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DESIGN AND IMPLEMENTATION OF AN AERODYNAMIC BALANCE IN A SUBSONIC WIND TUNNEL AND VALIDATION THROUGH NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF LIFT AND DRAG PERFORMANCES ON AIRFOILS

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Abstract: *This work describes the construction of an external force aerodynamic balance of five components for a subsonic open circuit wind tunnel. The wind tunnel used in this study is an EWT (Educational Wind tunnel) of AEROLAB. After analyzing the characteristics of the aerodynamic balance, we proceed to make a computer-aided machining design. Once the mechanical structure is completed, the installation of force sensors and electronic system for control and data acquisition are performed. In addition, a software was developed in order to perform data reading and facilitate the use of the designed instrument. Experiments were carried out by performing measurements of lift and drag forces on several airfoil configurations, at different angles of attack as well as at different Reynolds numbers. Validations were made by performing numerical analysis using XFOIL code. The airfoils analyzed are symmetric NACA* 0012*, NACA* 0018 *and the asymmetric Eppler* 193*. These airfoils were machined using a CNC (Computer Numeric Control) milling machine.*
Keywords: *Fluid Mechanics, Sub-Sonic Wind Tunnel, Low Reynolds Airfoils, XFOIL*

1. NOMENCLATURE

T Temperature (K)
P Barometric pressure (Pa)
C_d Drag coefficient
C_l Lift coefficient
C_p Pressure coefficient
Re Reynolds number
α Angle of attack (deg)
L Lift force (N)
A Airfoil area (m^2)
D Drag force (N)
R_h Relative humidity
e_s Saturation pressure of water (Pa)
ρ Fluid density (Kg/m^3)
ρ_∞ Free stream fluid density (Kg/m^3)
u Fluid velocity (m/s)
u_∞ Free stream fluid velocity (m/s)
p Fluid pressure (Pa)
p_∞ Free stream fluid pressure (Pa)
P_{sta} Static pressure (Pa)
P_{tot} Total pressure (Pa)

2. INTRODUCTION

A wind tunnel is an instrument for the study of different phenomenon produced by air flow around a solid body. In it the object being studied remains static while the air flows around it. Fundamental parameters to be considered in an aerodynamic experiment are: pressure, wind velocity, temperature, flow direction and forces generated on the object. Wind tunnels have been used extensively through history since Frank H. Wenham, a council member of the Royal Aeronautical Society, who is credited for designing and operating the first wind tunnel in 1871. Wenham constructed various types of wind tunnels for measuring lift and drag forces, obtaining momentous results for the history of aeronautics. During the same period, Konstantin Tsiolkovsky determined drag coefficients of spheres, cylinders and flat plates in an open-section wind-tunnel in 1897.

The wind-tunnel used in this work, an "Eiffel" type tunnel, was first built by Gustave Eiffel in 1909. His design improved the efficiency of the tunnel by enclosing the test chamber, using a honeycomb air flow straightener and introducing a diffuser after the test chamber and before the downstream fan.

Most aerodynamic experimental problems are related to the study of a body moving in a static medium (direct approach). The experiment can be reversed by studying the flow around a static body in a wind tunnel (reverse approach). When dynamic conditions are strictly inverted and the tunnel boundaries are neglected, the fluid mechanics laws are the same for the direct and inverse approach. Among the most important variables in wind-tunnel experiments, pressure is one that allows most comprehensive understanding of phenomena, since it permits complete knowledge of the thermodynamic properties of the fluid. Specially, pressure distribution is fundamental to determine forces and moments acting on airfoils. For instance, all points of an airfoil have a particular pressure coefficient. Knowing the forces and moments acting upon a body as it moves through the air is essential to the automotive, aeronautical and civil industries.

The most direct way to quantify the acting forces on a body is by using an aerodynamic balance. Therefore, in this work we have designed and implemented a five components aerodynamic balance, as the one presented in Abe *et al* 2003.

It must be noted that experimentation in a wind tunnel is done on scale models, much more manageable and cheaper than life size models. In a classic series of experiments, Osborne Reynolds (1842-1912) from the University of Manchester, demonstrated that the flow patterns on scale models are similar to that of full scale models if certain parameters are the same in both cases. One of the fundamental parameters in this work is the Reynolds number, which can be expressed in terms of the cord length of the airfoil c, air density ρ, dynamic viscosity μ and free stream air velocity u_∞ with the following equation:

$$Re = \frac{c\rho u_\infty}{\mu} \tag{1}$$

The relation between forces acting on a moving body in a fluid medium and velocity is captured by the aerodynamic coefficients. These coefficients are dimensionless numbers used in aerodynamic studies to express forces and moments experienced by any moving body in a fluid. In aerodynamics, the coefficients of greatest interest are the pressure coefficient (C_p, used to represent the pressure distribution), lift coefficient (C_l), drag coefficient (C_d), pitch, roll and yaw moment coefficients. These coefficients will be used in this work to quantify the lift and drag forces that are produced on different airfoils (NACA 0012, NACA 0018 and Eppler 193).

Although the number of publications of experimental results is yet limited, low Reynolds-number applications of airfoils represent nowadays a growing research area. This work pursues the validation of results obtained using an aerodynamic balance, designed and built for the sub-sonic wind tunnel of the Mechanics and Energy Laboratory (LME) of the Engineering Faculty of the Universidad Nacional de Asunción (FIUNA). The experimental data is compared with numerical results obtained using XFOIL code, developed by Mark Drela and Michael Giles (1987). This code was chosen due to its simple use and good results in other similar studies.

Ramjee *et al* (1986) performed experiments on a NACA 0012 airfoil with progressively larger truncation (from 5 to 20% of the cord length). In all cases, lift coefficient gradient increases. Aerodynamic drag increases too, reaching up to 225% for the thickest airfoil. Hoerner and Borst (1985) performed experiments on a NACA 0018 profile with 5% truncation of the trail-end, resulting in a larger gradient in the linear part of the lift curve and higher maximum lift. However, no appreciable increase in aerodynamic efficiency is observed. More recently, Sant Palma (2014) analyzed the effects on lift, drag, aerodynamic efficiency among other parameters of tail-end geometry modification of a great range of NACA airfoils at low Reynolds numbers.

As a result of this work, a aerodynamic balance is built and validated by experimentation and comparison with numerical results obtained with the XFOIL code. Mean relative error from the measurements of the NACA and Eppler airfoils is 5%. Measurements of two modified NACA 0018 airfoils were performed, in order to determine the effect of tail-end geometry on performance. Conclusions from the cases under study are that truncation of the trailing edge does not improve aerodynamic performance, due to increased drag and lower lift.

3. EXPERIMENTAL APPROACH

3.1 Wind Tunnel

The wind tunnel used in this work is the open circuit tunnel, "Eiffel" type EWT from AEROLAB (see Figure 1). Its dimensions are 4.2 m long, 1.1 m wide and 1.8 m height. The test area dimensions are 300x300x600 mm^3. The wind speed ranges from 5 to 60 m/s and can be determined indirectly by the fan rotation speed. Turbulence levels are lower than 0.2% according to the manufacturer. The tunnel is equipped in the test chamber with the necessary instrumentation for pressure and wind velocity measurements and the required systems for the applications of airflow visualization.

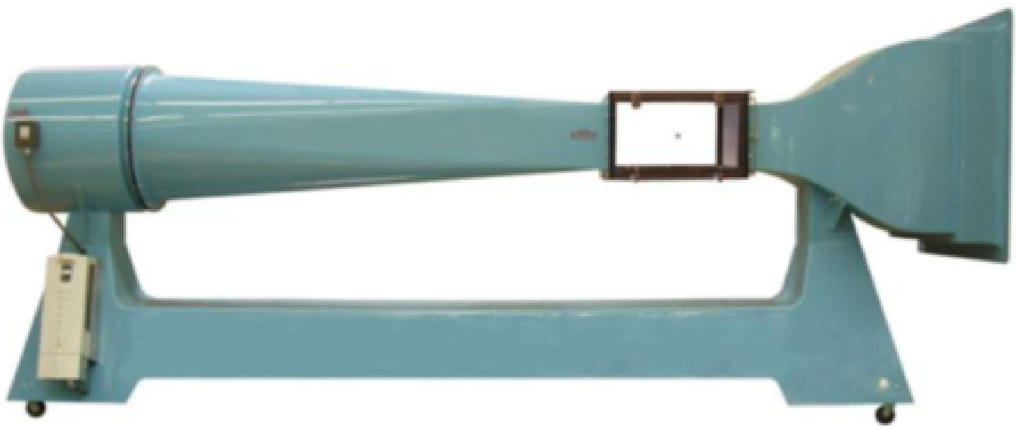

Figure 1: EWT AEROLAB - Wind Tunnel

Wind velocity estimation in the test chamber is obtained through an indirect measurement. In general, velocity is determined in an indirect manner based on either physical effects resulting from the medium flow or by relations between velocity and other physical parameters of easier measurement, such as pressure or density. The most common way to determine the velocity in a stable flow is by using Bernoulli equation.

The velocity u can be indirectly estimated using equation 2. Total pressure P_{tot} and static pressure P_{sta} are determined using a Pitot tube. The air density ρ_∞ is obtained using equation 3, suggested by Jones (Barlow *et al* 1999).

$$u = \sqrt{\frac{2.(P_{tot} - P_{sta})}{\rho_\infty}} \tag{2}$$

$$\rho_\infty = \left(\frac{0,0034847}{T}\right)(P - 0,003796 \times R_h \times e_s) \tag{3}$$

Where e_s is determined by the following equation.

$$e_s = \left(1,7526 \times 10^{11}\right) e^{(-5315,56/T)} \tag{4}$$

3.2 Aerodynamic Balance

The aerodynamic balance is an instrument that measures forces and moments on a model in the wind tunnel. The main characteristic to be considered is the number of variables one seeks to determine, which can varies from one to six, depending on the type of experiment.

Aerodynamic balances are classified in two groups, depending on where it is placed in the experimental system: external and internal balances, placed outside and inside the test area, respectively. The external balance is selected for this work. In this case, the total aerodynamic force and moments are separated in various components using various mechanical systems.

The connection between the model and the force measuring equipment is the moving or “floating” platform. This platform allows the separation of the total aerodynamic force in five components. There are three types of moving platforms: platform balances, yoke balances and pyramidal balances (Abe *et al* 2003).

The platform balance is chosen in this work. Its design allows the use of three or four points of support for the main structure (see Figure 2). The balance resolution center is not situated on the model, meaning that the pitching moment must be transferred from the center of the platform to that of the model. The lift force, drag force, pitch moment, roll moment and yaw moment are calculated with equation 5-9.

$$Lift = \text{-A+B+C} \tag{5}$$

$$Drag = \text{D+E} \tag{6}$$

$$\text{Pitch moment} = \text{C.m} \tag{7}$$

$$\text{Roll moment} = \frac{(A-B)l}{2} \tag{8}$$

$$\text{Yaw moment} = \frac{(E-D)l}{2} \tag{9}$$

Platform balances are robust and orthogonal, for these reasons it can be built and aligned with minimal difficulty. However, it has also disadvantages: the drag force produces a false pitching moment on the pressure gauges, these results must be subtracted from the measurements. The pressure gauges used in this work (five in total) are all FC22 type with a capacity to measure up to 11 kgf.

The design and implementation of the aerodynamic balance includes: construction of the mechanical structure (see Figure 3), installation of the electronic and electromechanical equipment for the forces sensors, as well as the control and data acquisition system (see Figure 4). For data acquisition, a hardware control system and a software capable of running on Windows operating system were developed. The implemented hardware is capable of measuring atmospheric conditions such as temperature, barometric pressure and relative humidity.

3.3 Experimental data

The airfoils analyzed are the symmetric NACA 0012 (see Figure 5), NACA 0018 and the Eppler 193 of a 70 mm chord length, with variations of the trailing edge truncated at 20% of the chord and truncated and rounded at 20% of the chord (see Table 1). The purpose of these modifications is to determine if any of them are useful as a means to reduce turbulent drag in a passive manner, and thus to improve the lift to drag ratio with simple geometric variations. All blades are machined using a CNC milling machine. The material chosen is nylon plastic, due to its low frictional drag (see Figure 6).

Experiments were done at room temperature. Drag and lift forces were measured between 0^o and 14^o. The balance rate was 10 Hz, and for each measurement a sample of 3 seconds was collected. Tests were carried out with ascending and descending wind speeds in order to reduce hysteresis effects. The balance uses a supporting rod to hold the test model in place, the effect of this equipment piece was compensated by subtracting lift and drag forces results of the rod alone. Superficial roughness is considered negligible in the range of Reynolds numbers analyzed as shown by Lissaman *et al* (1983).

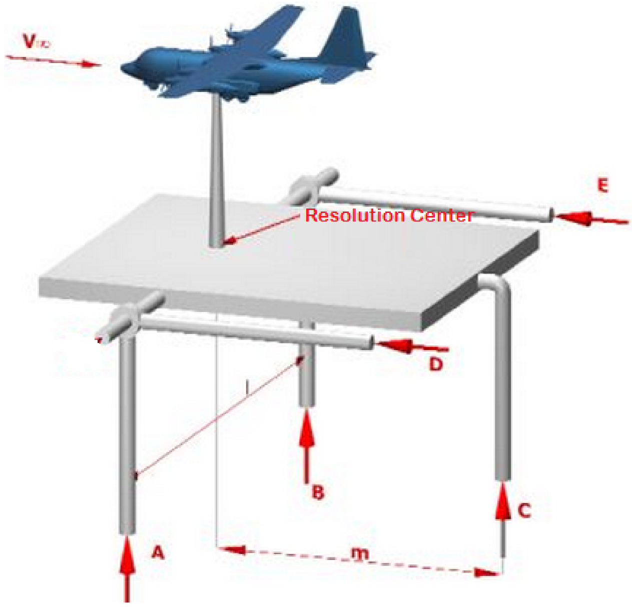

Figure 2: Aerodynamic Balance of the external force type

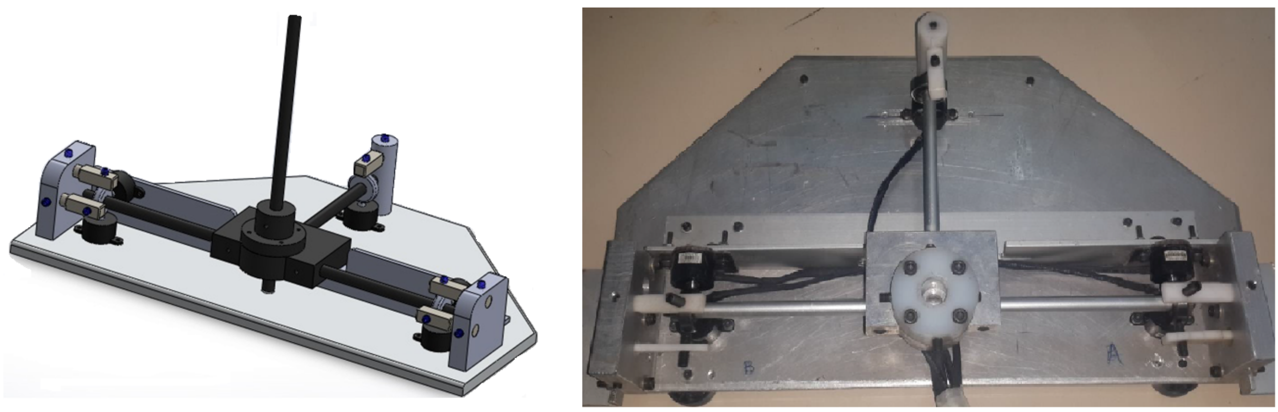

Figure 3: Computer model and final results of the Aerodynamic Balance

Figure 4: Aerodynamic Balance Control Hardware

Table 1: **Measurements of machined airfoils.**

Airfoil	Chord(mm)	Length(mm)
NACA 0018	70	272
NACA 0012	70	257
EPPLER 193	70	259
NACA 0018 rounded 20%	70	272
NACA 0018 truncated 20%	70	272

Figure 5: Airfoil blade in position for making measurements

4. NUMERICAL APPROACH

Once the aerodynamic balance was designed, constructed and experimental results were obtained, validation was done by comparing these results with numerical data. Measurements were done at three different Reynolds numbers for each airfoil, ranging from 1.1E05 to 2E05. The numerical results were obtained using the XFOIL code which is embedded in the QBlade v0.9 software. As input the software requires first of all the geometry of the airfoil. This can be obtained from the NACA library incorporated in QBlade or imported in .dat format. Once the geometry is defined, the Reynolds and Mach number must be defined. Since this study is performed at low wind velocities, the effect of the Mach number is considered negligible. The code allows viscous and ideal models. In this work, the model chosen included viscosity. To account for its effects, the code models the boundary layer with a two equation lagged dissipation integral and a transition criterion to determine free transitions within the flow. The specified parameter is Ncrit (factor that determines turbulence levels), that is assumed to be 9 for standard wind-tunnel tests. This value of Ncrit is used for the numerical analysis. Finally, the code requires the simulation range and angle intervals. Drag and lift coefficients were obtained for angles of attack from 0^o to 14^o with steps of 2^o.

5. MATHEMATICAL EQUATIONS

To represent experimental and numerical results in dimensionless quantities the aerodynamic coefficients utilized are drag, lift and pressure coefficients defined as follows (Equations 10-12).

$$C_d = \frac{2D}{\rho u^2 A} \tag{10}$$

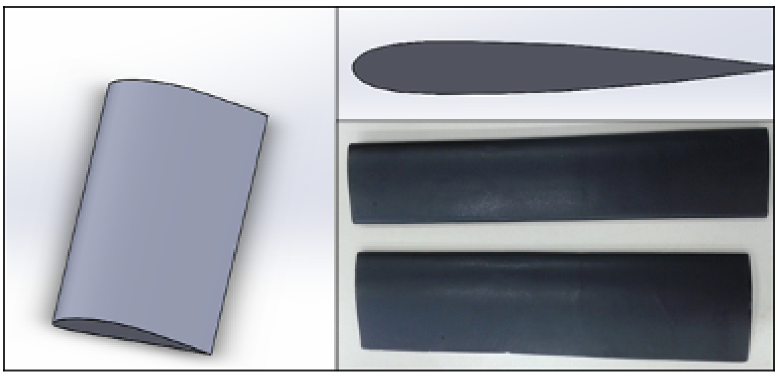

Figure 6: Computer model and machined airfoil blades

$$C_l = \frac{2L}{\rho u^2 A} \tag{11}$$

$$C_p = \frac{2(p - p_\infty)}{\rho_\infty u_\infty^2} \tag{12}$$

Fluid velocity in the test chamber is obtained with the Bernoulli equation 2.

6. RESULTS

6.1 Numerical results

A phenomenon observed during experimentation with the full cord length NACA airfoils of different thickness is the lighter post-stall slope in the lift coefficient curve for the NACA 0012 geometry in comparison with the thicker -0018. These different transitions can be associated with a corresponding event observed in the simulations. Re-circulation bubbles are a common occurrence in airfoils performing at low Reynolds numbers, in laminar flows. These bubbles are points of localized separation of the boundary layer generating constant pressure in the affected area (identified by the constant pressure coefficient, see Figure 7). They may evolve towards the leading or trailing edge. In thicker airfoils, the bubble usually grows towards the leading edge, causing a sudden loss in lift. In the case of thinner foils, the re-circulation bubble evolves towards the trailing edge, generating a much more gradual loss in lift.

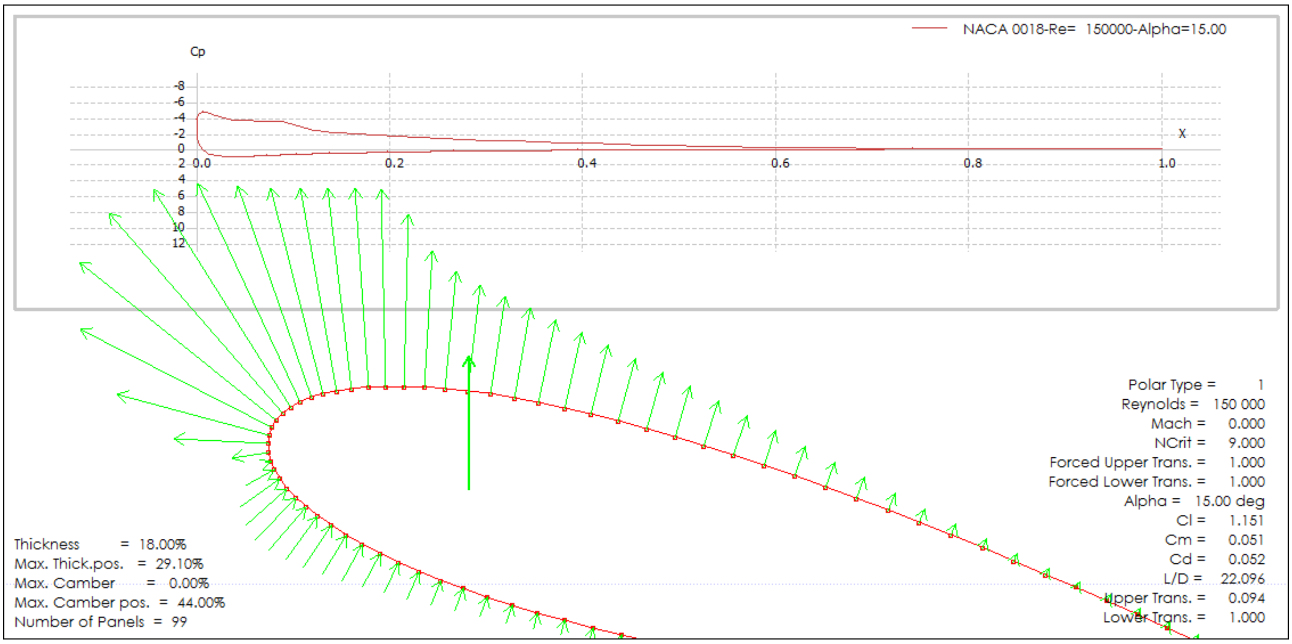

Figure 7: Pressure coefficient across the surface of a NACA 0018 profile at Re=150.000. Re-circulation bubble is represented as a constant pressure zone. QBlade v0.9

6.2 NACA airfoils

The symmetrical NACA airfoils were selected since both profiles have been the subject of a great number of studies and thus serve as good models for understanding the behavior of the aerodynamic balance.

6.2.1 Influence of Airfoil Thickness. NACA 0012 and NACA 0018

The experimental results show two main characteristics that make them different from the mathematical model and results from literature. Firstly, the balance registers in all measurements a positive lift at 0^o which does not disappear with the compensation (see Figure 8). Since both profiles are symmetrical, lift at this angle should be zero. Due to construction defects, the screws do not put initial compression on the pressure gauges in perfectly perpendicular directions. This means that measurements of lift and drag are not completely independent. The second noticeable effect is an early boundary layer separation which ends with an early stall. The experimental models develop highest lift coefficient at 10^o, while the XFOIL model reaches 12^o (see Figure 9).

Further research is needed to understand the reason for this phenomenon, the balance rod is suspected of triggering further turbulence that could cause this boundary separation. Pre-stall and post-stall behaviors are clearly similar between the mathematical and experimental results. It is in the critical region of the stall angle where results of XFOIL code represent a challenge when trying to reproduce the literature data.

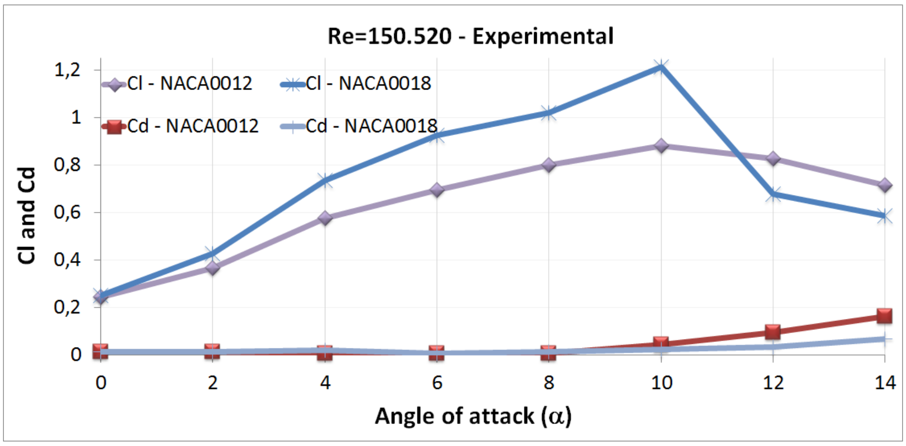

Figure 8: Lift Coefficient and Drag Coefficient vs Angle of Attack for NACA 0012 and NACA 0018 - Experimental

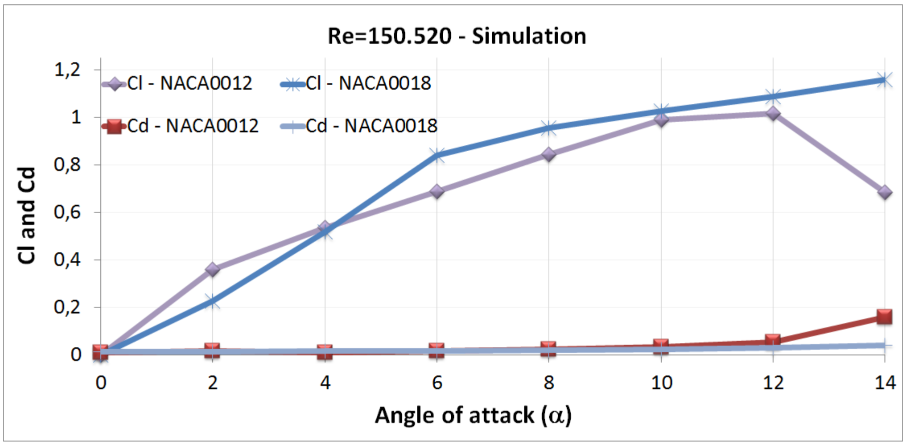

Figure 9: Lift Coefficient and Drag Coefficient vs Angle of Attack for NACA 0012 and NACA 0018 - Simulation

6.3 Eppler 193 airfoil

The Eppler 193 and modified airfoils were evaluated as particular geometries of interest in the continuous research for high aerodynamic efficiency geometries.

The Eppler 193 profile is specifically developed for high lift and low drag effects. This is clearly observed for all Reynolds numbers. Results obtained experimentally for the lift force are slightly higher than predicted by XFOIL. The lift coefficient critical angle of attack is 10^o (see Figure 10). Post-stall behavior displays about 20 % loss compared to the peak lift coefficient in the XFOIL model, experimental results show a greater post-stall effect. The drag coefficient presents a similar pattern for both the mathematical and experimental results. One distinction is the greater drag experimented by the airfoil at 0^o. This is mainly due to the protuberance of the balance rod that sustains the airfoil in place, under the airfoil model. The phenomenon could not be completely eliminated by the drag compensation. The post-stall effect is more noticeable at 15^o and higher in the experimental model, the drag coefficient being slightly higher than predicted by the code due to the turbulent boundary layer.

6.4 Influence of Airfoil Tail-End Modification

The lift coefficient curve maintains pre-stall slope similar to the original airfoil in the straight ended model, demonstrating the same process of boundary layer separation which originates an early stall. The critical angle of attack is 8^o for the experimental model (see Figure 11), while the mathematical model reaches critical point at 14^o (see Figure 12). The round-ended model preserves a better boundary adhesion, displayed by the greater slope of the pre-stall lift coefficient curve. The truncated profile with straight tail-end exhibits an early separation of the boundary layer at 10^o compared to the XFOIL code for all Reynolds numbers. From this angle on, there is a sharp increase of the drag coefficient witch marks the beginning of stall and is characteristic of the development of re-circulation bubbles on the surface. This bubble advances towards the edge of attack.

The rounded edge, in comparison results in a greater stall effect. The global effect of both modifications is a reduction in lift coefficient of 14 % and a critical angle 2^o earlier. Drag is augmented in both truncated models, meaning a diminution of aerodynamic efficiency.

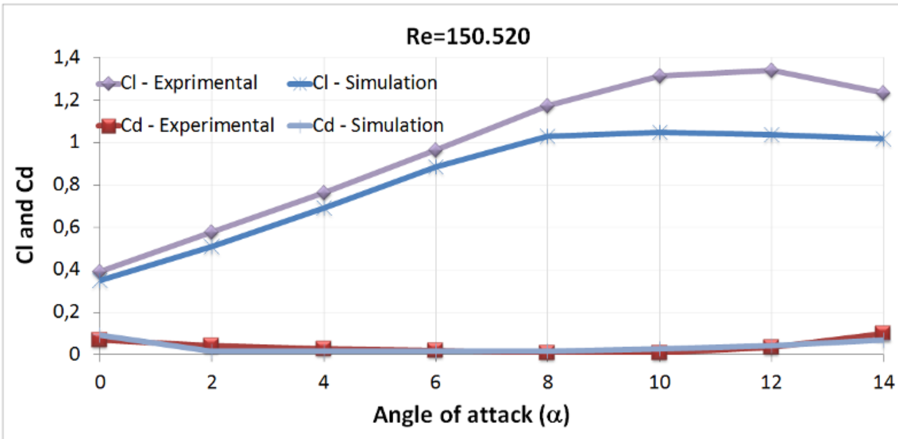

Figure 10: Lift Coefficient and Drag Coefficient vs Angle of Attack for Eppler 193 - Experimental and Simulation

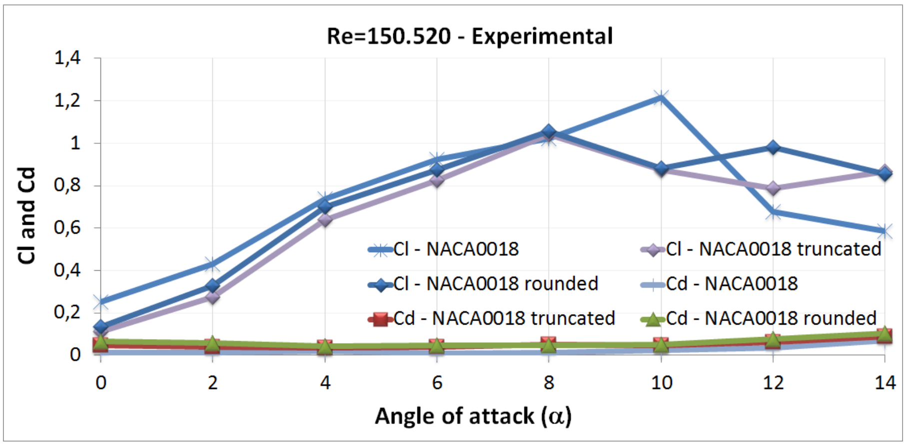

Figure 11: Lift Coefficient and Drag Coefficient vs Angle of Attack for NACA 0018, NACA 0018 truncated and NACA 0018 truncated rounded - Experimental

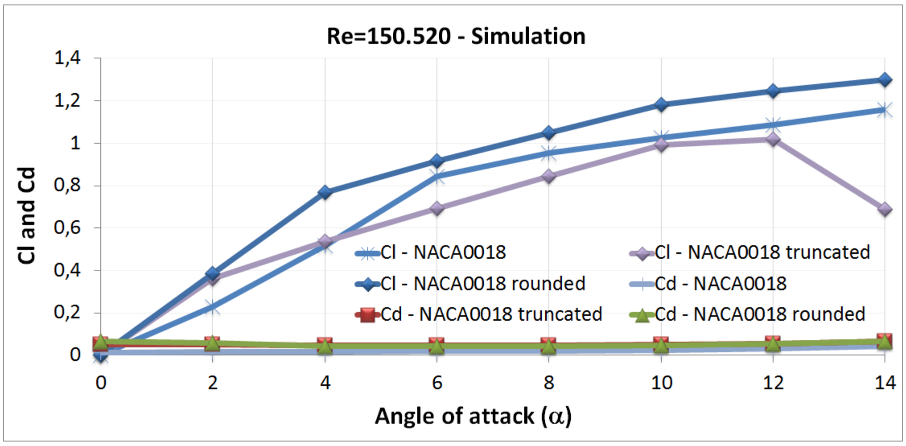

Figure 12: Lift Coefficient and Drag Coefficient vs Angle of Attack for NACA 0018, NACA 0018 truncated and NACA 0018 truncated rounded - Simulation

7. CONCLUSION

This article described the design and implementation of an aerodynamic balance of five components capable of measuring forces and moments on models studied in a subsonic wind-tunnel. The measurement instrument was built with no mayor difficulties thanks to the mechanical precision reached using CAM (Computer Aided Manufacturing).

Validation of the aerodynamic balance was done by comparing low Reynolds experiments performed on five different airfoil models with numerical results obtained using XFOIL code. Best results were obtained for a Reynolds number around 1.5E05 where the mean relative error was 5% for the NACA 0018, -0012 and Eppler 193. The largest error was obtained with Eppler airfoil, which coincides with the airfoil that creates greatest lift. This lifting force exerted on the balance is not properly managed by the screws that are used to generate initial pressure on the pressure gauges, increasing the measurement error.

Moreover, the balance results match with sufficient accuracy the numerical results and allow the conclusion that typical aerodynamic phenomena will be clearly and correctly visualized. In reference to the modified airfoils, no increase in lift was obtained. Meanwhile, drag increased in both modified airfoils, meaning a reduction in aerodynamic efficiency.

It can be concluded from the results obtained with the different airfoils that the aerodynamic balance satisfies the requisites to be used as a force measuring device in a subsonic wind-tunnel.

It is necessary be noticed that this is the first wind tunnel used in Paraguay and the the instrumentation, as well as the aerodynamic balance was entirely designed and developed also at the LME Laboratory of the Engineering Faculty of the Universidad Nacional de Asuncion.

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9. RESPONSIBILITY NOTICE