XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

Aerodynamic and aeroelastic analysis of the NACA0012 airfoil using CFD

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Abstract. The aerodynamic analysis represents the beginning of the conceptual planning of an aeronautical project. These analysis result in the establishment of important parameters, such as the maximum weight that the aircraft is allowed to have, as well as the aerodynamic coefficients, which define geometric and flight aspects. There are several ways of evaluating the aerodynamic coefficients of a wing, such as, for example, the use of wind tunnels (database in the laboratory), traditional analytical methods, or even computer modeling, which can be based on the method of panels, or finite volume method (FVM). In order to develop this work, FVM and the open source code called OpenFOAM (in C++ programming language) are used. The aim of this experiment is to analyze the activity of the aerodynamic coefficients with the increase of the angle of attack (AoA) of the airfoil NACA 0012, through a two-dimensional model, and apply these data to evaluate the aeroelastic phenomenon of divergence of a conceptual wing. The aerodynamic coefficients of lift and drag were evaluated for a Reynolds number 700000, by the consideration of a turbulence model of the RANS class of the Reynolds averages called k-omegaSST. For the computational solution, the implementation of pressure-velocity coupling was used, through the SIMPLE method. The angle of attack started from 0 degrees to the limit region for the start of the stall. The results were consistent with those established as a reference, which was obtained for data validation of the NACA 0012 airfoil. The rate of variation of the lift coefficient, as a function of the angle of attack of the airfoil, allows the evolution of the aerodynamic loading in the structure, an essential factor for the aeroelastic study of a project. The example discussed in this work does not fail structurally, and presents a divergence velocity value above the limit for the flight envelope.

Keywords: CFD, NACA0012, k-omegaSST, divergence speed

1 Introduction

With the development of aeronautical engineering, the need of obtaining higher levels of reliability and efficiency of aerodynamic data has driven the evolution of computational techniques, which allows the prior assessment of aircraft design parameters. The behavior of an aerodynamic airfoil of an aircraft can be widely studied and evaluated in the initial stages of any aeronautical project, making it possible to choose the best parameters that meet the flight characteristics of a project.

This paper will addresses the two-dimensional study of an airfoil moving in two degrees of freedom. In this study, we used computational techniques that simulate the pressure and velocity field acting on this airfoil, which initially evaluates the behavior of this airfoil for a range of attack angle values, allowing us to obtain the aerodynamic coefficients of lift and drag, and thus validates this data for the NACA 0012 aeroelastic airfoil calculation.

Using the data obtained from the two-dimensional analysis of the airfoil, it is the interest of this paper to perform an aeroelastic analysis for the static model of this airfoil, aiming to address the structural behavior of a wing with the addition of the aerodynamic loading acting on the structure. In this airfoil, structural parameters of a conceptual aircraft were used, and the threshold speed value for torsional divergence was calculated.

This paper begins with the introduction of aerodynamic and aeroelastic theory, and presents an approach to the equations used in the numerical methods used in the computational solution. Then, it presents a deepening of the numerical technique used, presenting the chosen computational model, the computational domain, and the study of the meshes for numerical solution. Sections 4 and 5 present the results of this paper, the last section concludes the presentation of these results and possible complementary works.

2 Theoretical basis

2.1 Aerodynamics

In aerodynamics, for a body immersed in a fluid, the pressure distribution and shear stress are the basis for obtaining the aerodynamic forces acting on this body, regardless of the geometry under analysis [1]. The Figure 1 presents an example widely used for the study of aerodynamics, an airfoil.

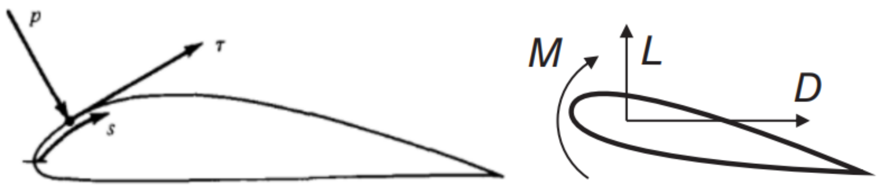

Figure 1. Airfoil - The figure on the left is taken from [1], and the figure on the right is taken from [2].

Through the resulting aerodynamics, it is possible to extract its aerodynamic coefficients, which are dimensionless variables, and numerically represent the capacity of an airfoil to generate lift (L), drag (D) and aerodynamic moment (M).The lift, as can be seen in the Figure 1, is the vertical resultant of the pressure field, and acts perpendicularly to the direction of movement of the airfoil, the drag force is the resultant contrary to the direction of movement of the airfoil. The aerodynamic moment represents the moment generated in the airfoil by the pressure field results [2].

The lift coefficient C_L, allows us to observe how much an airfoil can generate lift, however, lift is directly related to the angle of incidence of the fluid that travels through the body, and therefore, for a complete evaluation of the lift behavior, it is interesting to obtain the Cl/α derivative of an airfoil, which relates the lift coefficient as a function of AoA, analyzing the rate of this lift coefficient, which can be obtained by Equation 1.

$$\frac{\partial C_L}{\partial \alpha} = \frac{C_L(\alpha + \Delta\alpha) - C_L(\alpha)}{\Delta\alpha}. \tag{1}$$

2.2 Fluid mechanics governing equations

The aerodynamic analysis of airfoil, and the evaluation of the aerodynamic coefficients, can be developed by several methodologies. Before the computational advance present in the aeronautical industry, traditional methods and experimental data formed the theoretical basis for the aerodynamic study of a project, however, several effects can influence the reliability of empirical aerodynamic parameters, estimulating the research for a more precise and accurate analysis, which can be consistent with the design of a project, enabling investment in new techniques for predicting aerodynamic data. Computational fluid mechanics made possible an interactive and comprehensive process, which allows the evaluation of the flow behavior of a fluid.

The Navier-Stokes equations analytically describe the behavior of fluids through governing equations, which effects such as fluid compressibility, viscosity and energy dissipation [1] are taken into account.

The mass and momentum conservation equations promote the study of fluid dynamics, and are nonlinear second-order partial differential equations, which allow the determination of the pressure fields acting on the fluid, and consequently the evaluation of the velocity profiles of these particles.

2.3 Divergence aeroelastic phenomenon

Aeroelasticity is a branch of aeronautical engineering that studies fluid-structure interaction, and can be divided basically into two analyses: static, where the behavior of the structure does not depend on the influence of time, and dynamics, where there is the influence of weather structural response time. In this work, only the static phenomenon of torsional divergence will be addressed.

The Figure 2 shows a wing being deformed by torsion, a situation that must be avoided in the operational envelope of an aircraft.

Figure 2. Example of structural response to torsional displacement of a wing.

Divergence is one of the most important phenomena in the static study, which evaluates the behavior of the structure with aerodynamic loading. Assuming an aerodynamic airfoil wing, structural collapse can occur when the aerodynamic forces of the airfoil are greater than the elastic resisting forces of the structure.

The divergence evaluation occurs with the analysis of its flight limit speed, this speed represents the moment of structural failure of the wing. The Equation 2 represents the dynamic divergence pressure, which is composed by the structural and aerodynamic parameters.

$$q_{div} = \frac{K_t}{ec^2 \frac{\partial C_L}{\partial \alpha}} \tag{2}$$

Where q_{div} is the dynamic divergence pressure, which is a function of the fluid density and the velocity of the body, e represents the distance between the elastic center and the aerodynamic center of the airfoil, and c represents the cord of the airfoil [2]. The K_t is a structural parameter, which represents the torsional stiffness value of the airfoil. The divergence velocity is obtained through dynamic pressure and can be observed by the Equation 3.

$$q_{div} = \frac{1}{2}\rho {v_{div}}^2 \tag{3}$$

3 Numerical techniques

Numerical analysis via CFD can be performed by different solution methods, finite element, finite difference and finite volume methods are solution models traditionally used to approach computational problems [3]. Several software can be used for the computational fluid dynamic study, and, in this work, for the analysis of the aerodynamic coefficients, an open source program called Openfoam (Open source Field Operation And Manipulation) was used, which takes advantage of the finite volume method (FVM) for the solution of the Navier-Stokes equations. The programming language is developed in C++.

3.1 Computational domain and mesh option

Once the numerical method used for the solution via CFD is defined, another important parameter is the computational domain used, the Figure 3 presents the two-dimensional domain and the defined boundary conditions.

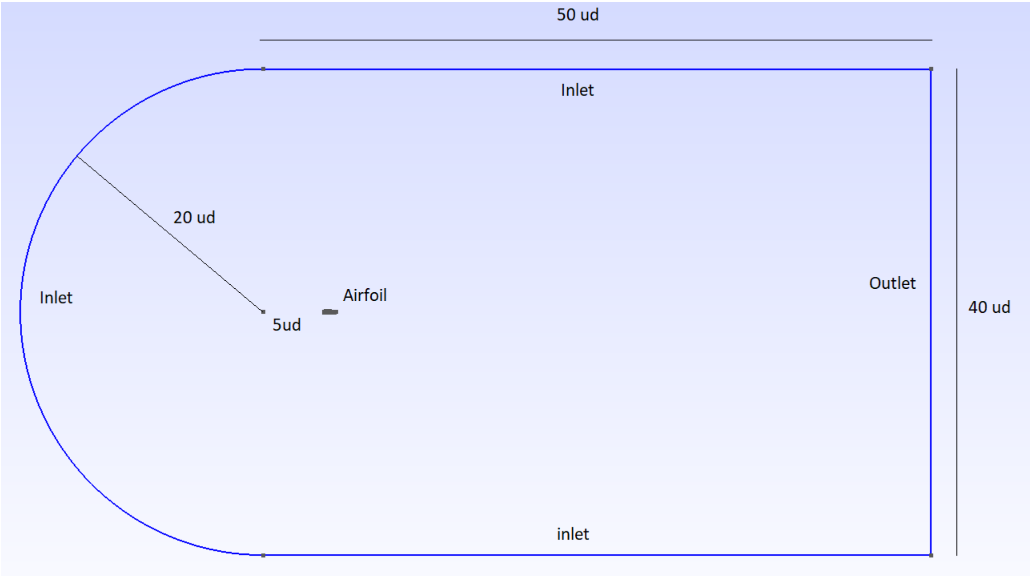

Figure 3. Computational Domain - NACA 0012

Inside the domain, the airfoil NACA0012 was placed with all the coordinates of the top and bottom of the airfoil, and with the help of the Bspline function, all points were interconnected, forming the curvature of the airfoil. A unit dimension (ud) of the airfoil chord was used, parameterizing the entire domain as a function of this dimension. The boundary condition *inlet*, was defined on the frontal semicircle face, and on the upper and lower faces of the domain. The *outlet* condition was defined on the vertical face at the end of the domain. On the airfoil, the boundary condition *airfoil* has been applied.

The boundary condition *inlet* was defined for uniform flow, with unit velocity and zero pressure gradient. In the *outlet* condition, the zero pressure and zero velocity gradient condition was applied. For the *airfoil*, zero pressure gradient was applied. The mesh used for the solution was created in gmesh [4], which makes it possible to represent a two-dimensional physical domain.

In the definition of the mesh, three refinement models were tested, the Table 1 presents the characteristics of the nodes and elements used for each mesh. The study was carried out for the zero angle of the airfoil in relation to the AoA, and all analysis were performed until the coefficient stabilized, evaluating these values with those of the [5] reference, obtained in a wind tunnel test.

Table 1. Mesh Analysis - Airfoil NACA 0012

Mesh	Nodes	Elements	$C_l - 0°$	$C_d - 0°$
Malha 1	41460	123484	0.0606	0.1224
Malha 2	114400	343234	0.0140	0.0833
Malha 3	150260	448202	0.0014	0.0081

Evaluating the three meshes used, the lift coefficient of mesh 3 obtained the closest value to the experimental reference value, 0.0067 for C_d and 0 for C_l. Once mesh 3 is defined, the analyzed coefficients present results close to the reference values. The Figure 4, presents the profile NACA0012 with mesh 3, used for the analysis of the aerodynamic coefficients.

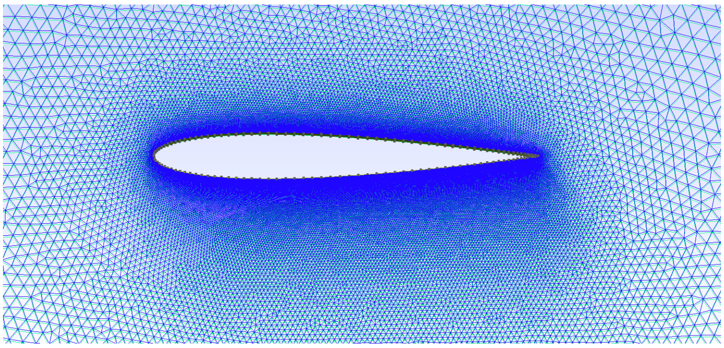

Figure 4. Mesh 3 - NACA 0012

4 Numerical solution and analysis of aerodynamic coefficients

The SIMPLE (Semi Implicit Methods Pressure Linked Equations) solution method was used to determine the pressure and velocity distributions [6]. The analysis occurs for a Reynolds number of 700000, being considered an incompressible flow and occurs by turbulent diffusion. The turbulence model used was the k-omegaSST, RANS (Reynolds Averaged Navier-Stokes), which relates the equation of the kinetic energy of turbulence, k, with the dissipation of the turbulence ω [7].

The aerodynamic analysis take place for a range of airfoil angle of attack, ranging from zero degrees to up to the thirteenth degree, with an increasing variation of 1 degree. For the present study, the AoA limit was defined at the thirteenth degree, because above this angle, the stall condition significantly influences the values of the coefficients, highlighting the beginning of the decay of the lift coefficient of the airfoil, and the accentuated increase of the coefficient of drag.

In order not to change the mesh for each interaction, the AoA was switched in the incidence velocity of the *inlet* boundary condition, being decomposed for each analyzed angle. The velocity remained unity for the entire analysis interval.

After performing all the computational interactions, the aerodynamic coefficients of lift and drag were defined by evaluating the response file, being chosen for the integration step that presented the convergence of values. The validation of the aerodynamic coefficients was carried out in comparison with the experimental curves obtained in a wind tunnel test, compared with the reference [5]. The Figure 5 presents the behavior of the lift coefficients obtained in the simulations, designated by (Flores, 2022).

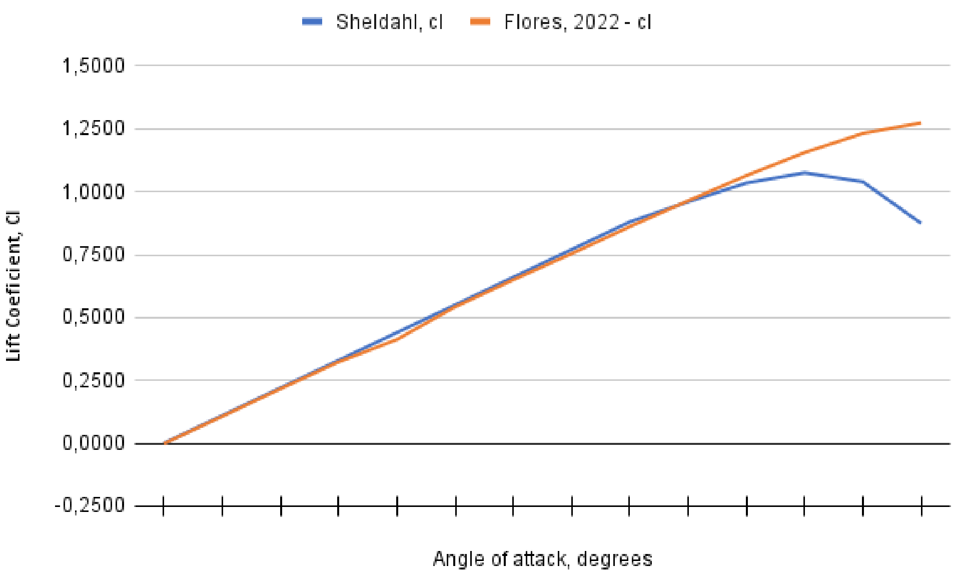

Figure 5. cl - Re700000

It is observed that the coefficient values were satisfactorily close to the reference values for AoA from zero to tenth degree, showing the beginning of discrepancy between the eleventh and thirteenth degree, characterizing the beginning of the stall condition.

As with the lift, the Figure 6 presents the behavior of the drag coefficient for the AoA proposed in the study. Evaluating the obtained data in comparison to the theoretical data, for the first attack angles, where the airfoil is relatively parallel to the air flow, the values walked towards the convergence, which occurred for the angles between 4 and 5 degrees and for the limiting angle of this analysis.

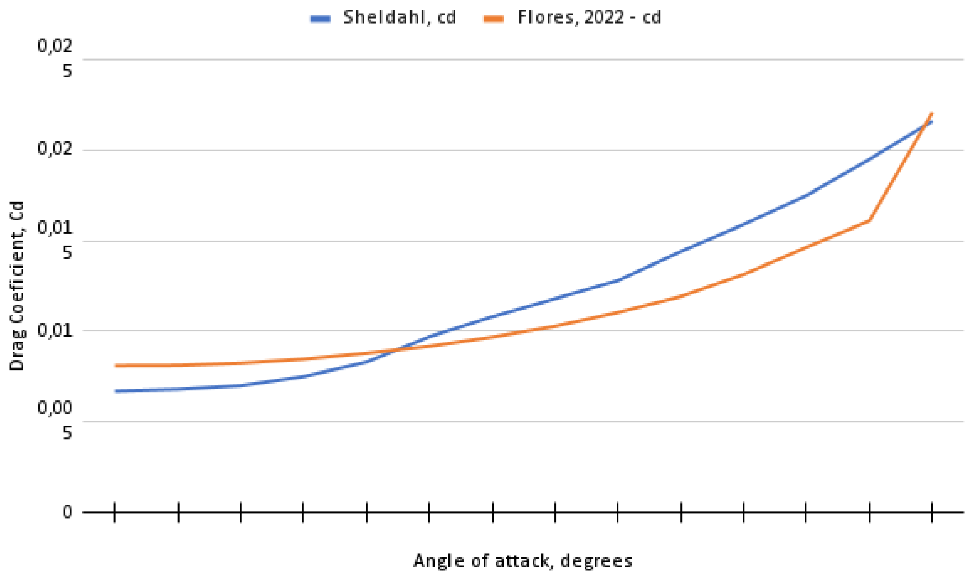

Figure 6. cd - Re700000

5 Analysis of lift coefficient and divergence velocity

Given the aerodynamic coefficients, the derivative of the lift coefficient as a function of AoA is obtained through the parameters developed computationally in this work, and calculated through the data shown in the Figure 5. The aerodynamic profile divergence speed calculation used the structural parameters of an aircraft wing airfoil, Table 2 presents the parameters used to calculate the divergence speed for the NACA0012 airfoil.

Table 2. Structural parameters of a wing - taken from the AM2018 project - UFJF microraptor team

Structural parameter	Nomenclature	Value
Torsional stiffness	k_t [N.m]	75.20
Wing chord	c [m]	0.240
Distance AC and CE	e [m]	0.080
Derivative	$\frac{\partial C_L}{\partial \alpha}$	5.816
Air density	ρ [kg/m3]	1.225

Through the Equation 2, the pressure of divergence is calculated, and consequently, with the aid of the Equation 3, the speed of divergence of the airfoil NACA0012 can be visualized by Table 3. The aeroelastic analysis presents the value of 2086 $N.m$ of dynamic pressure and 67.68 m/s of divergence velocity, values that are outside the flight envelope of the aircraft used as a reference.

Table 3. Aeroelastic results for airfoil NACA0012

Divergence pressure (Pa)	Divergence speed (m/s)
2086	67.68

6 Conclusion

For the purposes of the work, as mentioned in the initial part of this paper, the divergence speed is a parameter of structural stability, which must be outside the operational envelope of an aircraft. Using the k-omegaSST turbulence model, and a mesh defined in the Figure 4, the NACA 0012 airfoil presents validated values for an analysis with Reynolds number 700000.

Validating the values of aerodynamic coefficients, the divergence velocity was calculated, presenting a value of 67.68 m/s. This value, for the aircraft used, is far from operational flight speeds, since the cruise speed of this aircraft is 29.50 m/s.

In general, the aerodynamic analysis of the coefficients presented experimentally predicted results, validating the numerical techniques, the computational domain and the numerical solution. Finally, an aeroelastic analysis is performed so that the airfoil of a wing does not present significant torsional displacements along the flight, so the NACA 0012 airfoil of this work will not present deformations like the example presented in the Figure 2.

As a complement to this work, analysis of other families of airfoil can be performed. Another suggestion is the analysis of other aeroelastic phenomena for the NACA0012 airfoil, such as the command reversal phenomenon.

Acknowledgements. The authors would like to thank to the Post Graduate Program in Civil Engineering (PEC), to the Federal University of Juiz de Fora (UFJF)

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