Implementation of a Low-Cost Instrumentation for an Open Cycle Wind Tunnel to Evaluate Pressure Coefficient

Cristian P. Topa, Esteban A. Valencia, Victor H. Hidalgo, Marco A. Martinez

***Abstract*—**Wind tunnel experiments for aerodynamic profiles display numerous advantages, such as: clean steady laminar flow, controlled environmental conditions, streamlines visualization, and real data acquisition. However, the experiment instrumentation usually is expensive, and hence, each test implies a incremented in design cost. The aim of this work is to select and implement a low-cost static pressure data acquisition system for a NACA 2412 airfoil in an open cycle wind tunnel. This work compares wind tunnel experiment with Computational Fluid Dynamics (CFD) simulation and parametric analysis. The experiment was evaluated at Reynolds of 1.65 e^5, with increasing angles from -5° to 15°. The comparison between the approaches show good enough accuracy, between the experiment and CFD, additional parametric analysis results differ widely from the other methods, which complies with the lack of accuracy of the lateral approach due its simplicity.

***Keywords*—**Wind tunnel, low cost instrumentation, experimental testing, CFD simulation.

I. INTRODUCTION

WIND tunnel is a techno-scientific tool developed to obtain specific data from fixed parameters experiments. The main reason to use wind tunnel testing is to improve the aerodynamic bodies performance without the high cost of field tests [1]; though, the use of specific measuring instruments to obtain precise data is required.

In small countries, the low demand of high precision instruments increases the importation costs, resulting in expensive materials. For this reason, experimental approaches in fluid mechanic lectures, are not feasible. Multiple purposes measure equipment could be adapted into wind tunnels to work as affordable instruments replacement, despite its important uncertainty. Accessible instruments bring the possibility to compare theory and practice. Theoretical resolutions are not only old-school hand calculations, but also, sophisticated methods, such as parametrical analysis and CFD.

CFD simulation and parametric analysis are approaches that can be used to solve fluid mechanic problems. The CFD of diverse bodies in wind tunnel conditions, usually shows accurate predictions with respect to the corresponding experiment [2]. Parametric analysis tools such as XFOIL are used as cornerstones for airfoils designs and their selection [3], as well as a CFD comparison model [4]. Even though those approaches show expected results, an experiment is needed to validate them.

The wind tunnel for this experiment is an open cycle wind tunnel with a max speed of 0.1 Mach. The general dimensions are showed in Fig. 1. Properties like wind speed, pressure at test zone, and temperature are measured, in case of the remaining stations speed or pressure are calculated. The wind tunnel is in Quito, and the atmospheric conditions for this case of study are shown in Table I. The aerodynamic body is placed in testing zone 2 (Fig. 1).

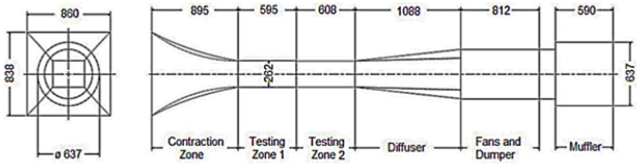

Fig. 1 Wind tunnel dimensions

TABLE I
ATMOSPHERIC CONDITIONS QUITO

Property	Value
Atmospheric Pressure	73112 Pa
Density	1,23 kg/m³
Dynamic Viscosity	1,785 e^{-5} kg/ms
Cinematic Viscosity	1,480 e^{-5} m²/s
Temperature	288,15 °K

The body to test in the wind tunnel is a NACA 2412 profile, with 15 measuring points (GP). The NACA profile is made by 3D printing and its dimensions are 16 cm of chord (c), 12 cm of span (w), and 2.5 mm of GP diameter. Firstly, the model was developed as a solid piece with 90° inner ducts, witch in practice showed larger losses that compromise the data collection. To avoid this, the profile was built as a shell-like profile with 2 mm of thickness (sw), as shown in Fig. 2, which enables the use of flexible hosepipes with an inner diameter of 1.5 mm that can shape according to the geometry of the wind tunnel and reduce the pressure losses. Those hosepipes connect the GP with a pressure transductor, which registers the physical phenomena as a digital sign.

C. P. Topa is with the Escuela Politécnica Nacional, Quito, Ecuador (e-mail: crisstopin1@hotmail.com).
E. A. Valencia, V. H. Hidalgo and M. A. Martinez are with the Departamento de Ingeniería Mecánica, Escuela Politécnica Nacional, Quito, Ecuador (e-mail: esteban.valencia@epn.edu.ec, victor.hidalgo@epn.edu.ec, marco.martinez02@epn.edu.ec).

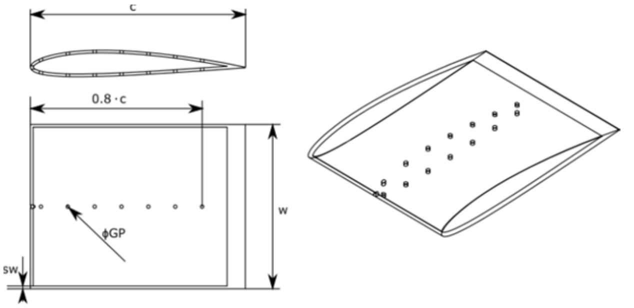

Fig. 2 Airfoil specifications

II. Methodology

This section describes the implementation process of the data acquisition (DAQ) system and the measuring instrumentation comparison with numerical methods. The stages in this process are: the weighted selection to establish an adequate instrumentation alternative, the DAQ software development, and the comparison of the set-up against numerical approaches. Fig. 3 shows the roadmap carried out to implement the wind tunnel instrumentation.

A. DAQ System Selection

A weighted selection for the DAQ system is done. The weighted value was defined to satisfy the objective of the present work. The criteria taken were: cost (30%), specifications (25%), assembly (20%), maintenance (15%), and lifetime (10%). In the selection matrix, the maximum value corresponds to 10 points and this means that the alternative fully satisfies the criteria.

The three alternatives selected for the test-rig, based on their cost and level of accuracy for the case of study, are:

A. Pressure scanner ZOC22B and rad 4000 measurement system [5].
B. Honeywell DC005NDC4 pressure transducers, and PCI-6224 A/D board [6].
C. Honeywell SSCSNB005NDDAA5 pressure transducers, and a National Instruments USB 6009 board. [7]

B. Test Rig Configuration

The DAQ system platform is developed in LabVIEW software. This platform processes the signal form sensors distributed over the profile and shows the result in pressure coefficient terms. The pressure sensor has a linear potential output from 2.57 V (equivalent to 0 Pa) to 4.93 V (equivalent to 122.5 Pa). The DAQ board connects the pressure sensor with the PC as shown in Fig. 4.

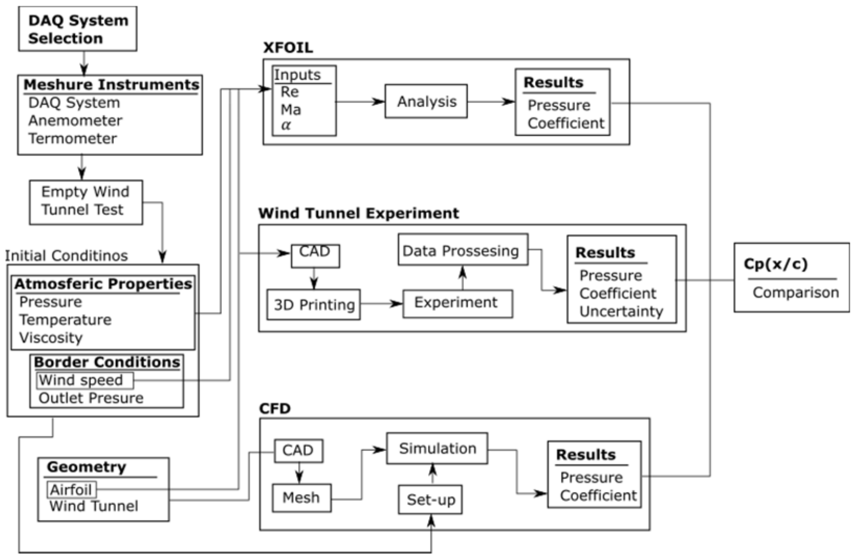

Fig. 3 Methodology of evaluated approaches

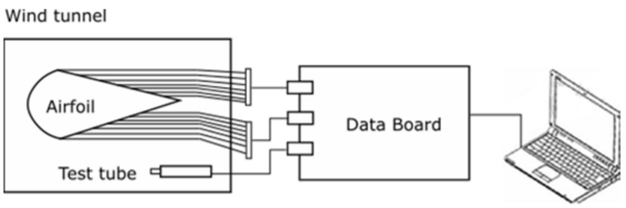

Fig. 4 DAQ system scheme

C. Standard Conditions Determination

For this phase, an anemometer (SMART SENSOR AR816+) is used to measure the air speed at the entry of contraction, test zone 2, and the diffuser. Employing static pressure taps in the wind tunnel, the static pressure at the entry of contraction zone and test zone 1 inlet are determined. The static pressure at test zone 2 and diffuser inlet were calculated using Bernoulli equation and continuity.

D. Wind Tunnel Experiment

Using airfoil geometry, a CAD model is developed and 3D printed. The profile is placed in the test zone 2, at the corresponding angle of attack (α). Also, the DAQ system is connected and set with the atmospheric conditions. The wind tunnel is turned on and using a flow valve, the speed of the wind tunnel is controlled. In the PC, the data collected is stored for each case run in the wind tunnel and then these data are plotted, including the uncertainties immersed in the measuring process.

E. Uncertainty at Pressure Sensor Analysis

The uncertainty of the measures has two parameters, the random uncertainty (U_A), caused by the statistic factors and the systematic uncertainty (U_B) caused by the measure equipment. The terms for the further equations correspond to: measurements (X), measure number (n), Instrument error (E), sensitivity of resolution (R_{out}) and the number of sensors (N).

$$U_A = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}} \quad (1)$$

$$U_{B1} = \frac{E}{\sqrt{3}} \quad (2)$$

$$U_{B2} = \frac{R_{out}}{2\sqrt{3}} * N \quad (3)$$

$$U_{Total} = \sqrt{U_A^2 + U_{B1}^2 + U_{B2}^2} \quad (4)$$

F. CFD Simulation

The geometry of the wind tunnel and airfoil is used to obtain a fluid domain. The meshing of the fluid domain is constructed in ICEM CFD. With this information a structured mesh is developed [8]. For the adequate simulation using $k - \omega SST$ model the Y+ criteria achieved is lower than 1. The general mesh distribution, at inlet and outlet is shown in Fig. 5 (a). The inner mesh around the profile is refined taking the Y+ parameter and block construction around the profile, as shown in Fig. 5 (b), to ensure the mesh quality. The mesh has 480,000 elements. Using the orthogonal quality criteria, the mesh has an overall quality superior to 0.90.

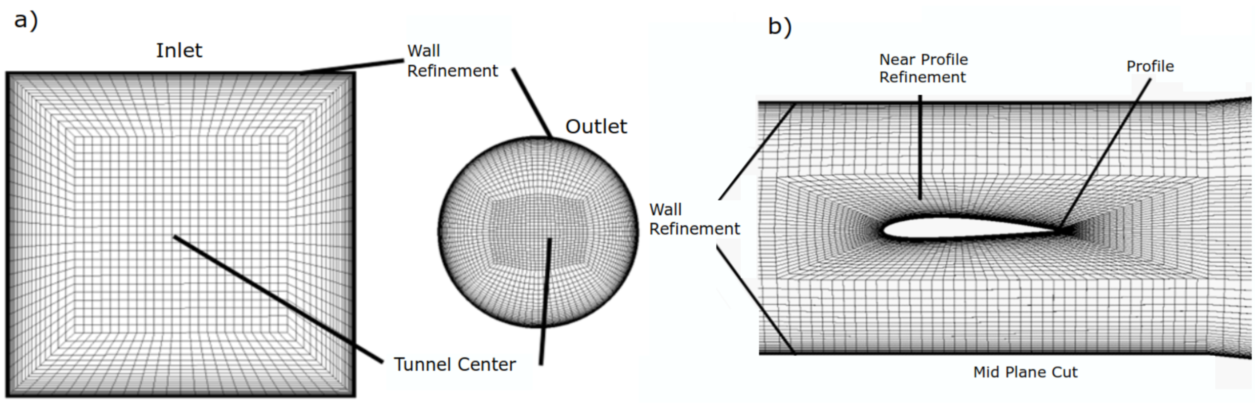

Fig. 5 Structured Mesh a) Inlet and outlet, b) Mid-plane cut

The turbulence model $k - \omega$ SST is selected for the simulation. The reason was because of the low wind speed and the interference between the wind tunnel wall and the profile influence.

The initial conditions of pressure, temperature, density and viscosity are set using the conditions shown in Table I. The boundary conditions are 0.9 m/s for the inlet, and the outlet is -12 Pa.

The solving method selected for this simulation is SIMPLEC, with moment condition of Second Order Upwind, and Turbulence condition of First Order Upwind, for a quicker resolution. The convergence criteria are obtaining residual values lower than 1 e^{-4} and/or stability on residuals at least in 100 iterations.

III. Results and Discussion

In this section, the results are displayed and interpreted. It starts with the alternative selected, followed by the pressures measured. Using as the parameter for comparison, Cp , the measured values are contrasted against numerical approaches.

The evaluation for the DAQ system is shown in Table II. Using the weighted selection method, the alternative C shows the best match for the required conditions, and as observed, this mainly relates to its low cost. Therefore, this alternative of the pressure sensor and data board were the chosen.

TABLE II
Weighted Selection Alternatives

Criteria	Alternative A	Alternative B	Alternative C	Weight
Cost	5	9	10	0.3
Specifications	9	8	8	0.25
Assembly	9	8	9	0.2
Maintenance	9	9	9	0.15
Lifetime	10	10	10	0.1
$\sum$	7.9/10	8.65/10	9.4/10	

The pressure values measured at the inlet of each zone are shown in Table III. The air speed used for the current analysis is 8 m/s, which is based on the requirements for the airfoil potential applications in the UAV sector.

TABLE III
Pressure Values at Wind Tunnel Principal Zones Inlets

Zone	Static Pressure
Contraction	73 112 Pa
Test Chamber	73 050 Pa
Diffuser	73 097 Pa

Figs. 6-8 show the comparison between three approaches at different angles of attack, and in this figure the uncertainty computed has been included. In Fig. 6, it is shown the Cp at an angle of attack of 5; it is clear that the trends are captured and there is a good match with the CFD approach, which is expected since this model was set to account for the viscous losses. In this graph, the case of XFOIL has been included for the sake of completeness and to determine the error induced, when this approach is used for preliminary airframe designs.

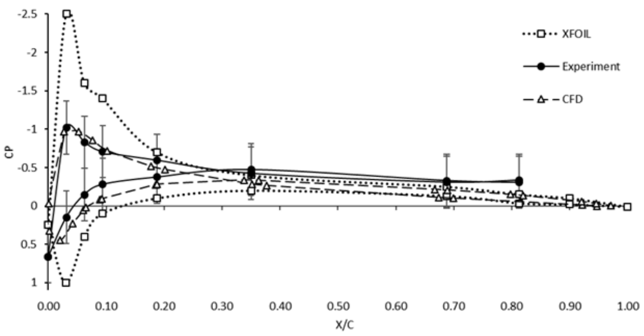

Fig. 6 α -5 degress

In Fig. 7, the Cp for an angle of attack of 10° is displayed. For this case, it is observed a similar behavior as at 5°.

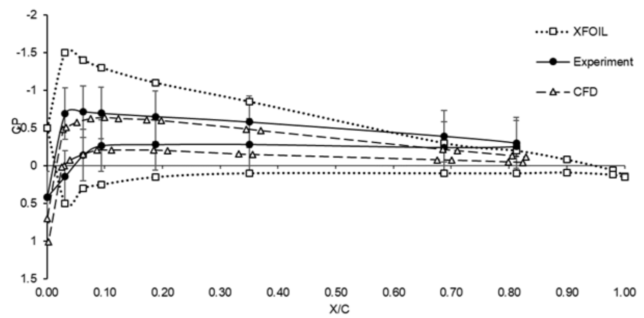

Fig. 7 α 10 degrees

The curves displayed in Fig. 8 are for angle of attack of 15°, which is the maximum angle of attack for the case of study. From the comparison, it is observed that CFD predicts with good enough accuracy, the measured results up to this angle of attack. At the trailing edge however, there is a mismatch between the CFD and experimental, which can be related to the separation that occurred in the experiment where a plateau of static pressures is achieved.

In Table IV, the average error of each approach for the different angles of attack is displayed. The tendency shows that at a bigger angle of attack, the error at XFOIL increases, while the CFD error decreases. The minimum error is for CFD at 15° with an error of 12.83%, which represents good accuracy.

To summarize, it is observed that for the range of velocities and angles of attack for the case of study, CFD predicts with good accuracy the pressure coefficient along the NACA 2412 airfoil. Furthermore, it is observed that the low-cost instrumentation implemented in the wind tunnel, which arises to a cost of 964.88 USD, delivers a good enough accuracy compared with the investment.

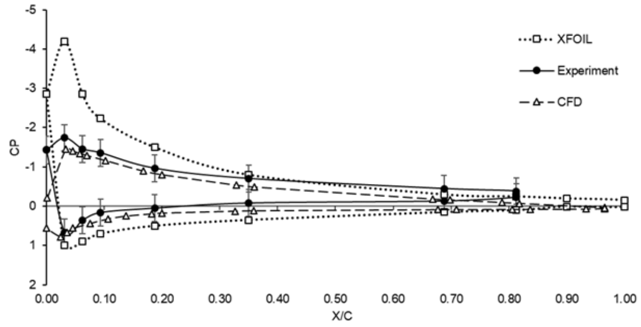

Fig. 8 α 15 degrees

TABLE IV
ERROR SUMMARY

Angle of Attack	XFOIL Error	CFD Error
-5°	27.25%	34.23%
5°	53.25%	27.40%
15°	89.35%	12.83%

IV. CONCLUSION

A low cost DAQ system was developed using a Honeywell SSCSNB005NDDAA5 pressure transductor, a National Instruments USB 6009 board and Labview self-developed graphic interphase. Upon its wide uncertainty, the results are satisfactory.

XFOIL presents an error of 55.96% and CFD an error of 29.77%, which shows that the CFD approach is the better option for the analysis of airfoils. However, considering the simplicity in terms of time and computational resources of the XFOIL software, its use for preliminary design might not be a bad option, since this latter approach is observed to capture the trends in Cp. CFD is a valid method of comparison, and the principal error of this method is that it considers the profile as a perfect surface, when it has numerous microdefects that causes variation over the surface pressure.

The CFD simulation showed satisfactory results that keep inside the uncertainty zone of the experiments, with errors lower than 35% (and the minimum error of 12.83%), while the XFOIL analysis presents an error at lower than 90% (and minimum error of 27.25%).

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by Escuela Politécnica Nacional for the development of the project PIJ 15-11, PIS 16-20 and PIMI 15-03

REFERENCES

[1] B. Chanetz, “A century of wind tunnels since Eiffel,” *Comptes Rendus Mécanique*, vol. 345, no. 8, pp. 581–594, Aug. 2017.
[2] W. D. Janssen, B. Blocken, and H. J. van Wijhe, “CFD simulations of wind loads on a container ship: Validation and impact of geometrical simplifications,” *J. Wind Eng. Ind. Aerodyn.*, vol. 166, no. Supplement C, pp. 106–116, Jul. 2017.
[3] M. Tahani, G. Kavari, M. Masdari, and M. Mirhosseini, “Aerodynamic design of horizontal axis wind turbine with innovative local linearization

of chord and twist distributions," *Energy*, vol. 131, no. Supplement C, pp. 78–91, Jul. 2017.

[4] J. Morgado, R. Vizinho, M. A. R. Silvestre, and J. C. Páscoa, "XFOIL vs CFD performance predictions for high lift low Reynolds number airfoils," *Aerosp. Sci. Technol.*, vol. 52, no. Supplement C, pp. 207–214, May 2016.

[5] Q. Li, Y. Kamada, T. Maeda, J. Murata, and N. Yusuke, "Effect of turbulence on power performance of a Horizontal Axis Wind Turbine in yawed and no-yawed flow conditions," *Energy*, vol. 109, no. Supplement C, pp. 703–711, Aug. 2016.

[6] S. G. Pouryoussefi, M. Mirzaei, M.-M. Nazemi, M. Fouladi, and A. Doostmahmoudi, "Experimental study of ice accretion effects on aerodynamic performance of an NACA 23012 airfoil," *Chin. J. Aeronaut.*, vol. 29, no. 3, pp. 585–595, Jun. 2016.

[7] Honeywell, "TruStability Board Mount Pressure Sensors SSC Series'Standard Accuracy, Compensated/Amplified." Honeywell, 2016.

[8] E. Valencia and V. Hidalgo, "Innovative Propulsion Systems and CFD Simulation for Fixed Wings UAVs," 2017.