Multi-objective Aerodynamic Optimization of an Unmanned Aerial Vehicle

T. J. Rezek*, E. R. da Silva**, R. G. R. Camacho*** and K. G. Kyprianidis**

*Mechanical Engineering Graduation Student, Instituto de Engenharia Mecânica, Universidade Federal de Itajubá, Itajubá, Brasil.
(E-mail: *thiagorezek@unifei.edu.br*)
**Future Energy Center, Department of Mälardalen University, Västerås, Sweden
(E-mail: *edna.dasilva@mdh.se ; konstantinos.kyprianidis@mdh.se*)
***EPFL Ecole Polytechnique Federal Lausanne Visiting Professor
(E-mail: *ramirez@unifei.edu.br*)

INTRODUCTION

Unmanned Aerial Vehicles (UAV's) have been designed for several decades for military and civil applications, such as surveillance, transportation, commerce, entertainment and many other purposes. Some of these applications require a design that provides high lift force at low angles of attack. One example of these applications is small remote controlled competition aircrafts. High lift airfoils, which offer high lift coefficients at low angles of attack and low Reynolds numbers are commonly used in these cases. The disadvantage such airfoils are the higher drag force and higher moment which their geometry often provides.

This work presents a direct multi-objective optimization methodology applied to increase the lift force of a high lift low Reynolds number airfoil (Selig 1223) while reducing the magnitude of the moment generated by the integration of the pressure and viscous forces along the geometry.

The geometry of the airfoil is parameterized with the aid of Bézier curves. By changing the coordinates of the Bezier curves control points, it is possible to slightly modify the airfoil geometry and investigate the effects of the modification. This allows to easily automatize the geometry generation, making the whole process completely user independent

The optimization process is based on the integration of computational processes of geometry generation - Bezier curve generator code (Sousa 2008), commercial mesh generation and finite volume method software. The software integration and optimization algorithm is provided by the commercial multi-objective optimization and design environment. The developed methodology can be applied to various problems in the area of the thermal-fluid-mechanics with few adjustments, including three-dimensional and transient applications, offering versatility and reliability at a variable computational cost.

METHODOLOGY

The optimization strategy consists of the integration of computational processes. Each process is responsible for one task in order to create an automatic and fully user independent optimization routine. The routine consists of geometry generation, mesh generation, computational fluid dynamics analysis and results report. After the cycle is completed, the variables are modified by the optimization algorithm, generating a new geometry and starting a new cycle. The flowchart of the processes' integration is shown in Figure 1:

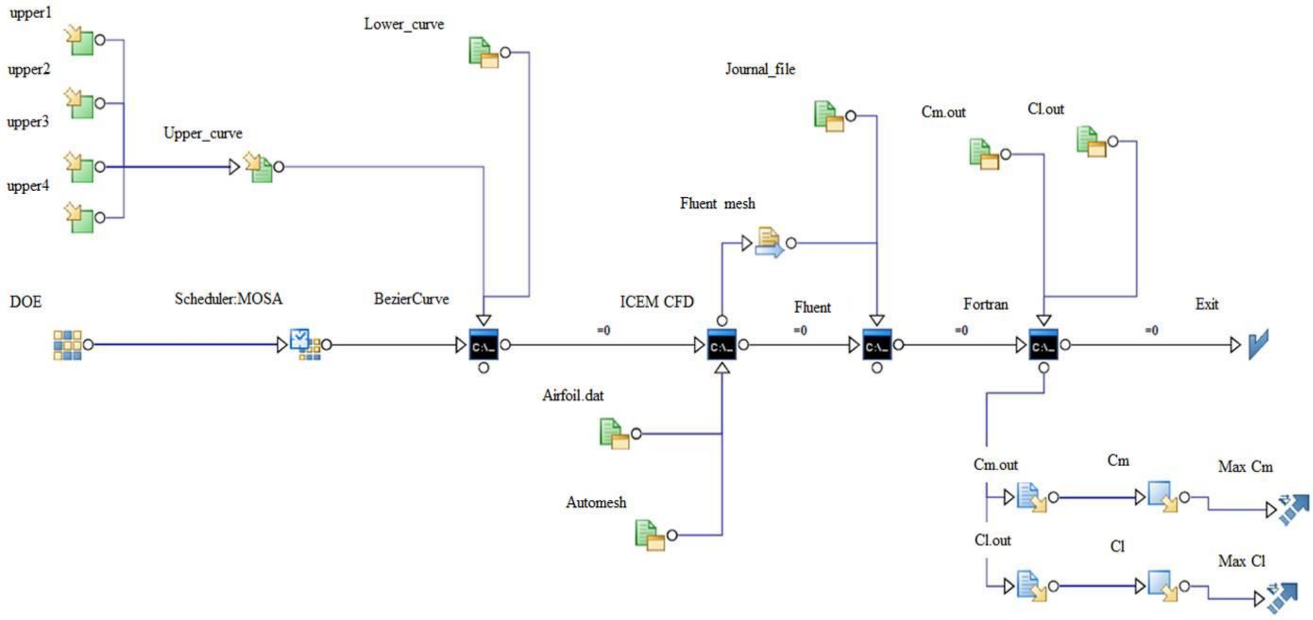

Figure 1: Processes' Integration Flowchart

The individual details of each computational process are described in the next section one:

Airfoil Geometry generation

To allow easy modification of the airfoil geometry it is necessary to describe it mathematically with parameters which can be varied or a straight forward manner. The choice was to describe the airfoil geometry by Bézier curves, which allows to slightly modifying the airfoil's geometry by changing the vertical coordinates of the control points. A Bézier curve can be parametrized by the coordinates of the control points through Equations (1) and (2):

$$x(t) = \sum_{i=0}^{n} \frac{n!}{i!(n-i)!} t^i (1-t)^{n-1} X_i \tag{1}$$

$$y(t) = \sum_{i=0}^{n} \frac{n!}{i!(n-i)!} t^i (1-t)^{n-1} Y_i \tag{2}$$

In the expressions, X_i and Y_i are the coordinates of the control points (always n+1 points), this points are responsible to control the curve shape, with parameter t that variety of the 0 to 1. These points are responsible to control the form of the Bézier curve. Figure 1 show the airfoil Selig 1223 and its control points.

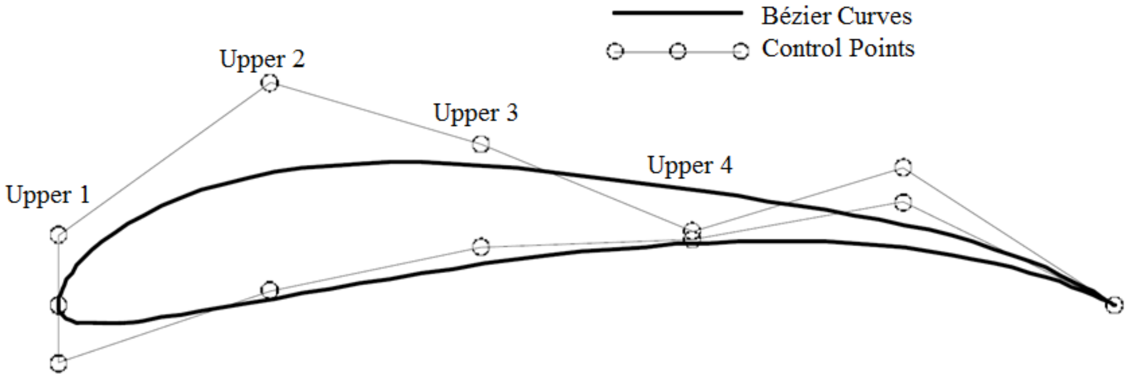

Figure 2: The Selig 1223 High Lift Airfoil and its Control Points

The upper surface of the airfoil was chosen to be optimized by changing the y coordinate of four of its seven control points (upper 1, upper 2, upper 3 and upper 4) closer to the control board airfoil attack that are more representative of the problem. Only the vertical coordinates of the points has been changed, there is no need in this problem to make changes in horizontal coordinate.

The BezierCurve program (Sousa 2008) receives the files containing the control points of the upper and lower surface and generates the file which contains the points of the Bézier curves corresponding to the airfoil's pressure and suction surface. By varying the y coordinate of the upper surface control points, the geometry created by the program varies, altering the airfoil's geometry.

The maximum variation of each control point's y coordinate was chosen to be 50% higher and 50% lower in relation to the original coordinate.

Mesh generation

After the geometry generation, instructions are used for the domain's automatic meshing (domain size, blocking, number of elements, element growth) varying only the airfoil's geometry at the center of the domain. This is possible because the commercial software used names each imported point according to its creation order (Eleni *et al* 2012).

This way, slightly varying a point's position while keeping its creation order does not change the mesh structure, resulting in similar meshes to different airfoils as shown in Figure 3. The total quadrilateral elements are approximately 300000.

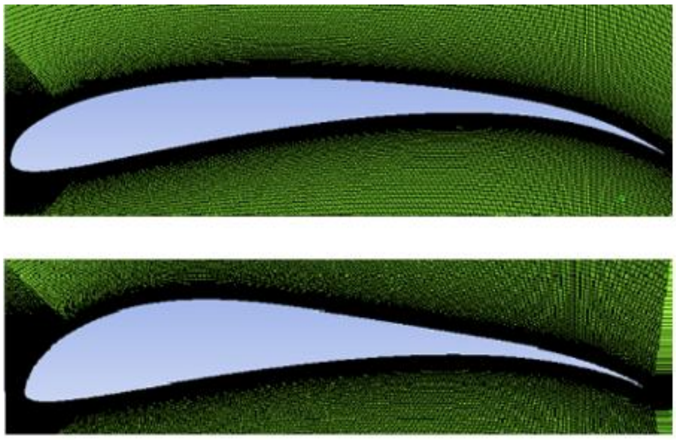

Figure 3: Different Airfoils with Similar Meshes.

Flow simulation

After the mesh generation, the mesh is transferred to the finite volume method software. To automatize the simulation process, it is necessary to create a journal file from a previous simulation. The journal file contains all the instructions given to the program to realize the simulation according to the chosen simulation parameters (steady state analysis, turbulence model, boundary conditions, under relaxation factors).

The problem was approached as a two-dimensional steady state case. The considered Reynolds Number and angle of attack were 2 x 10^5 and 0º, respectively.

The turbulence was modeled with the aid of the Reynolds-Averaged Navier-Stokes (RANS) equations, which considers the variables as the average value of the quantity plus a fluctuation portion.

The chosen turbulence model was the Spalart-Allmaras model, which is a relatively simple model designed specifically for aerospace applications. The Spalart-Allmaras is a one equation turbulence model that solves a modelled transport equation for the kinematic eddy viscosity.

The turbulence model follows the Boussinesq hypothesis, in which the Reynolds stress tensor is approximated by an Eddy Viscosity ($\tilde{\upsilon}$), making the RANS equations to assume the form described by Equation (3)

$$\frac{D\bar{V}}{Dt} = -\frac{1}{\rho}\vec{\nabla}p + (\upsilon + \upsilon_t)\nabla^2\bar{V} \tag{3}$$

The additional differential equation to be solved when this model is applied is the equation for the modified turbulent viscosity, which is related to the turbulent viscosity by Equation (4):

$$\upsilon_t = \tilde{\upsilon} f_{v1} \tag{4}$$

Where

$$f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3} \tag{5}$$

$$\chi = \frac{\tilde{\upsilon}}{\upsilon} \tag{6}$$

The transport equation for the modified turbulent viscosity is:

$$\frac{D\tilde{\upsilon}}{Dt} = c_{b1}\tilde{S}\tilde{\upsilon} + \frac{1}{\sigma}[\vec{\nabla}((\upsilon+\tilde{\upsilon})\vec{\nabla}\tilde{\upsilon}) + c_{b2}(\vec{\nabla}\tilde{\upsilon})^2] - c_{w1} f_w \left(\frac{\tilde{\upsilon}}{d}\right) \tag{7}$$

The expressions for the unknown terms of this equation are:

$$\tilde{S} = S + \frac{\tilde{\upsilon}}{\kappa^2 d^2} f_{v2} \tag{8}$$

$$f_{v1} = 1 - \frac{\chi}{1+\chi f_{v2}} \tag{9}$$

$$f_w = g\left(\frac{1+c_{w3}^6}{g^6+c_{w3}^6}\right)^{1/6} \tag{10}$$

$$g = r + c_{w2}\,(r^6 - r) \tag{11}$$

$$r = \frac{\tilde{\upsilon}}{S\kappa^2 d^2} \tag{12}$$

Where S is the vorticity magnitude, κ is the Von Kármán constant and d is the distance from the wall. The other parameters present in the equation are constants (Ribeiro 2012).

After each geometry simulation, the software reports the log of lift, c_l, and moment, c_m, coefficients) to *cl.out* and *cm.out* files, respectively. These files contain the values calculated for the objective functions after every calculus iteration. As the interested values of the objective functions are those obtained at the end of the calculation, the FORTRAN® program shown in Figure 1 is used to capture the value of the last iteration.

The FORTRAN® program then writes this value to another text file which is connected to the output variable icon in order to maximize the value contained in this new file.

Optimization process

To begin the optimization process it is necessary to generate some geometries with initial combinations of the interested variables via Design of Experiments (DOE). The DOE is generated by the workflow software using a user defined rule. To generate the first 20 geometries, the variables are randomly combined within the defined interval of variation.

The criteria adopted to evaluate the optimum combinations of the objective functions (c_l and c_m) was the Pareto Frontier, which is the group of solutions which possess the most interesting combinations of the objective functions (c_l and c_m). These solutions are called “non-dominated solutions” (Sousa 2008).

After the generation of the first 20 airfoils, the algorithm represented in Figure 1 was executed and the first 20 geometries generated via DOE were simulated. After the simulation of the first 20 geometries, the Multi Objective Simulated Annealing (MOSA) optimization algorithm started to automatically generate the new geometries.

The Simulated Annealing is a local search algorithm which chooses a new element with a semi-aleatory method. The optimization method evolves level after level, simulating temperature levels at a cooling process. At the beginning of the process, almost every point generated by the algorithm is accepted. As the process evolves, the number of accepted points decrease until only points that improve the objective function are accepted. This methodology allows the Simulated Annealing to escape from local optimizers of the objective function and to seek for the global optimum (Haeser 2008).

The optimization process generated 263 different geometries and obtained six non-dominated solutions. The results are shown next.

RESULTS AND DISCUSSION

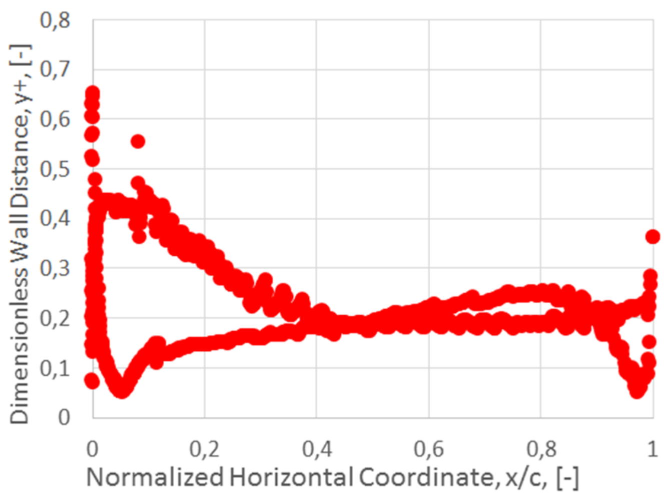

Figure 4: Dimensionless Wall Distance along the Chord

Evaluation of y^+

To verify the refinement quality of the automatically generated meshes, it's useful to evaluate the mesh dimensionless wall distance (y^+) at the airfoil surface. For the Spalart-Allmaras turbulence model, it is recommended to have an average y^+ on the airfoil surface of 1 or less to guarantee best results. Figure 4 shows that the mesh refinement is adequate as it keeps all the y^+ values lower than 1.

Obtained solutions

The optimization method obtained 263 different solutions to the problem. Six of these solutions form the Pareto frontier, which is the group of solutions with the best combinations for the studied objective functions (lift and moment coefficients), as shown in Figure 5.

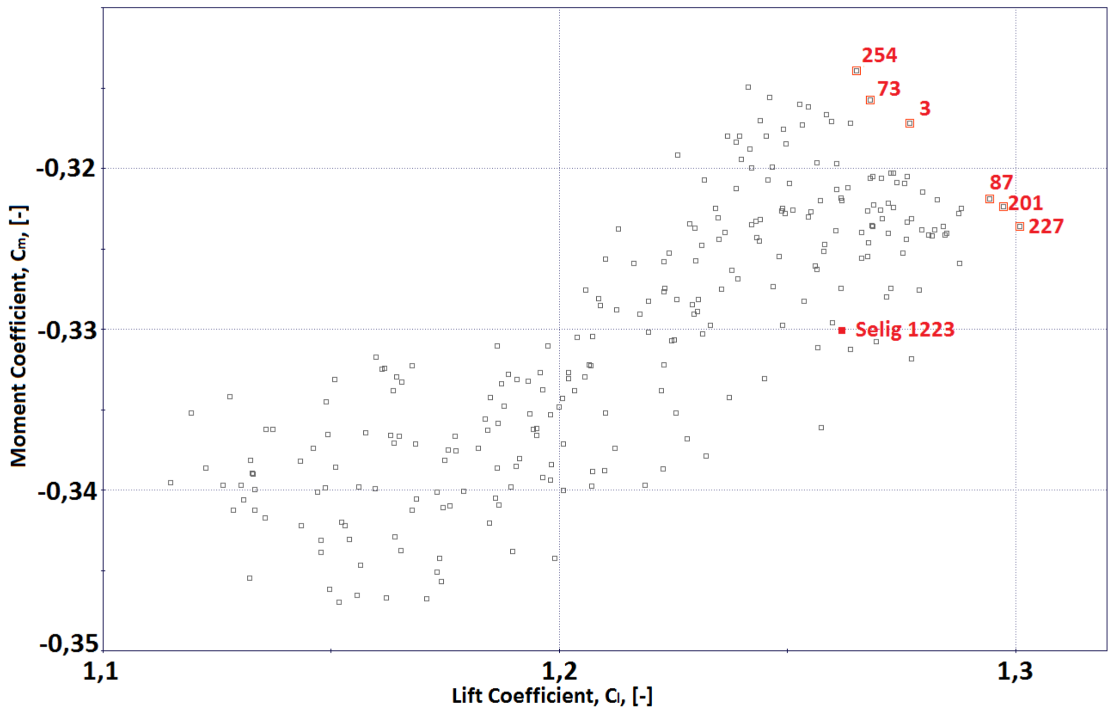

Figure 5: The Pareto Front Obtained for the Optimization Problem

It is interesting to compare the geometry of the obtained solutions to the original Selig 1223 geometry as shown in Figure 6.

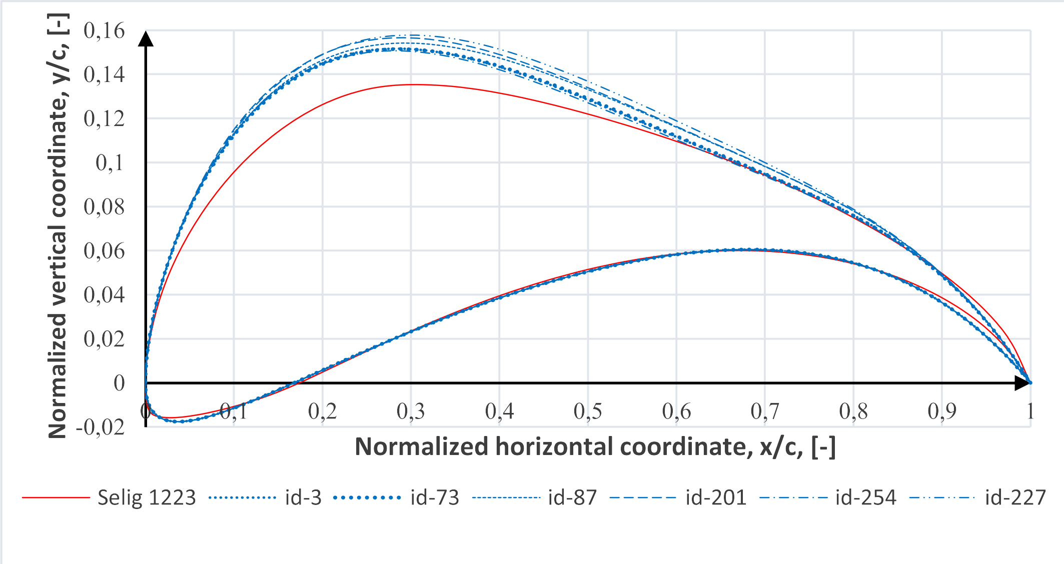

Figure 6: Comparison between the Obtained Solutions and the Original Selig 1223

Notice that all the optimum solutions obtained by the optimization process tend to increase the maximum thickness and maximum camber of the original airfoil. This change generates higher velocities in the upper surface of the airfoil, which provokes higher pressure drop by consequence, increasing the lift force.

For the airfoil id 87 and the Selig 1223, the curves of moment and lift coefficients versus the angle of attack (AOA) were obtained by simulation (for Reynolds = 2 x 10^5). The results of these simulations are shown in Figures 7 and 8. It is possible to notice an increment on the lift and moment coefficients along the studied angle of attack interval.

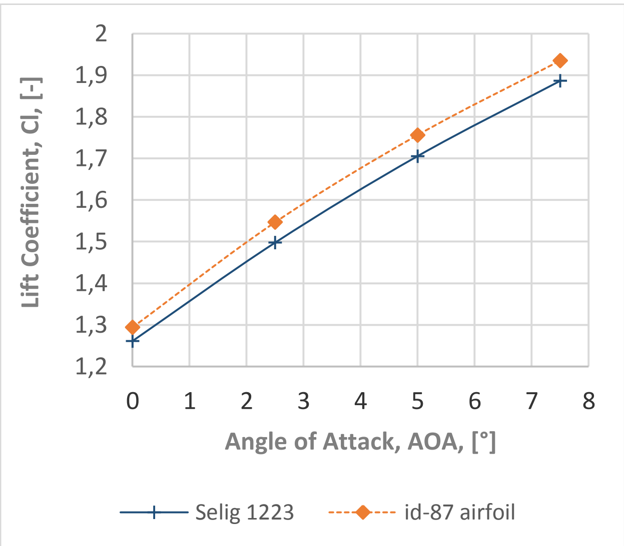

Figure 7: Lift Coefficient vs AOA

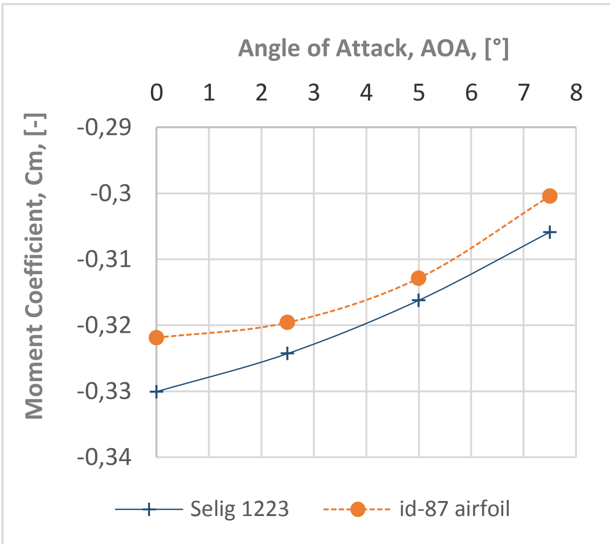

Figure 8: Moment Coefficient vs AOA

CONCLUSIONS

The proposed optimization methodology revealed successful results to the problem of the multi-objective optimization of a high lift airfoil for UAV applications by obtaining higher values of lift coefficient while minimizing the magnitude of the pitch moment generated by the aerodynamic forces.

The strategy used to solve the problem can be easily extended to other problems in thermal-fluid-mechanics and many other engineering areas. While the computational cost to solve the presented problem is reasonable, more complex problems involving heat transfer, multiphase flows and 3 dimensional geometries can be computationally very expensive, since every proposed solution needs to be simulated via Finite Volume Method. Nonetheless, the optimization methodology based on computational processes' integration shows to be a versatile and reliable optimization strategy.

REFERENCES

Eleni. D. C., Athanasios, T. I., Dionissios, M. P. 2012 "Evaluation of the turbulence models for the simulation of the flow over a National Advisory Committee for Aeronautics (NACA) 0012 airfoil." *Journal of Mechanical Engineering Research* Vol. **4**(3), pp. 100-111. Available online at http://www.academicjournals.org/

Haeser, G., Ruggiero, M. G. 2008. "Aspectos teóricos de *simulated annealing* e um algoritmo duas fases em otimização global." *Trends in Applied and Computational Mathematics* **9**.3, 395-404.

Ribeiro, A. F. P. 2012. Otimização e Dinâmica dos Fluidos Computacional Aplicadas a Turbinas Eólicas. (Master Dissertation, Federal University of Rio Grande do Sul).

Sousa, B. S. 2008. Projeto de Perfis Aerodinâmicos Utilizando Técnicas de Otimização Mono e Multiobjetivos. (Doctoral Dissertation, Federal University of Itajubá, MG, Brasil).