of only one load cell. Each load cell of the force measuring systems has one single strain gage, lying on the inner surface, to monitor the load cell deflection. On the other hand, the pitching moment measuring system has one single load cell with four strain gages, two mounted on the inner and two on the outer surface. Thus, each of the components is monitored by four strain gages, which are connected in such a way to form a Wheatstone-Bridge arrangement. When the cells undergo deflection due to the loads geneterated by the incoming wind tunnel flow, the Wheatstone bridge loses its electrical balance and generates a non-zero electrical output signal. This electrical signal is translated into aerodynamic forces and moment after previous calibration. Figures 3 and 4 are photographs of the instrumented deflection set of the balance that highlights, in red, yellow and green, the load cells responsible for the measurement of the drag and lift forces, and the pitching moment, respectively.

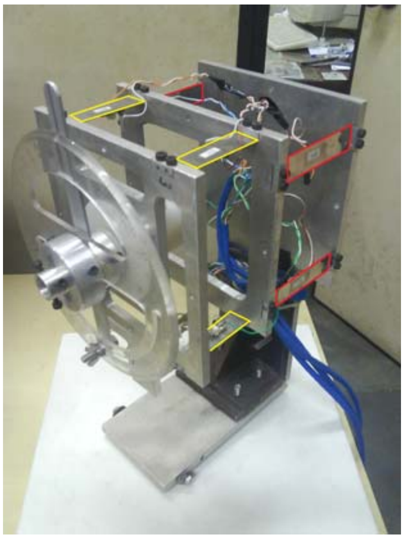

Figure 3. General view of the balance.

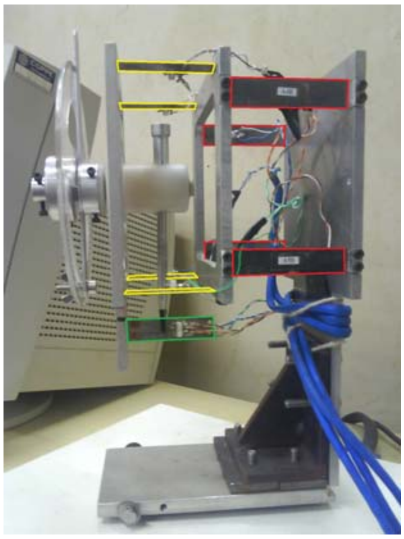

Figure 4. Side view of the balance.

Figure 5 shows the layout of the strain gages mounted on two load cells of the balance. As shown, the lift load cell, in yellow, has a strain gage glued to its inner surface. This mounting is repeated on each one of the four lift load cells and also on each one of the four drag load cells. The pitching moment load cell, in green, has two strain gages glued to each surface of the cell, thus forming a complete four-strain-gage Wheatstone bridge.

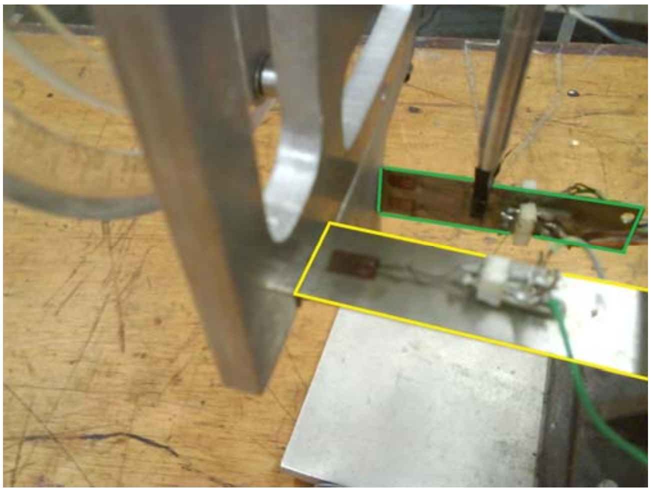

Figure 5. Zoom into the lift and pitching-moment strain-gage mounting.

The graph of Figure 6 shows the calibration curve obtaiend for a typical strain gage mounted on the load cells of the balance. From this graph, we can deduce a calibration curve expressed by the linear equation

$$V = 2.5F - 0.3 \tag{1}$$

where the output voltage, V, is measured in mV and the force, F, in N. The uncertainty for these measurements is ± 0.005 mV. Equation (1) relates the force acting on a single load cell that has only one strain gage to an electric output voltage signal of a Wheatstone bridge. Since the balance has four strain gages per Wheatstone Bridge, Eq. (1) must be multiplied by 4 so that the balance sensitivity is quadrupled. Thus, Eq. (1) becomes

$$V = 10.0F - 1.2 \,. \tag{2}$$

Figure 7 shows a photo of a strain gage being tested by a traction machine in the Metrology Laboratory of UFRJ during a standard calibration test.

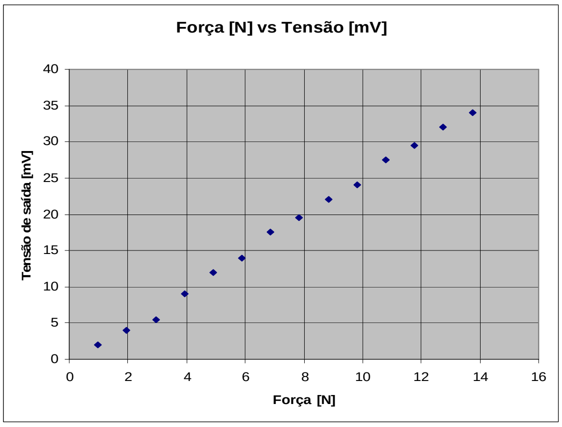

Figure 6. Calibration curve of a strain gage.

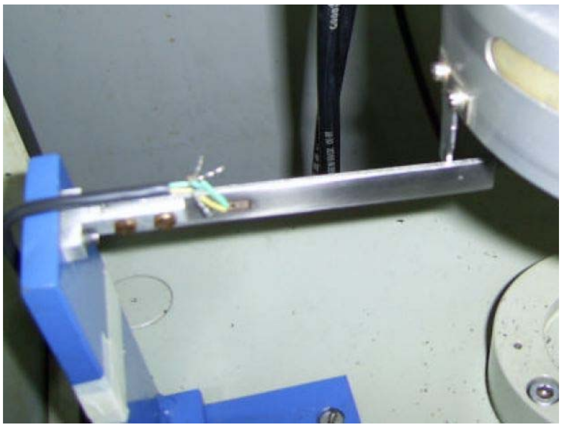

Figure 7. Standard calibration test of a strain gage.

The LabView software for data acquisition uses the inverse relation of Eq. (2), that is,

$$F = 0.10V + 0.12 \,, \tag{3}$$

which translates the strain gage output signal for each component of the balance into lift, L, and drag, D, forces, where $D = 8F$ and $L = 8F$, and into pitching moment, M, according to the relation $M = F \times l$, where the force F and l is the distance from the point where the force is applied to the point where the pitching moment load cell is clamped to the balance structure. The values of the lift and drag forces are eight times the force F because each force measuring system is comprised of two deflection sets that make up the balance, one on each side of the wind tunnel test section, and each deflection set has four load cells.

Knowing the aerodynamic forces, the LabView software calculates the aerodynamic lift, drag and pitching moment coefficients from their respective definitions, that is,

$$C_L \equiv \frac{L}{(1/2)\rho U^2 cb}, \tag{4}$$

$$C_D \equiv \frac{D}{(1/2)\rho U^2 cb}, \tag{5}$$

$$C_M \equiv \frac{M}{(1/2)\rho U^2 c^2 b}, \tag{6}$$

where ρ is the air density, U is the wind tunnel speed, c is the airfoil chord and b is the airfoil span (which is equal to the test section width). The values of c and b are known for the given profile, the air density is determined using the ideal gas relation from measured ambient temperature and pressure, and the tunnel speed is measured using a Pitot-static tube.

Figures 8, 9 and 10 show the deflection sets that represent the deflections suffered by the load cells of the balance as a result of the lift and drag forces and the pitching moment, respectively. The yellow arrows represent the forces and moment acting on the balance, while the lines in red represent the displacements suffered by the deflection sets of the balance due to the deflection of their load cells.

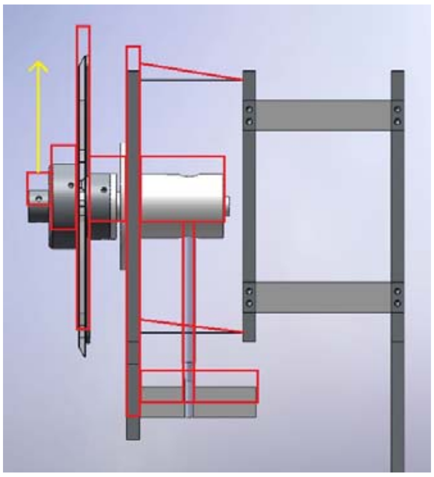
Figure 8. Lift deflection set.

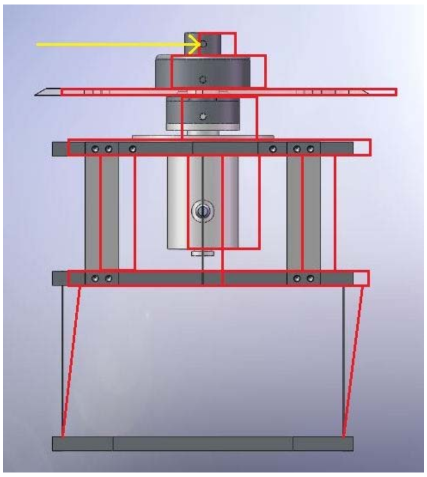
Figure 9. Drag deflection set.

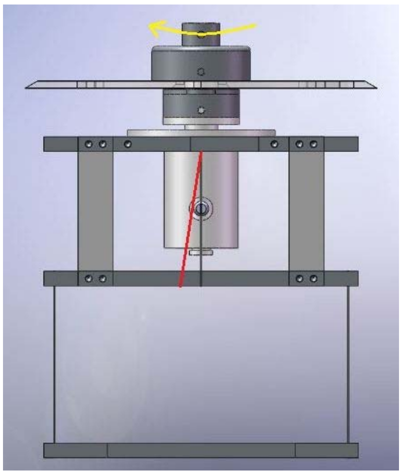
Figure 10. Moment deflection set.

To set and measure the angle of attack during the experiments, the balance has a system designed specifically for this purpose attached to its outermost edge of the instrumented deflection set. Three-dimensional modeling of this system, developed on the SolidWorks platform, can be seen in Figs. 11 and 12, shown in isolation and mounted on the balance, respectively. Figure 13 shows a picture of the angle-of-attack measurement system attached to the balance, illustrating how we can change the angular position of the airfoil model in the range 0° to 90°. This system allows the airfoil to move freely with respect to the deflection set structure and to the angle-of attack measuring system in order to set the desired angle of attack. The measurement is performed by visual interpolation from a protractor that is mounted on the delfection set structure, as shown in the figures. The protractor resolution is 0.1°.

Figure 11. SolidWork modeling of the angle-of attack protractor.

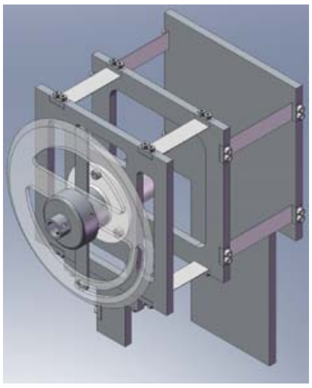

Figure 12. SolidWork modeling of the angle-of attack measuring system.

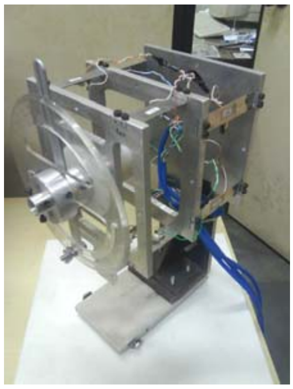

Figure 13. General view of the measuring system.

3. EXPERIMENTAL SETUP

Figure 14 shows a photograph of the wind tunnel used in the experiments to test the balance. The wind tunnel is a low-speed open-circuit tunnel with a fan installed downstream of the test section, which makes it a suction tunnel. Figure 15 illustrates the test section of the tunnel, which is 30 cm high, 40 cm wide and 150 cm long. The flow generated by the tunnel is very uniform and with low turbulence intensity. The airfoils tested in this tunnel have span equal to the width of the test section, so that a nominally two-dimensional flow is produced. In all experiments the wind tunnel is operated at low speed, in the sense that the flow is essentially incompressible.

Figure 14. General view of the wind tunnel.

Figure 15. General view of the test section.

The airfoil models used in the experiments belong to the NACA 4-digit family. Specifically in our experiments, we have used the NACA 0012 profile with chord length equal to 133 mm, made out of balsa wood and covered with a plastic material that is commonly used to build model airplanes. This material combination provide a very light model with a very smooth surface. Figures 16 and 17 illustrate two of these profiles.

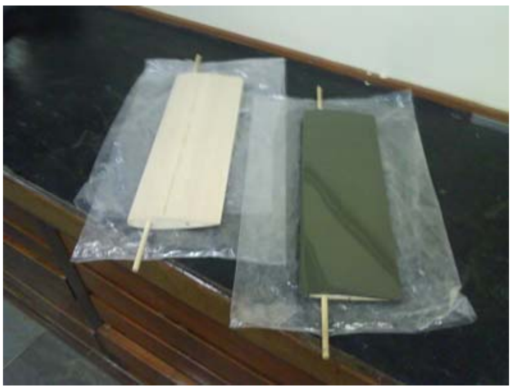

Figura 16. View 1 of two airfoil models.

Figura 17. View 2 of two airfoil models.

The speed of the tunnel is measured using a Pitot-static tube connected to a U-tube manometer. Figures 18 and 19 show photographs of the Pitot-static tube and the multitube variable inclination manometer, respectively, used for freestream speed and static pressure measurements on the surface of the models. In the multitube manometer, the U-tube attached to the Pitot tube corresponds to the two rightmost tubes. The fluid used is ethanol.

Figure 18. Pitot-static tube.

Figure 19. Multitube variable inclination manometer.

The three output signals generated by the Wheatstone Bridges are input to a SCC-SG-04 module from National Instruments. These modules also generate the electrical signals that are input to the Wheatstone-bride arrangements mounted on the balance. These SCC modules work connected to a circuit board of the connector-block type, model SC-2345, also from National Instruments. The connector block allows connection of up to twenty modules through slots, which makes possible the simultaneous input of forty electrical signals, since each slot and each module has two input channels. In the case of our balance, we use a total of three input channels, one for each module, and each module is hooked up to a slot. Each of these channels is used for one of the three components of the balance. The connector block is linked to a computer through a data acquisition board, which is installed directly on the computer motherboard. The data acquisition board used to collect the data that comes from the balance is the PCI-6221, also manufactured by National Instruments. Figure 20 shows a photo of the SCC modules connected to the connector block. From left to right, we can see the lift, drag and pitching moment modules, respectively. Figure 21 shows a photo of the data acquisition board PCI-6221.

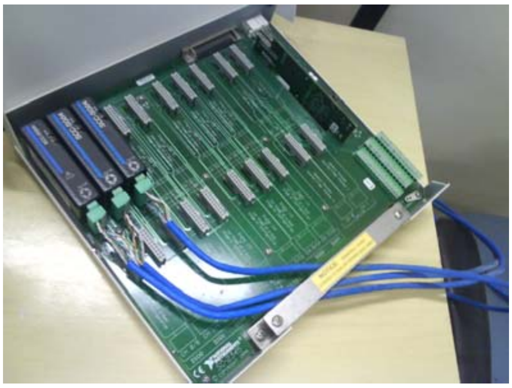

Figure 20. Connector block SC-2345.

Figure 21. Data acquisition board PCI-6221.

The electrical signals entering the computer are translated into forces, moment, and their respective aerodynamic coefficients by means of a software developed on the LabView platform. This software is called “Virtual Instrument” (VI) and was designed specifically for our experiments. The software VI is divided into two parts: the front panel and block diagram. Figure 22 illustrates the screen of the VI’s front panel used for the tests in the wind tunnel with the balance. Through the input of the flow speed, the airfoil chord length and angle of attack, and the ambient temperature and pressure, this program is able to calculate the aerodynamic force coefficients as a function of the angle of attack. The three windows on the left show, in real time, the lift force, the drag force and the pitching moment to which the body is subject during testing. The other three windows on the right plot the lift, drag and pitching moment coefficients for a given period of time. In Figure 23, we see the screen of the VI's block diagram. It is in the block diagram window that programming of the equations is carried out so that the VI is capable of translating electrical output signals coming from the balance into aerodynamic force and moment coefficients.

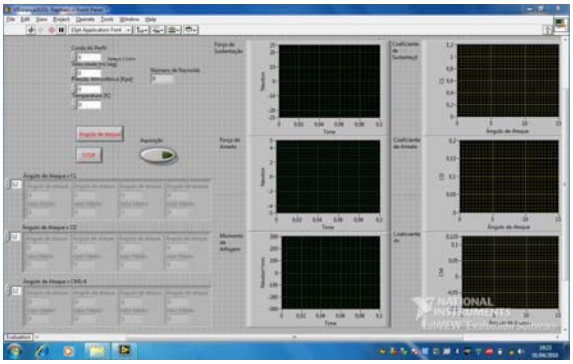

Figure 22. VI's front panel screen.

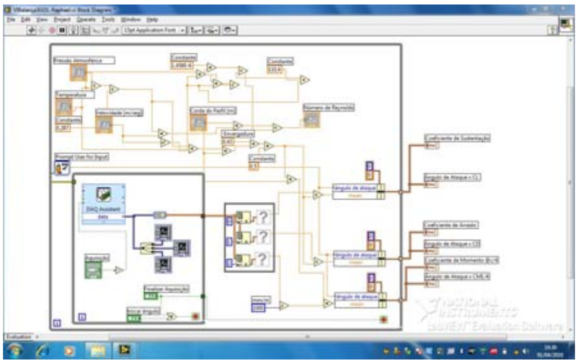

Figure 23. VI's block diagram screen.

4. RESULTS AND DISCUSSION

We now present the measurements obtained with the balance during preliminary wind tunnel tests. The figures below refer to measurements of aerodynamic force and moment coefficents conducted for a NACA 0012 profile, with a chord Reynolds number equal to 1.7×10^5.

Figure 24 shows the results obtained with the balance for the lift, drag and pitching moment coefficients, C_L, C_D and C_M, superimposed on a single graph. Figures 25 and 26 compare the results for the lift and drag coefficients measured with our balance to the experimental data obtained by NACA (Blevins, 1984), the former NASA. As one can see in these figures, the two sets of results show good agreement with the experimental data. The comparison for C_M was not possible because the reading of the values off the plot provided in Blevins (1984) is not accurate. This lack of accuracy is due to the fact that C_M and C_D are plotted on the same graph with the same scale, and the values of C_M are much lower than the values of C_D.

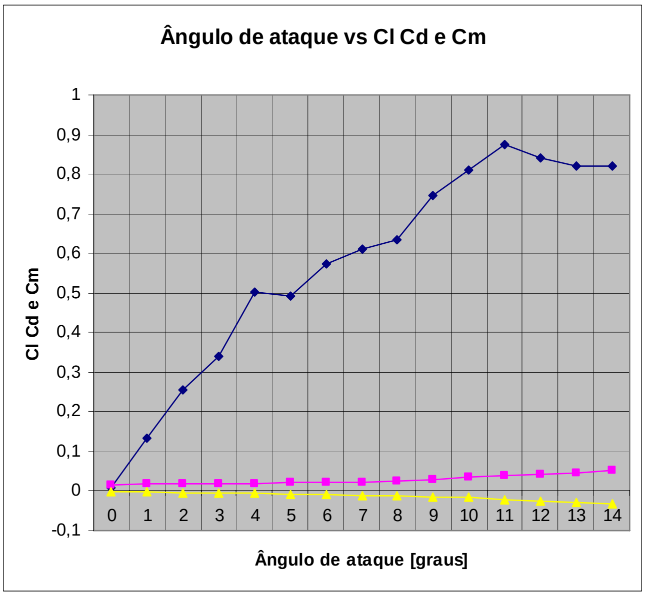

Figure 24. Measured data for the lift, drag and pitching moment coefficients as a function of the angle of attack.

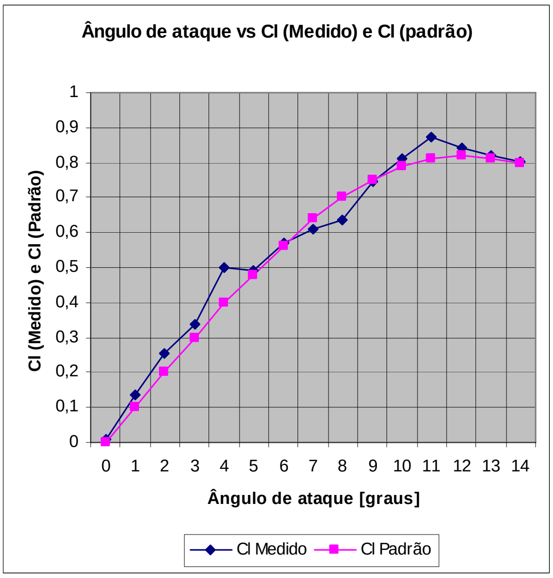

Figure 25. Comparison with the NACA data (Blevins, 1984): lift coefficient

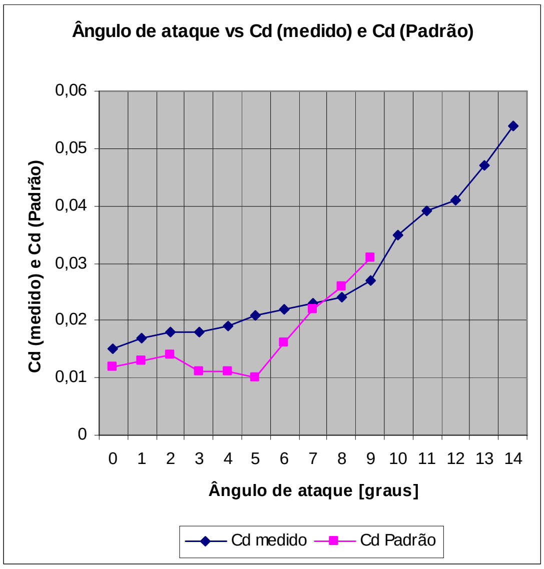

Figure 26. Comparison with the NACA data (Blevins, 1984): drag coefficient

These results are the first data set measured with the balance. There is undoubtedly need to conduct a larger number of experiments for statistical quantification of the measured data and subsequent comparison with the results of NACA. A larger set of tests with the balance using the NACA 0012 profile, in addition to other NACA family profiles are currently in progress. The system itself is at the moment undergoing several improvements, such as the automatic reading of the freestream flow speed by using a pressure transducer and its inclusion in the VI program. Furthermore, new load cells are being designed for a new series of experiments with bluff body models.

6. CONCLUSIONS

The results we have obtained present good overal accuracy when compared to the experimental data used as reference. Throughout the tests carried out so far, the balance has shown its enormous potential as an accurate instrument capable of performing direct measurements of aerodynamic loadings in a tunnel wind. Direct force measurements present great advantage over other indirect methods, such as those using stress sensors on the body surface, surveys of the velocity and pressure profiles in the vicinity of the body, or those that rely on the flow computation using the equations of motion based on measured body motion. In addition, the balance has a design that is flexible enough to be used with any type of body, either aerodynamic or blunt.

Although the results are still quite preliminary, we can safely conclude that the results obtained so far corroborate the success of the balance design and its potential as a tool for measuring aerodynamic forces on bodies.

ACKNOWLEDGEMENTS

We would like to acknowledge CNPq for sponsoring this project, either through funding or through undergraduate scholarships. The second author would also like to acknowledge all the former students who have contributed, one way or another, to the development of the balance, that is: Patrick P. Pereira, Marcelo C. Bonniard, Fabiano O. R. Rosa, Henrique M. Lima, Leonardo F. Rubino and Gabriel M. Tavares.

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