26th International Congress of Mechanical Engineering
COBEM 2021
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-1590
COMPUTATIONAL FLUID-DYNAMICS MODELING OF PARAFOILS

João Pedro Leal Vieira
Manuel Nascimento Dias Barcelos Júnior
Universidade de Brasília, Faculdade UnB Gama - FGA, Área Especial de Indústria Projeção A, Setor Leste, Gama, CEP: 72.444-240
joaopedro.jacinto@hotmail.com, manuelbarcelos@unb.br

Abstract. *The study of the aerodynamics of ram-air parachutes, or parafoils, has historically had an empirical basis from analysis made in wind tunnels. Numerical computational approaches are an alternative with greater accessibility and a reasonable assessment of the internal and external flow. Therefore, tests on a conventional closed airfoil, with well-defined aerodynamic coefficient values, have been made to validate a mesh and a turbulence model for a given geometric characteristics, more precisely the thickness, found in the Ascender airfoil, which is a reference model in this research. The membrane structure was considered rigid at its geometric position of optimum performance. The fluid dynamics numerical simulations run in a two-dimensional form, with a Reynolds Number of 300,000 in a steady-conditions glide, using the finite-volume discretization method of the RANS (Reynolds-Averaged Navier-Stokes) equations, applied by the software ANSYS Fluent. It is possible to identify performance drops in aerodynamic efficiency and a decrease in the stall angle, both associated with the air recirculation bubble generated by the opening in the leading edge through previous studies. This work aims to compare and analyze empirically referenced results achieved by the inner-out pressure differential of the Ascender parafoil with results obtained numerically. Therefore, verifying the usability of computational modeling for lower cost analysis before tests in a wind tunnel. Besides, the simulations performed to evaluate the lift coefficient's decay compared to the closed airfoil, as predicted by the theory. We found solutions for three different Ascender airfoil geometric models, with closed (rounded and straight) and opened leading edges, making it possible to visualize the influence of internal pressure on aerodynamic parameters. For the first two geometry models, previous results obtained from a panel method approach permitted an evaluation of its validity in the presented case. Finally, the results demonstrate reasonable accuracy with the proposed reference, considering the instability of aerodynamic characteristics in an open-airfoil.*

Keywords: *Parafoil, Computational fluid dynamics (CFD), Aerodynamics, Internal Pressure, Pressure Coefficient.*

1. INTRODUCTION

The parafoil, invented in 1964 by Domuna Jalbert, consists in a rectangular wing with an opening on its leading edge which allows it to inflate and conform its geometry to the desirable aerodynamic properties. The structure of the parafoil is divided in sections named cells. Its applications sparked special interest in the part of the military sector, for usage in personnel transportation and supply missions in situations which did not offer appropriate conditions for aircraft landing, as mentioned by Fogell (2014) and Lingards (1995).

The aforementioned missions had been so far performed by traditional parachutes and the invention of the parafoil allowed better control and navigation, solving many problems associated with climate susceptibility. The inclusion of autonomous navigation systems and GPS receiver control made parafoils the ideal choice for rapid supply transportation and launch vehicle systems recovery missions (Fogell (2014)).

Having thus presented the advantages of the parafoil, interest in aircraft delivery systems development has been renewed, although general landing accuracy has still not found itself as precise as is desired, being inferior to a well trained skydiver in control of a similar system (Fogell (2014)).

Differing from rigid wings, the parafoil has unique characteristics pertaining its structural malleability, presenting critical failure points due to deformations of the optimal profile geometry. Another distinctive aspect of the parafoil is its leading edge air intake, which causes adversities to the aerodynamic efficiency of the parafoil, limiting the operational range of missions (Mashud and Umemura (2006)).

Studies relating to this theme, in a general sense, have always been done in an experimental manner, using a diverse array of tests which in turn greatly increased the cost and effort required, therefore making computational modeling and simulation a valid alternative for parafoil design (Fogell (2014) and Ghoreyshi *et al.* (2016)).

Research previously performed by Mohammadi and Johari (2009) and Fogell (2014) obtained results that suggest the existence of vortexes in the interior of the parafoil, caused by a bubble on the lower lip of the leading edge. This bubble is created by an abrupt change in the direction of the flow streamlines bellow the stagnation point which follow the cell opening and reach the lower lip of the leading edge.

The present study hopes to reach two main objectives: the identification of aerodynamic effects related to the parafoil profile through the usage of numerical tools; The understanding of the models, the fluid dynamics simulation tools and the limitations of the latter for representing such system.

2. NUMERICAL METHODS

In accordance with the proposal of applying numerical methods for the study of aerodynamic evaluation of parafoils, computational fluid dynamics simulation software have been utilized, including the panel method (Xflr5) and finite volume analysis (Ansys). Following the initial considerations, the panel method was applied on continuous leading edge profiles, in both rounded and closed - that is, having the air intake geometry present in place of the rounded tip, but sealed with a straight line - tip configurations. From the observations acquired, the analysis was elaborated on by using the finite volumes for approximated RANS (Reynolds-Averaged Navier-Stokes Equations) applied to turbulence models.

Initial mesh analysis was thus necessary for validating a similar model to the one in the proposed problem. For such purpose, an aerofoil with well defined experimental results for a Reynolds number of 300.000 was chosen, presented by Williamson *et al.* (2012), where solutions for three turbulence models are present, allowing the definition of a final methodology for this study.

2.1 Panel Method

According to Erickson (1990), the method is made of numerical implementations for solving the Glauert-Prandtl equation for laminar, non-viscous and non-rotational flow at subsonic or supersonic free-stream Mach numbers. This method shows some advantages over the RANS method, among which is the greatly reduced computational cost and pre-processing times, as described by Nelson and Kouh (2017). Furthermore, the method is useful for preliminary ram-air parachutes airfoil evaluations.

$$\tilde{\nabla}^2\phi = \left(1 - M_\infty^2\right)\phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \tag{1}$$

Considering the fluid as incompressible and subsonic, the Laplace equation follows.

$$\Delta\phi = 0 \tag{2}$$

The Glauert-Prandtl and Laplace equations are presented in Eq.(1) and Eq.(2), respectively.

Despite greater accessibility, the method in question, due to its requirements for the described flow characteristics, does not offer acceptable results for flow separation, skin-friction drag and transonic shocks, Erickson (1990). Considering the existence of a vortex in the open profile model, this method was therefore used only for comparisons pertaining the rounded tip and closed tip models, further discussed.

2.2 Finite Volumes Method

The finite volumes method consists in the fractioning of the solutions domain in a finite number of smaller control volumes, using for such the integral form of the conservation equation, presented in Eq.(3) below.

$$\int_S \rho\phi\mathbf{v}\cdot\mathbf{n}dS = \int_S \Gamma grad\phi\cdot\mathbf{n}dS + \int_\Omega q_\phi d\Omega \tag{3}$$

Where ρ is the fluid density, ϕ is viscosity dissipation rate, **v** is the velocity of the fluid, **n** is the normal unit vector, S is the volume surface area, Γ is the diffusivity of ϕ, q_ϕ is the source of ϕ and Ω is the control volume.

Fluid properties are calculated locally for each face center node of each element of the mesh by using the appropriate equations in its applications. When surface or volume integrals are present in said equations, numerical approximations should be used, as presented by Ferziger *et al.* (2019) and Anderson (2001), in conjunction with the method so as to attain the values for each node.

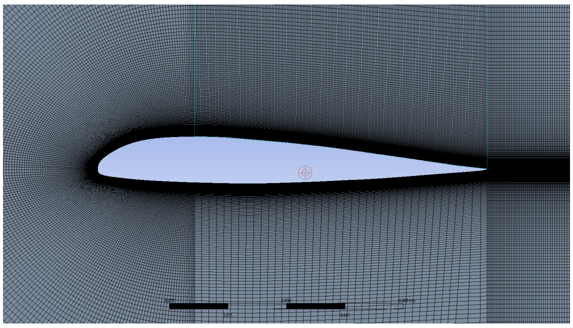
Therefore, the method utilizes simple geometries with known local behaviours in order to obtain approximations for global results of more complex flows.

2.3 Mesh Grid

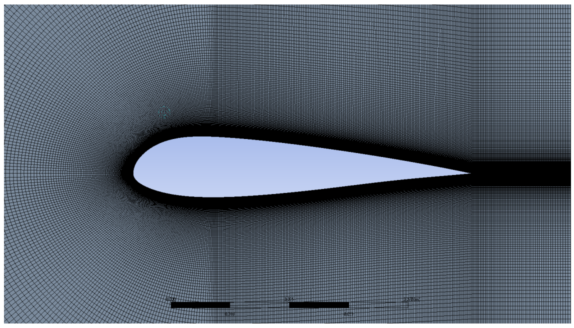
The mesh utilized for attainment of the comparative results was comprised by rectangular shaped elements, yielding values considered sufficient in the turbulence model comparison. 259,750 elements and 260,739 nodes have been used, having the mash been refined when near the outer edges of the parafoil. The end model was thus reached following refinement iterations with a criteria of 25 elements representing the boundary layer, ensuring greater trust and better discernment of the fluid behavior, characteristics which are paramount to the final parafoil evaluation. The mesh and its elements values are shown respectively in Fig. 1 and Tab. 1.

Table 1. Characteristics of Meshes Used

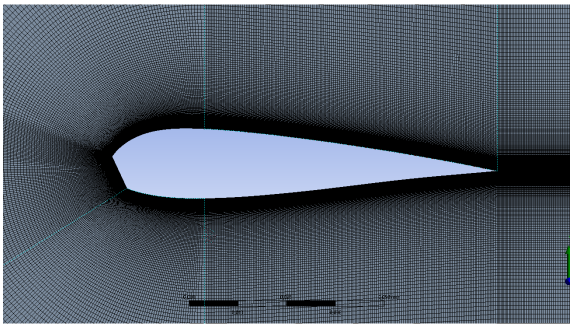
Profile	Nº of Nodes	Nº of Elements
Naca 43012A	260739	259750
Ascender (Rounded)	293324	292240
Ascender (Closed)	292616	291500
Ascender (Open)	435947	434976



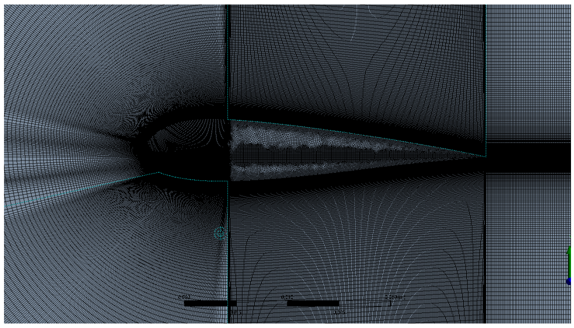
(i) NACA Airfoil 43012A.



(ii) Ascender Airfoil (Rounded).



(iii) Ascender Airfoil (Closed).



(iv) Ascender Parafoil (Open).

Figure 1. Constructed Meshes

Another concern in mesh grid refinement was ensuring a recommended value for the non-dimensional wall distance defined as y+. As shown in figure 2, the mesh construction process adopted the y+ value below 1.

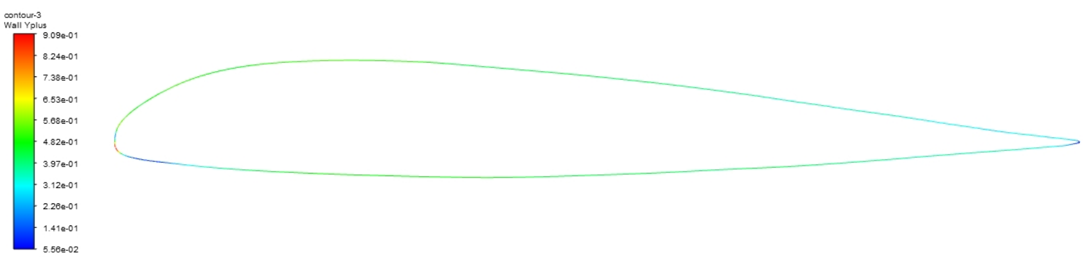


Figure 2. Wall Y+

Finally, the mesh refinement was increased by a factor of 1.5 in every detailing of the mesh and results were obtained for an angle of attack of 0º for the NACA 43012A airfoil, intending to certify the mesh independence.

Table 2 shows the low difference between results when increasing the mesh refinement.

Table 2. Comparison Between Meshes

	260739 nodes	580469 nodes	Relative Difference
Cl	1.5575e-1	1.5329e-1	1,57%
Cd	1.4030e-2	1.4072e-2	0,29%

2.4 Boundary Conditions

For the boundary conditions, the control volume inlet and outlet were well defined, as shown in Fig. 3, forcing the airflow of both to act in the same direction. At the inlet, a velocity of 43.84 m/s was defined, for an air density of 1,225 kg/m³, viscosity of 1.7894E-05 kg/m-s, and a chord of 0.1 m, it is obtained a Reynolds of approximately 300,000. The wall was considered stationary, rigid and with no heat flux.

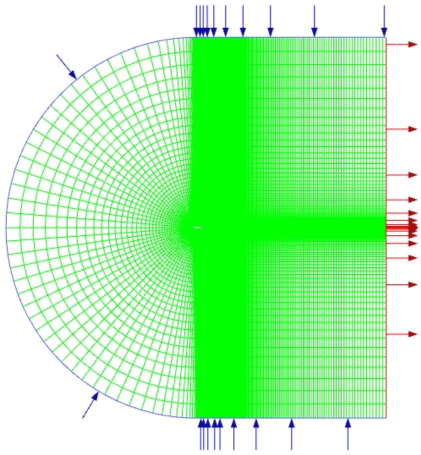


Figure 3. Control Volume

2.5 Turbulence Models

The choice of the turbulence model to be used stemmed from decisions on theoretical principles and results obtained in similar conditions to the ones found in this study. The aerofoil chosen for this comparison was the NACA 43012A, of which the values for lift coefficient - obtained experimentally by Williamson *et al.* (2012) - were extracted and compared. Among the models analysed, the K-Epsilon, K-Omega SST and Spalart-Allmaras were used for testing. The problems analysed in this paper are all in the linear region of the lift curve, therefore do not contemplate separations caused by stall.

Table 3. Lift Coefficient results of different turbulencce models on NACA 43012A

AoA	Results - Cl				Relative Error %		
	Kw - SST	**Ke**	**SA**	**Experimental**	**Kw - SST**	**Ke**	**SA**
0º	0.156	0.153	0.157	0.144	8.157	6.557	8.890
4º	0.553	0.533	0.562	0.582	4.918	8.391	3.519
10º	1.103	0.932	1.137	1.156	4.606	19.37	1.647
12º	1.238	1.108	1.297	1.325	6.540	16.37	2.136

Table 4. Drag Coefficient results of different turbulencce models on NACA 43012A

AoA	Results - Cd x 10²				Relative Error %		
	Kw - SST	**Ke**	**SA**	**Experimental**	**Kw - SST**	**Ke**	**SA**
0º	1.403	4.596	1.434	0.938	49.45	389.5	52.78
4º	1.576	3.088	1.602	1.163	35.50	165.5	37.72
10º	2.581	9.356	2.521	2.082	23.98	349.4	21.11
12º	2.340	6.982	3.146	2.429	3.666	187.5	29.52

From the results presented in Tab. 3 and Tab. 4, a better approximation for the values can be observed in the K-Omega

SST and Spalart-Allamara models when compared to the K-Epsilon model, particularly in relation to the drag coefficient. Therefore, taking into consideration the superior performance of the K-Omega SST for boundary layer separation and adverse pressure gradient conditions, Menter (1992), it was chosen to perform simulations at the Ascender parafoil, being as such used for comparing and understanding the behavior of the flow in open profiles. When considering the errors presented, it must be mentioned that experimental data had been taken from graphs with software assistance, and thus errors associated with the software precision may be involved.

3. RESULTS

The results obtained were evaluated in a mostly qualitative manner, in accordance with the goal of developing an understanding of the aerodynamic behaviours of parafoils. For this purpose, results were initially compared to approximated data from experiments done on the same airfoil studied by Benedetti and Veras (2021)

Following the congruence validation with theory and experimental data, the aerodynamic performance of the three profile models (rounded, closed and open) were compared. Hence, it was possible to evaluate the usage of the panel method and the finite volume method for approaching parafoil design.

3.1 Results Validation

From the approximations obtained by Benedetti and Veras (2021) using experimental data, the following evaluations could be made.

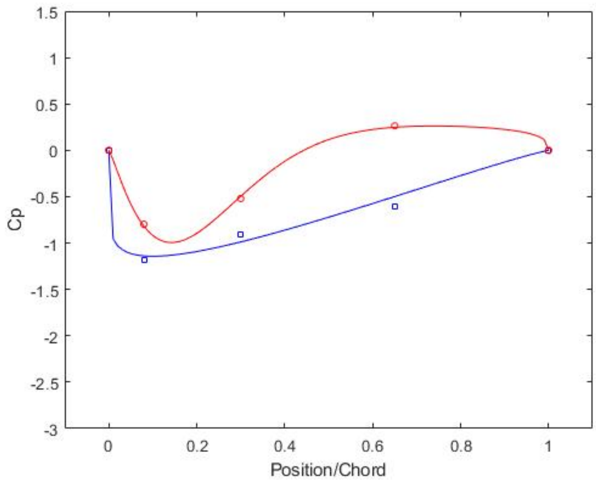


Figure 4. Pressure Coefficient - Experimental Data Approximation - AoA = 0º

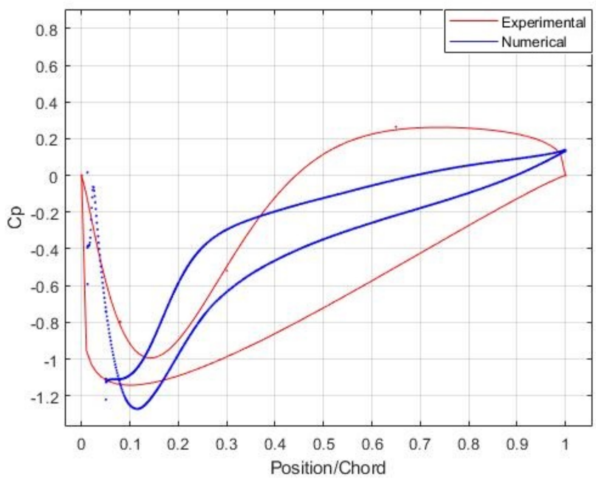


Figure 5. Pressure Coefficient - Comparison with Simulation Data Obtained - AoA = 0º

From Fig. 4 and Fig. 5, it is possible to evaluate the presence of a pressure drop at the lower lip of the leading edge, which theoretically implies decrements in the lift values of the parafoil. Also of note is the increase in pressure at 25% of the chord length at the upper surface, which does not appear in the model approximated by experimental data. Such effect may take place due to the numerical approximation used in the experimental problem that had few data points or by the internal fluid behavior model assumed.

Yet another characteristic worthy of mention is the evaluation of the internal pressure coefficient, which due to the velocity applied to the fluid, reached an stagnation point in a shorter relative chord percentage than the one presented by Benedetti and Veras (2021).

Moreover, utilizing another approach, it was possible to verify the coherence of the results, therefore allowing characterization of certain particularities relating to the theory. In addition to the pressure coefficient demonstrating the existence of a separation bubble inside the parafoil flow, as described by Mohammadi and Johari (2009) and Fogell (2014), the vortex in the parafoil interior could also be observed through the flow velocity vectors and the bubble at the lower leading edge through the flow path lines representations.

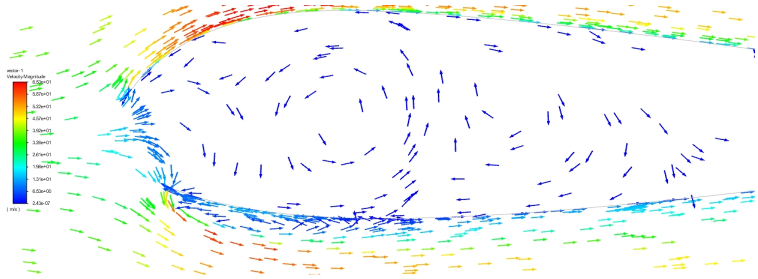


Figure 6. Velocity Vectors of the Flow (Open) - AoA = 0º

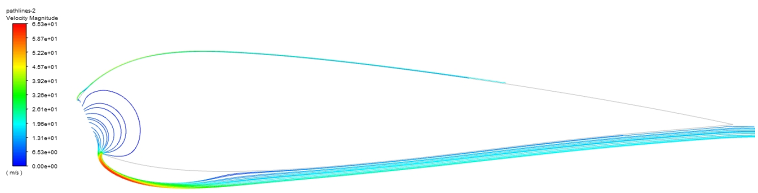


Figure 7. Pathlines at the Opening (Open) - AoA = 0º

From the Fig. 6 and Fig. 7, the direct influence that the changes in flow direction on the stagnation point have on the recirculation bubble at the leading edge becomes apparent, as is possible to see the flow disattaching from the lower leading edge after the change in direction, taking a path almost perpendicular to the wall. Such effect is described by Fogell (2014) with the explanation that the sharp edge at the lower leading edge results in a high vorticity area as the flow is redirected by the inlet face and flows past the corner to rejoin the rest of the flow.

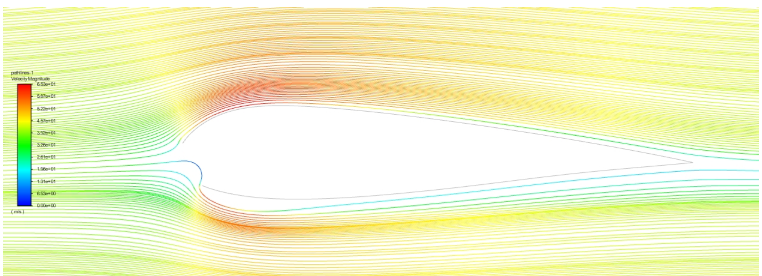


Figure 8. Path Lines of the Main Flow (Open) - AoA = 0º

Figure 8 present the pathlines in terms of velocity magnitude, featuring the opening influences on the main flow outside the wall.

3.2 Aerodynamic Performance of Parafoil Profile Models

In order to visualize the direct effects caused on the aerodynamic characteristics by its opening, results where obtained so as to analyse the performance variation of the aerodynamic coefficients of the three proposed profiles.

Table 5. Lift Coefficient results of different geometry models on Ascender

AoA	Results - Cl				
	Rounded	Closed	Relative Difference to Rounded	Open	Relative Difference to Rounded
0º	0.1850	0.2081	12.49 %	0.2475	33.78 %
5º	0.6891	0.6439	-6.561 %	0.5855	-15.03 %
10º	1.1284	Stall	-	Stall	-

Table 6. Drag Coefficient results of different geometry models on Ascender

AoA	Results - Cd				
	Rounded	Closed	Relative Difference to Rounded	Open	Relative Difference to Rounded
0º	0.01560	0.0190	22.00 %	0.03480	123.2 %
5º	0.01927	0.0239	24.33 %	0.05674	195.1 %
10º	0.03020	Stall	-	Stall	-

From Tab. 5 and Tab. 6, it is possible to recognize an increase of 123% and 195% in drag, and, for a 5° angle of attack, a decrease of 15% in lift, both of which coincide with the studies presented by Fogell (2014). For a 0° angle of attack, an increase in lift of 33% due to the influence of the internal flow could be noted, implying a predominance of the lift generated by internal flow over the loss generated by the flow separation on the lower surface of the ram-air parachute airfoil in evaluation. Due to the increase in angle of attack, a reduction in stall can be noticed caused by the opening when considering uniform flow behaviour for the rounded profile and the separation in the open profile.

3.3 Comparison Between Numerical Methods

Apart from the results presented for the fluid flow, it was possible through this study to compare it to data acquired by different numerical methods, or, more precisely, the panel method and the finite volumes method.

Table 7. Lift coefficient results of different numerical methods on rounded Ascender parafoil

Cl	Rounded		
AoA	Finite Volumes (Ansys)	Panel Method (Xflr5)	Relative Difference
0º	0.1850	0.178	3.790 %
5º	0.6891	0.768	11.45 %
10º	1.1284	1.214	7.586 %

Table 8. Lift coefficient results of different numerical methods on closed Ascender parafoil

Cl	Closed		
AoA	Finite Volumes (Ansys)	Panel Method (Xflr5)	Relative Difference
0º	0.2081	0.200	3.900 %
5º	0.6439	0.658	2.195 %
10º	Stall	0.692	-

Table 9. Drag coefficient results of different numerical methods on rounded Ascender parafoil

Cd	Rounded		
AoA	Finite Volumes (Ansys)	Panel Method (Xflr5)	Relative Difference
0º	0.0156	0.0135	13.52 %
5º	0.0192	0.0169	12.04 %
10º	0.0302	0.0250	17.35 %

Table 10. Drag coefficient results of different numerical methods on closed Ascender profile

Cd	Closed		
AoA	Finite Volumes (Ansys)	Panel Method (Xflr5)	Relative Difference
0º	0.0190	0.0224	17.63 %
5º	0.0239	0.0215	9.992 %
10º	Stall	0.0582	-

From the results yielded from Tab. 7, Tab. 8, Tab. 9 and Tab. 10, it is possible to evaluate the increase in the error in relation to the drag calculations, which occurs due the numerical approximations made by the Xflr5 software on the viscous fluid results. Nevertheless, for the rounded and closed configurations the evaluations for lift are found to be relatively close to one another, confirming preliminary characterization assessments for the panel method.

4. CONCLUSION

The analysis objectives proposed for the aerodynamic behaviour of the Ascender parafoil have been met so as to consolidate the given references, implying the presence of a separation bubble on the lower surface of the airfoil near the leading edge and its effects. In addition to the qualitative behaviour, results were also obtained for the pressure coefficient, drag coefficient and lift coefficient of the three proposed geometrical models of the Ascender parafoil, all of which suggests qualitative behaviours similar to those of previous ones presented in the references, even though an increase in the lift coefficient for an angle of attack of 0° for the open tip profile is present in the results data, inferring it has a large influence in this form of lift in the internal flow. Apart from the finite volumes, the effectiveness of the panel method could also be evaluated from analysing the geometric models for the closed leading edge configuration, representing valid approximations which suggests it being a valid option for low cost early approaches in other studies. Therefore, this work contributes to the research on parafoils with simulation data and validates previous experimental results. Finally, the presented model is considered to be of use for approaching the evaluation of parafoils on flights bellow the stall angle yielding adequate solutions, as well as being adaptable for more complex scenarios.

5. ACKNOWLEDGEMENTS

The author would like to show his appreciation to the efforts of Fundação de Apoio à Pesquisa do Distrito Federal in having the initiative and giving continuous support to this research.

6. REFERENCES

Anderson, J., 2001. *Fundamentals of Aerodynamics*. Aeronautical and Aerospace Engineering Series. McGraw-Hill. ISBN 9780072373356. URL `https://books.google.com.br/books?id=CaBTAAAAMAAJ`.

Benedetti, D.M. and Veras, C.A.G., 2021. "Wind-tunnel measurement of differential pressure on the surface of a dynamically inflatable wing cell". *Aerospace*, Vol. 8, No. 2. ISSN 2226-4310. doi:10.3390/aerospace8020034. URL `https://www.mdpi.com/2226-4310/8/2/34`.

Erickson, L.L., 1990. *Panel methods: An introduction*, Vol. 2995. National Aeronautics and Space Administration, Office of Management.

Ferziger, J., Perić, M. and Street, R., 2019. *Computational Methods for Fluid Dynamics*. Springer International Publishing. ISBN 9783319996936.

Fogell, N., 2014. *Fluid-structure interaction simulations of the inflated shape of ram-air parachutes*. Ph.D. thesis, Citeseer.

Ghoreyshi, M., Bergeron, K., Jirásek, A., Seidel, J., Lofthouse, A.J. and Cummings, R.M., 2016. "Computational aerodynamic modeling for flight dynamics simulation of ram-air parachutes". *Aerospace Science and Technology*, Vol. 54, pp. 286–301.

Lingards, J., 1995. "Precision aerial delivery seminar, ram-air parachute design". In *13th AIAA Aerodynamic Decelerator System Technology Conference, Clearwater Beach*.

Mashud, M. and Umemura, A., 2006. "Improvement in aerodynamic characteristics of a paraglider wing canopy". *Transactions of the Japan Society for Aeronautical and Space Sciences*, Vol. 49, No. 165, pp. 154–161.

Menter, F.R., 1992. "Improved two-equation k-turbulence models for aerodynamic flows". *NASA technical memorandum*, Vol. 103975, No. 1.

Mohammadi, A. and Johari, H., 2009. "Computation of flow over a high performance parafoil". In *20th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar*. p. 2979.

Nelson, B. and Kouh, J.S., 2017. "The aerodynamic analysis of a rotating wind turbine by viscous-coupled 3d panel method". *Applied Sciences*, Vol. 7, No. 6, p. 551.

Williamson, G.A., McGranahan, B.D., Broughton, B.A., Deters, R.W., Brandt, J.B. and Selig, M.S., 2012. "Summary of low-speed airfoil data, vol. 5". *University of Illinois, Champaign, IL*, Vol. 204.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.