



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-0971

WING OPTIMIZATION USING THE OPENMDAO FRAMEWORK AND LOW-FIDELITY AERODYNAMICS

Marco Aurélio Leonel Matunaga

Instituto Tecnológico de Aeronáutica, DCTA/ITA, São José dos Campos, SP, Brazil
marco.matunaga@gmail.com

João Luiz F. Azevedo

Instituto de Aeronáutica e Espaço, DCTA/IAE/ALA, São José dos Campos, SP, Brazil
joaoluiz.azevedo@gmail.com

Abstract. *The present work aims to perform a study regarding the process of wing optimization using low-fidelity aerodynamics. The use of such tools is justified due to the large number of design variables and configurations that one needs to assess during the design process. In the present work, the computational framework can be summarized into two modules, one for the aerodynamic calculations and another for the optimization algorithms. The wing aerodynamic data are obtained through the linear lifting line theory. The optimization of the wing geometry uses the information from the aerodynamics module and applies different types of optimizers from an open source framework, known as OpenMDAO. The aerodynamic calculations are made by a Fortran subroutine, which is, then, connected to the optimization process through a Python script. The results obtained so far are quite encouraging and demonstrate the applicability of the present approach.*

Keywords: *Optimization, Linear Lifting Theory, OpenMDAO, Derivative-free optimization*

1. INTRODUCTION

Numerical simulations of complex engineering systems are an important subject in industry and academia. They provide useful information regarding the performance and the flow phenomena of these components. The data obtained from these numerical evaluations are used to help the designers and engineers to find an optimum configuration or a good solution considering specific performance criteria. However, find the best solution is not a simple task, usually involves different aspects of the numerical and the optimization algorithms that were chosen to perform these analysis.

Regarding the computational methods, which are used to evaluate an engineering system, there are different fidelity models for the same problem. For example, to optimize an airfoil it is possible to use the solutions of a potential or a Navier-Stokes formulation. The potential one, which is an example of low-fidelity model, can be useful to calculate the lift coefficient, but it would not provide reliable information about the drag one. On the other hand, a Navier-Stokes simulation provide the engineers a good knowledge about the flow phenomena around the airfoil. In relation to the computational cost, a low-fidelity solution tend to be too much cheaper compared to a high one. Therefore, the choice of the numerical method are strongly related to the objective of your optimization problem and with the resources that are available. Moreover, other details will affect your problem formulation, such as, the function of the component that you studying, how to deal geometry changes and others. In many real engineering applications there are several design variables to analyze, which makes the computational time and memory space important in order to choose the best suitable optimization methodology. Usually the results found by a low-fidelity solver give an initial configuration that will be refined by other higher-fidelity numerical tool. For the present study the authors will perform an aerodynamic calculation using a low-fidelity tool to assess the wing aerodynamics loads.

Concerning the optimization algorithms, they are divided into two categories. The first one is known as gradient-free methods, sometimes it is referred as zeroth order methods. This category includes grid searching, genetic algorithms, neural networks and simulated annealing. One significant limitation of many of these gradient-free algorithms is the computational time tends to increases exponentially with the increment of new design variables. Another concern in optimization problems is the quality of the solution. Many optimization techniques do not find an optimal global, usually the free-gradient approach deal with this issue, but not guarantees that a global optimum can be found. In the present study the optimize solvers has been implemented in a Python package called OpenMDAO, more details can be found in Gray *et al.* (2019).

In the present work is presented an evaluation of a low-fidelity numerical method to optimize the aerodynamic of an

airplane wing. As discussed before, the advantages of such technique is justified in the initial design phases, when the engineers have a lot of possible configurations to evaluate under a restricted time. Therefore, a low-fidelity can provide a lot of useful in a short time. The authors expected in the future to create a optimization framework with a high-fidelity optimization tool and then assess the performance of both methods and have a well suitable optimization process for different phases of an engineering project. In the present work, the optimization is made using two different optimizers implemented in the OpenMDAO framework (Gray *et al.*, 2019). Inside this framework there are many routines that are free-gradient and gradient optimization techniques.

2. METHODOLOGY

The computational program used to obtain a solution for the optimization problem can be divided into two modules. One that computes the aerodynamics coefficients of the wing and other that runs the optimizer from the OpenMDAO framework. In the next two subsections, an overview of the numerical methods will be presented.

2.1 Aerodynamic Module - Lifting Line Theory

The Linear Lifting Line Theory was introduced by Prandtl in 1918. This technique can provide an accurate prediction of lift generated by a wing. However, it has limitations such as the prediction of wing stall angles. The Prandtl's theory impossibilities the application of the method above the airfoil's stall angle. Moreover this theory can not be applied for general wings, only for an elliptic form. In order to surpass this drawback, the general distribution of wing circulation can be described as a Fourier series instead of an elliptical one used in the original theory. This change makes the approach applicable for general wings (Houghton *et al.*, 2012). The procedure is presented in Sect. 2.1.1 and follows the Ref. Houghton *et al.* (2012).

2.1.1 Lifting Line Theory (LLT) - General Wing

The algorithm used to perform the aerodynamic calculations can be divided into five steps. First, the wing is divided into different segments, as the number of segments increases more precise is the method. Moreover, it is interesting to have many divisions in the wingtip. In the next step, one has to determine the angle of each section, basically for the first wing section the angle is zero and the last one is equal to 90 degrees. For the intermediate sections the angle value is given by 90 degrees divided by the number of segments. Figure 1 shows how the wing division works and could give to the reader a better overview of the methodology used in the present paper. In this example the wing is divided into 5 segments.

The following step is calculate the Fourier coefficients, from A_1 to A_n ,

$$\mu(\alpha_0 - \alpha) = \sum_{n=1}^N A_n \sin(n\theta) \left(1 + \frac{\mu n}{\sin(\theta)}\right), \quad (1)$$

where the μ coefficient is given by

$$\mu = \frac{\overline{C}_i C_{l_\alpha}}{4b}. \quad (2)$$

In Eqs. (1) and (2), the variable b is the wing span, α_0 is the segment's zero-lift angle of attack and α . The C_{l_α} variable denotes the slope of the lift curve in function of the angle α . The next evaluation is determine the segment's lift coefficient, denoted by C_{L_i}

$$C_{L_i} = \frac{4b}{C_i} \sum_{n=1}^N A_n \sin(n\theta). \quad (3)$$

The last step is determine the wing aerodynamic coefficients using the following relations

$$C_{LW} = \pi \cdot AR \cdot A_1, \quad (4)$$

$$\delta = \sum_{n=2}^N n \frac{A_n^2}{A_1^2}, \quad (5)$$

$$e = \frac{1}{1 + \delta}, \quad (6)$$

$$C_{D_i} = \frac{C_{LW}^2}{\pi \cdot AR \cdot e}. \quad (7)$$

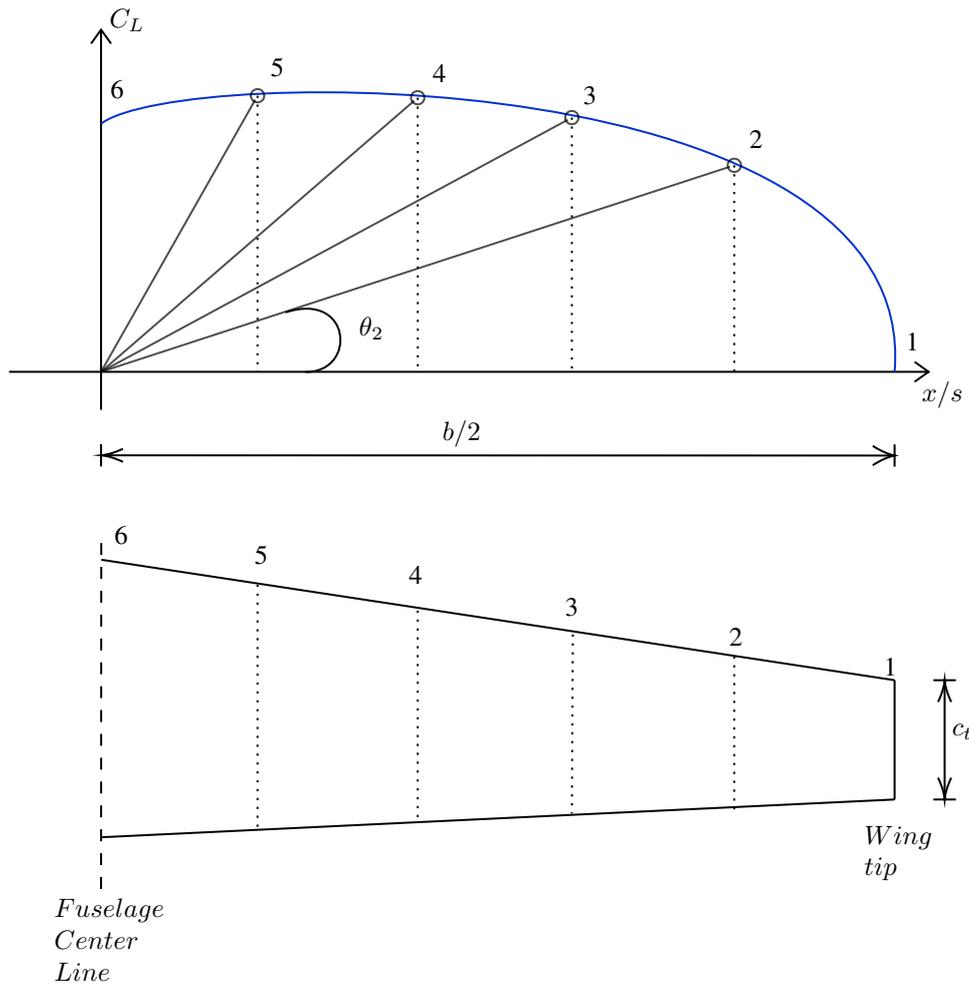


Figure 1. Example of a wing divided into 5 sections.

The lifting line theory can also be used to determine the addition of lift by introducing a high-lift device. These increment can calculated by the following expression

$$\Delta\alpha_{0,flap} = -1.15 \frac{c_f}{c_r} \delta_f, \quad (8)$$

this equation is an empirical relation given by Ref. Sadraey (2012). As stated in Eq. (8) the changing in lift can be related to the change in the wing zero-lift angle of attack. The high-lift device position is near the wing root, with this location this mechanism can generate more lift and the rolling moment will not interfere the airplane flight. Therefore, in the present LLT implementation the flap was inserted in the section of wing root, moreover there is a variable b_f/b . This ratio represent the relation between the flap span of the wing span, with this value it is determine the section where the high-lift device ends. It is important to observe that in a real airplane the flap will not be located exactly at the wing root. However, it is not possible to impose any alteration in the middle of a wing division, only exactly at the one division.

In order to verify the correctness of our Lifting Line implementation the authors look at Ref. Sadraey (2012), which provides examples for a similar implementation of the present method. Moreover, it provides a MATLAB routine that can be used to test different LLT calculations for different wing configurations. In present paper the authors will provide the results obtained by just one test run. The parameters of the test case are shown in Tab. 1.

The comparison between the results obtained through the MATLAB routine given by Ref. (Sadraey, 2012) are presented in Fig. 2.1.1. The MATLAB routine does not determine the influence of a flap in the lift coefficient. Therefore, the result presented in Fig. 2.1.1 is for a deflection equal to zero. Table 2 and Tab. 3 shows results obtained by the LLT solver for different number of wing divisions. The tables presents the solution obtained, respectively, for the Oswald factor and for the lift coefficient. These data was used as a way to see how the solution changes with the increment of wing divisions. This evaluation can give us enough information to determine a “N” value which will give a converged solution, *i.e.*, a solution that not changes for higher numbers of wing segments. Considering the data from these tables 15 divisions it is a good number, because the difference is proportional to 10^{-4} .

Table 1. Test case parameters used to verify the correctness of the LLT theory.

Number of Segments	Wing Area (m^2)	Aspect Ratio	Taper Ratio	Twist Angle (deg.)	Wing AoA (deg.)	$\frac{dc_l}{d\alpha}$ (1/rad)	α_0 (deg.)
10	25	8	0.6	-1	2	6.3	-1.5

Table 2. Oswald factor for different wing divisions.

N	e	N	e
5	0.992293000962582	25	0.993332205915495
10	0.993331847706310	50	0.993276114371380
15	0.993368573473205	100	0.993240936558790

Table 3. Lift coefficient for different values of wing sections.

N	Lift Coefficient	N	Lift Coefficient
5	0.266214154147072	25	0.270196837741400
10	0.268687967176991	50	0.270712539843931
15	0.269520058996437	100	0.270973296190577

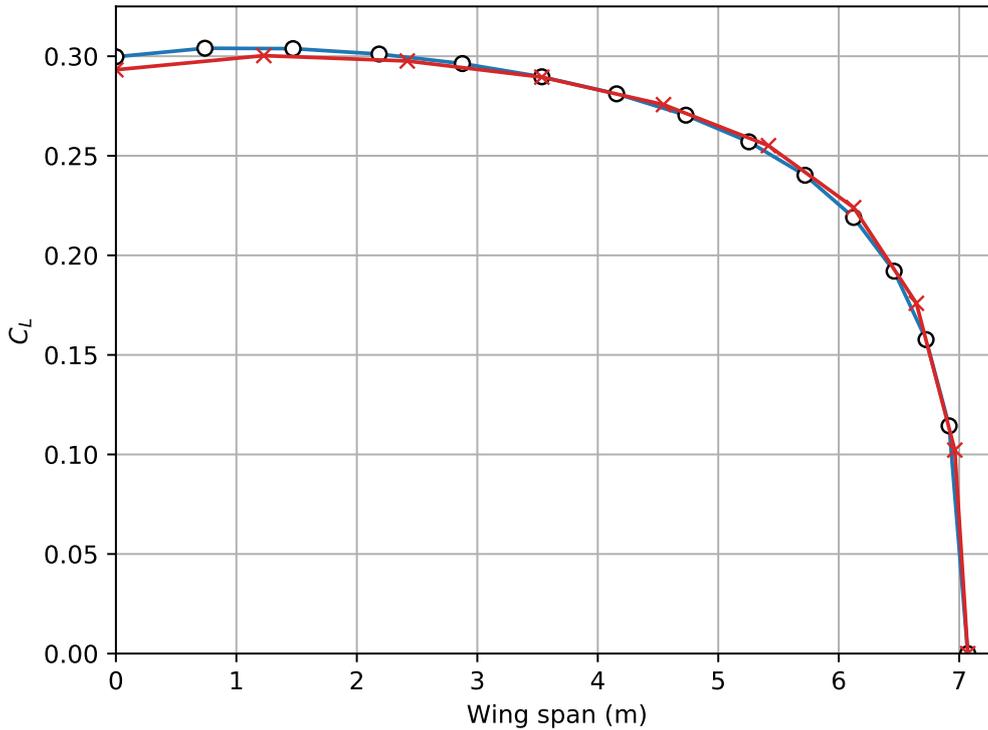


Figure 2. Graphics showing the comparison between the results obtained from the MATLAB routine from Sadraey (2012) (red) and the author's implementation in FORTRAN90 (blue).

2.2 Optimization Module - OpenMDAO

For the present paper the optimization process is made using a technique known as COBYLA, which stands for constrained optimization by linear approximation. The COBYLA algorithm was introduced by Powell (1994) and it is a free derivative algorithm. The other algorithm used in the present paper is known as SLSQP, which stands for Sequential Least Squares Programming. None of these two algorithms were implemented by the authors instead was used the

OpenMDAO implementation. These two methods are also part of the SciPy package.

2.3 Optimization Test Case

In order to test the optimization algorithms implemented inside the OpenMDAO framework, a simple running test was performed, which can be described as:

$$\begin{aligned}
 & \max. && e \\
 & w.r.t. && \lambda, AR \\
 & s.t. && 0.4 \leq \lambda \leq 1.0, \\
 & && 5 \leq AR \leq 9.0,
 \end{aligned} \tag{9}$$

where AR means Aspect Ratio and λ stands for taper ratio. These two variables are wing geometric parameters defined by the relations

$$AR = b/S^2, \tag{10}$$

$$\lambda = c_t/c_r, \tag{11}$$

where b denotes wing span, c_t and c_r stands for tip chord and root chord, respectively.

This is a simple case and can be used as our validation case, once the solution can be easily verified through experimental data or information about the Oswald factor in the literature. For instance, Fig. 2.3 from the Ref. McCormick (1979), shows that for the optimization problem of Eq. (9) the optimum will be near 0.4 for taper ratio and 5 for aspect ratio. Moreover, it is known that the maximum value possible for this parameter is one. Therefore, our optimum solution is

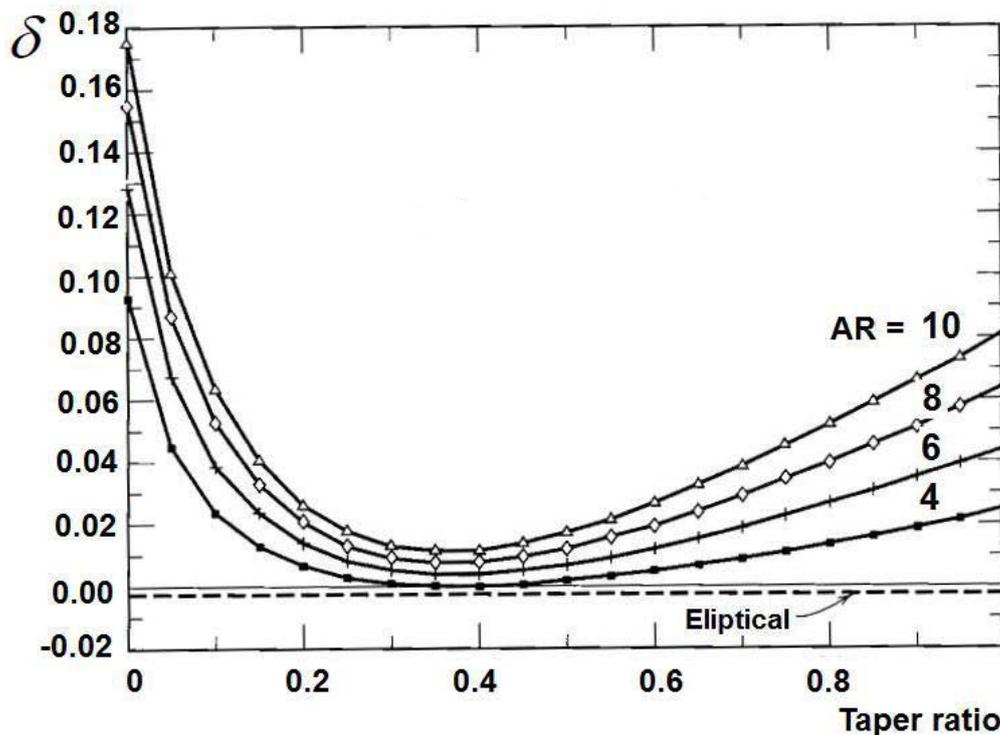


Figure 3. Graphic illustrating the relation between δ and the geometric parameters AR and λ . (McCormick, 1979)

expected to be close to unity.

2.4 Wing Optimization

For this problem the authors will design a wing for a light aircraft, *i.e.*, a vehicle capable to carry about one ton as gross weight. In order to perform a wing optimization the authors followed a methodology, which is described in Fig. 4. This method is similar to another method present by Ref. Sadraey (2012). The first step is to define a high-lift device. In the present work the flap effects on the wing lift is determined by Eq. (8). As stated by the expression this is a general

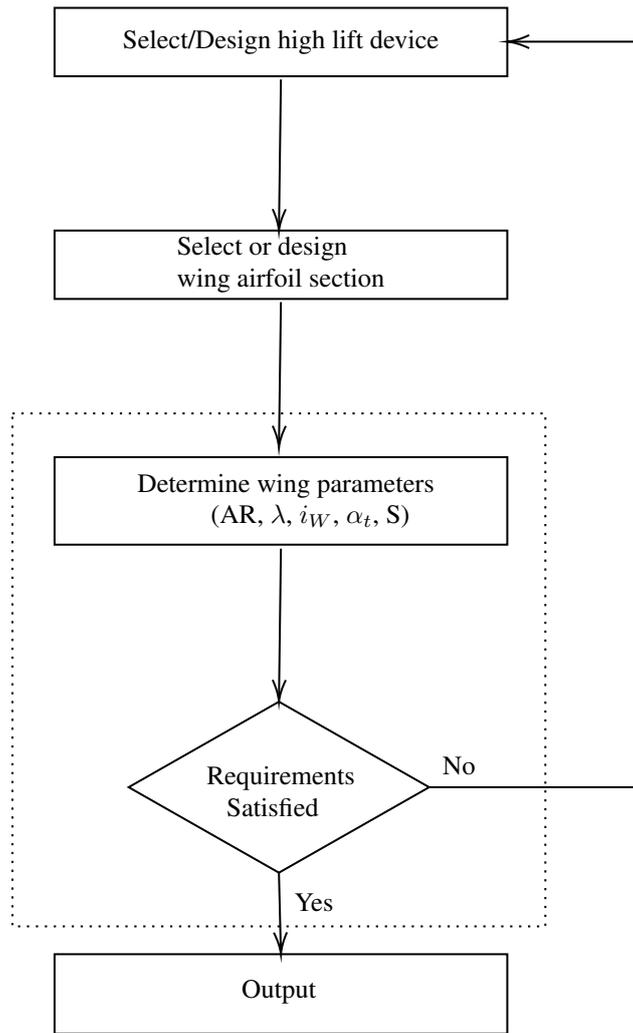


Figure 4. Wing design flowchart.

form to described the influence of a high-lift device. The flap deflection at the initial process is set to be zero, *i.e.*, it is defined that the wing does not have a flap. The second step is to select the wing airfoil. It was chosen the NACA 2412, because it is similar to used for light aircraft such as Cessna 172. The third step is to evaluate the wing parameters, in this step it is performed the optimization process. There are variables that are maintained fixed such as the twist angle (α_t), incidence angle (i_W) and wing area (S), the optimizer will seek the optimum for the wing taper ratio and the wing aspect ratio. If any of the requirements is achieved the design starts again with an higher value of flap deflection until the maximum value allowed for flap deflection is reached. If the requirement does not be satisfied, then the twist angle and the incidence angle can be altered or the flap sizing (flap chord ratio or flap span ratio).

The two requirements for this problem are the lift coefficient at the take-off, calculated by

$$C_{L_{TO}} = 0.85 \frac{2W_{TO}}{\rho V_{TO}^2 S}, \quad (12)$$

and the lift coefficient for cruise speed, which is given by

$$C_{L_c} = \frac{2W_{ave}}{\rho V_c^2 S}, \quad (13)$$

where W indicates the airplane weight where the subscript TO means take-off and ave average. V is the airplane velocity at take-off and at cruise, subscript TO and c , respectively.

The assessment of the requirements were made by studying different airplanes, some of them are described into the Tab. 4. The ideal lift coefficient for take-off is in the range of 0.41 and 0.76. These values consider an airplane with a wing area about $25m^2$. The density at take-off was considered as $1.156 kg/m^3$. The velocity of take-off is determined by the FAR part 23 resolution that states this velocity should be 20% higher than the stall velocity.

Table 4. Aircraft data used to estimate the lift coefficient values.

	Cessna 172	BeechCraft Musketeer	Diamond D40	Piper Cherokee
Maximum Takeoff Weight	10887,8	10683,1	11752,4	9564,8
Cruise Speed	62,78	52,50	77,50	55,56
Stall Speed	24,17	32,50	25,28	24,17

3. RESULTS

3.1 Optimization Test Case

The Eq. (9) shows the case, which is used to evaluate our aerodynamic model implementation within the OpenMDAO framework. In this section, the results for this case will be presented using the COBYLA and SLSQP algorithms. Figure 3.1 shows the results for the first case, it shows the values of Oswald factor evaluated by the two algorithms. The optimum Oswald factor is 0.9966, which is close to the maximum value possible for this parameter. This optimum point is found for taper ratio equals 0.606 and aspect ratio equals 5. As shown in Fig. 2.3 this result is close to what was expected for this problem.

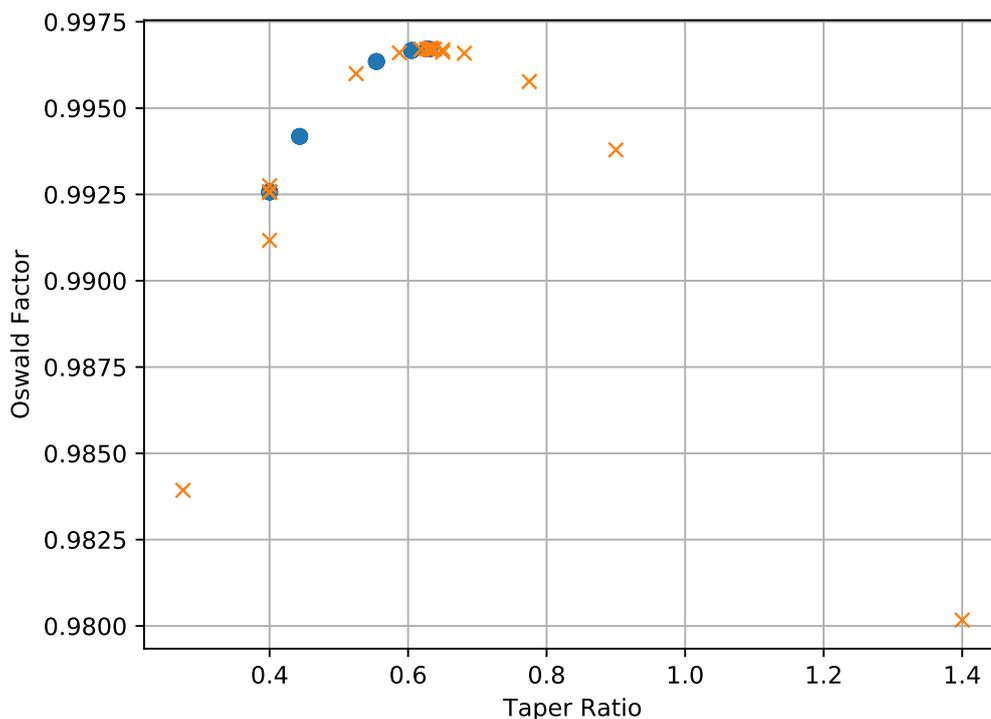


Figure 5. Chart showing the points obtained for Oswald factor considering different wing taper ratios. The × symbol stands for the COBYLA algorithm and the • denotes the SLSQP evaluations.

3.2 Wing Optimization Case

The wing optimization case was performed in order to obtain a wing configuration capable for generate enough lift for a light aircraft, *i.e.*, about 1000N. At the first running of the case, the output for the wing aspect ratio and for the taper ratio was respectively, 8 and 0.6989. The lift coefficient obtained for this problem was 0.3380, far from the ideal goal for the take-off. However, this value is enough to satisfy the cruise flight. After that, was imposed a flap deflection of thirteen degrees, which gives a lift coefficient of 0.5220, this is not enough for the take-off. For this case the high-lift dimensions were $b_f/b = 0.6$ and $c_f/c_r = 0.2$. Increasing the relation between the flap and the wing chord to 0.3, outcomes a new lift coefficient equals to 0.614 which are in the range of our objective.

4. CONCLUDING REMARKS

A optimization study was performed using the OpenMDAO framework, an open-source tool written in Python. It is a powerful package to elaborate different types of optimization tools or software to help student and engineers to enhance the design process. For a new project, instead of using expensive, time-consuming and subjective analyses, the designers can employ a better methodology. Moreover, since the framework is quite simple and intuitive, one can use external tools which are, then, embedded into the Python script. The present work is an example of a simple external code written in FORTRAN90 inserted into a Python script using the OpenMDAO framework. The results seems to be according to real aircraft data, which can support the results obtained by the authors.

For future work, it is interesting to compare the results obtained by the lifting line theory with those generated by a higher fidelity tool, such as CFD solvers which employ an Euler formulation or the full potential equation. Such comparison could provide a deeper understanding of the advantages and drawbacks of using one or other tool in a design process. It is quite possible that a more comprehensive design tool should incorporate modules addressing several levels of fidelity in order to achieve a cost effective design methodology. Moreover, it is interesting to also explore the inclusions of more restrictions and calculations into the model in order to evaluate other aspects of an airplane design such as airfoil optimization, load calculations and structural analysis.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support for the present research provided by Conselho Nacional de Desenvolvimento Científico e Tecnológico, CNPq, under the Research Grants No. 309985/2013-7, No. 400844/2014-1, No. 443839/2014-0 and No. 403904/2016-1. The work is also supported by Fundação de Amparo à Pesquisa do Estado de São Paulo, FAPESP, under Research Grant No. 2013/07375-0. The support provided by Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, CAPES, through a graduate scholarship for the first author is also greatly appreciated.

6. REFERENCES

- Gray, J.S., Hwang, J.T., Martins, J.R.R.A., Moore, K.T. and Naylor, B.A., 2019. "OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization". *Structural and Multidisciplinary Optimization*.
- Houghton, E.L., Carpenter, P.W., Collicott, S.H. and Valentine, D., 2012. *Aerodynamics for Engineering Students*. Elsevier Science.
- McCormick, B.W., 1979. *Aerodynamics, Aeronautics, and Flight Mechanics*. Wiley.
- Powell, M.J.D., 1994. *A Direct Search Optimization Method That Models the Objective and Constraint Functions by Linear Interpolation*, Springer Netherlands, pp. 51–67.
- Sadraey, M.H., 2012. *Aircraft Design: A Systems Engineering Approach*. Aerospace Series. Wiley.

7. RESPONSIBILITY NOTICE

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