COB09-1331 - AIRFOIL AERODYNAMIC SCALING THROUGH GENETIC OPTIMIZATION ALGORITHMS

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Abstract. *During the development and testing of new aircraft concepts, the use of prototypes is required to validate the dynamic behavior of the proposed aircrafts. The use of scaled-models is interesting due to reduced fabrication costs and the use of remote piloting. But in order to achieve a meaningful scaled model, the scale of dynamic and aerodynamic properties must be made. While dynamic scaling ensures that the flight dynamics scale, aerodynamic scaling assures that the scaled airplane, especially the airfoil, has the same aerodynamic properties (such as lift and moment coefficients, derivatives and stall behavior) as the full size airplane or airfoil, despite the reduced Reynolds number associated with the change in length scales, air speeds, and air properties. The present study presents an approach for computer-based automatic aerodynamic scaling using genetic algorithms coupled with parametric airfoil modification. It is capable of modifying the original airfoil in such way that its behavior in the lower Reynolds number is similar to the real size aircraft airfoil. A comparison between previous results for the original airfoil of the Aeromot 200S Super Ximango motor glider, a 20% scaled model made through the use of manual airfoil geometry modification and the results obtained by the use of the present algorithm is made.*

Keywords*: Airfoil Design, Aerodynamic Scaling, Genetic Algorithm, Multiobjective Optimization*

1. INTRODUCTION

The use of low Reynolds number airfoils can be found in many areas, such as unmanned aerial vehicles, gliders, small-scale planes and human-powered aircrafts. The low-Reynolds number regime is usually considered to extend to chord based Reynolds numbers of up to 500,000. For such low Reynolds numbers, boundary layers can remain laminar over a large portion of the airfoil. Laminar boundary layers have a lower skin friction drag than turbulent boundary layers. But they are, even at small angles of attack, more prone to separate in the presence of adverse pressure gradients. Of particular interest in that respect is the appearance of laminar separation bubbles which can significantly degrade performance. This performance is strongly affected by factors such as free stream turbulence, surface roughness, and acoustical disturbances.

The research reported upon in this paper contributes to the investigation of the possibilities and limitations of scaled flight research. Dynamically scaled model aircrafts can be employed for exploring flight envelopes of existing full size aircraft that would be unsafe, or for the testing new designs and design modifications. Scaled flight research can be employed to determine the aerodynamic characteristics of full-scale aircraft, to verify theoretical predictions, and to provide data where theory is deficient. Using scaled remotely piloted vehicles for flight testing of new aircraft has numerous potential advantages: During the design of new aircraft or when existing airplanes are modified, expensive design iteration or optimization steps can be explored with the scaled model. This has the potential of greatly reducing development time and cost by allowing for the testing of new technologies on a much cheaper flight platform compared to the full size airplane. In addition, it eliminates the risks involved for test pilots and lowers the environmental impact. In the context of scaled flight research, the problem of aerodynamic scaling arises. When a geometrically scaled model of a full size aircraft is build and flown the airfoil chord Reynolds number is much smaller than for the full size aircraft because of the smaller chord length and the lower airspeeds. While this is of a lesser concern when the fully stalled flight regime is explored, it is undesirable for flight testing within the normal operating envelope. The change in Reynolds number is usually such that, while the original aircraft operates in the high-Reynolds number, the model airplane operates under low-Reynolds number conditions. This is where the concept of aerodynamic scaling becomes important.

The present work report computer methods that were developed in order to assure that the aerodynamic coefficients and their derivatives are as close as possible to those for the full size wing. The overall goal of this research project is to develop the necessary technology and scientific tools to conduct scaled flight research and to demonstrate that scaled flight research can be very beneficial in substantially reducing the need for full-size flight tests, applying techniques previous developed for aerodynamic optimization by (Oliveira, 2008) and (Correa, 2009) to the requirement of designing an scaled airfoil with similar behavior of the full-scale airfoil.

2. SCALING PROCESS

For scaled model flight research, the laws of dynamic scaling have to be satisfied (Fasel, 2008). In particular, for dynamical scaling the Froude number, defined by equation 1, has to be kept constant for the full size and the model.

$$Fr = \frac{v}{\sqrt{gl}}$$

Thus, total mass, moments of inertia, velocities, and simulation results have to be scaled according to the dynamic scaling laws. Comparative flight testing of the full size and the model plane allows for a validation of the scaling laws by direct comparison of the recorded flight data from the model and the full size airplane. If deemed necessary, additional dependencies and corrections to the scaling laws could be formulated.

For aerodynamic scaling the Reynolds number, a ratio between inertial and viscous forces in fluids has to be kept constant.

$$Re = \frac{vl}{\nu}$$

If compressibility effects were of concern the Mach number would have to be kept constant as well.

Requirements from the Froude number and Reynolds number scaling generally contradict each other. Therefore, a common approach is to keep one parameter constant, where the choice depends on the flow conditions, and then try to manipulate the other free parameters such that the remaining similarity conditions are satisfied as closely as possible. For example the comparison of the aerodynamic characteristics of the scaled model with those of a model of different scale may not be appropriate if Froude number similitude requirements are not met. A difference in Froude number could result in dissimilar angles of attack. This is particularly appropriate for scaled models of advanced aircrafts that are currently used to investigate stability, control, and handling qualities. One of the prime factors necessary to determine the limitations of data obtained from a model is the degree to which the similitude requirements have been met.

3. AIRFOIL CHARACTERISTICS EVALUATION

For aeronautical purposes, there are basically two types of codes used in computational fluid dynamics. The first, namely Panel Methods, is widely used for cases where steady, potential-flow is representative. Panel Methods use Biot-Savart equations to find intensities of vortices and sources based on no-penetration boundary conditions to describe surfaces.

XFoil (Drela, 2008), a well known code for airfoil parameters estimation, uses a linear-vorticity stream function panel method for the inviscid calculations. Karman-Tsien corrections are available, allowing subsonic compressibility corrections. Integral boundary layer formulation and e^n transition model are used, allowing reasonably accurate prediction of the drag by calculating the wake momentum thickness downstream the airfoil.

The second type of method finds an approximate solution for Navier-Stokes equations. This method has a potential of providing accurate results for turbulent, non-stationary or compressible flow. Problems in this method appear when it is considered that they are computationally onerous, making it inviable for complex simulations. Most of the approaches rely on turbulence models to simplify the solutions, with the drawback of sometimes compromising the accuracy of the solution.

Given the necessity of evaluating a great number of airfoil geometries, XFoil was chosen as the most suitable code for optimization methods.

4. OPTIMIZATION METHODS

4.1 Genetic Algorithms

The genetic algorithm is implemented by the use of bit-string or real-value chromosomes, each one attached to a specific parameter of the aircraft or the airfoil. The population is initialized by selecting an initial guess, and by setting a random variation of each parameter.

After the full fitness evaluation, the population is then given the chance of evolution, by applying crossover and mutation operators, each one driven by a probability. The selection schema consists of four different methods: the classic fitness proportionate selection and tournament selection, and two methods proposed by (Raymer, 2002): The Breeder Pool (like the tournament selection, but applied only to some percentage of the best individuals) and the Killer Queen (selection of the best individual, and further extreme mutation).

4.2 Airfoil Parametric Modification by the use of Genetic Algorithms

In this technique, the airfoil is modified by changing its camber and thickness through the use of Bernstein Polynomials, f_n, shown in Figure 1 . These functions have the property of changing specific points of the normalized airfoil coordinates, without disrupting its continuity. These functions are given below, where *n* is the number of discretization points used to form the function base, and *x/c* is the x-coordinate of the airfoil, normalized by its chord.

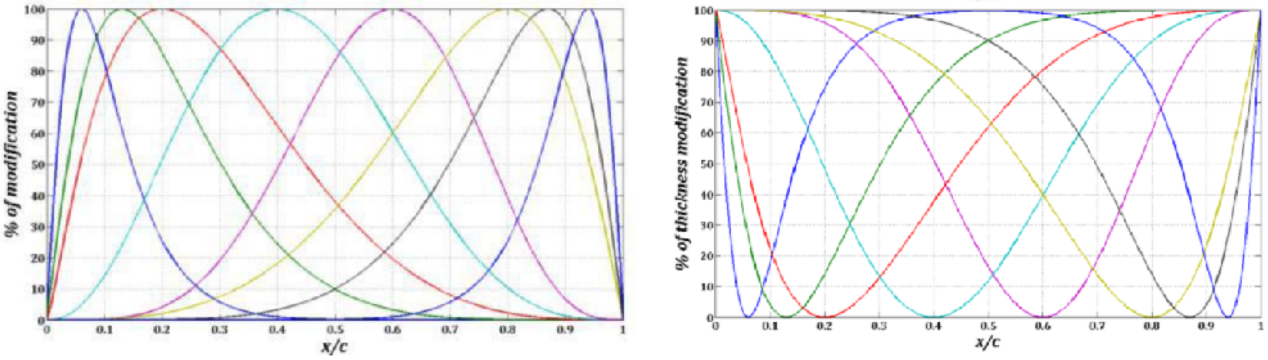

Figure 1 - Airfoil Modification Functions

$$Bernstein_{v,n}\left({}^{x}/_{c}\right) = \binom{n}{v} \cdot \left({}^{x}/_{c}\right)^{v} \cdot \left(1 - {}^{x}/_{c}\right)^{n-v}, \qquad v = 0, \ldots, n, \qquad \binom{n}{v} = \frac{n!}{v! \cdot (n-v)!}$$

The final airfoil coordinates are given by the sum of each function weighed by the genetic information C of each chromosome.

$$y_{camber}^{initial}(x) = \frac{1}{2} y_{lower}^{initial}(x) + \frac{1}{2} y_{upper}^{initial}(x)$$

$$thk^{initial}(x) = y_{upper}^{initial}(x) - y_{lower}^{initial}(x)$$

$$y_{upper}^{new}(x) = y_{camber}^{initial}(x) + \sum C_i f_i + \frac{thk(x)}{2} \sum C_j (1 - f_j)$$

$$y_{lower}^{new}(x) = y_{camber}^{initial}(x) + \sum C_i f_i - \frac{thk(x)}{2} \sum C_j (1 - f_j)$$

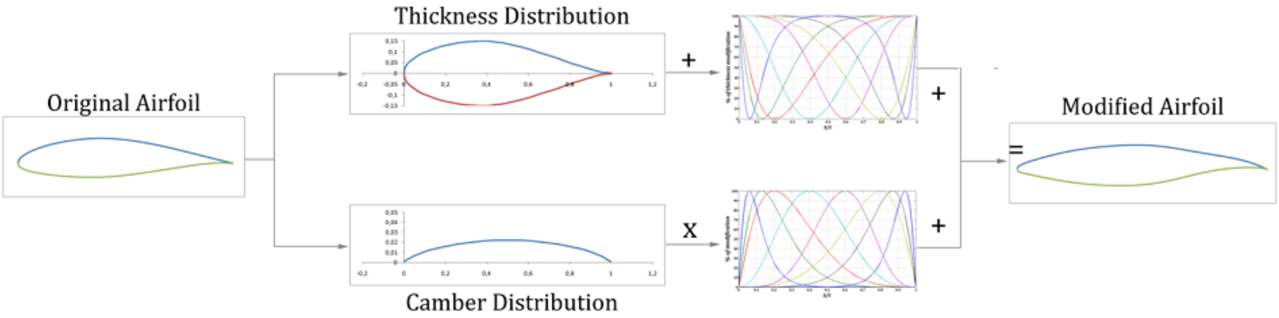

Figure 2 - Breakdown of the process of Parametric Airfoil Modification

The initial setup of the genetic algorithm is based on pre-existent airfoils. In order to improve convergence, a first run of the fitness evaluation through a database of 1168 different airfoils is made, so the optimization process always starts with a local optimum.

5. OPTIMIZATION RESULTS

We investigated the low-Reynolds number behavior of the Aeromot 200S airfoil which has a modified NACA 64_3-618 geometry. By "modified NACA" we refer to the airfoil geometry data that we measured when we mapped out the airplane geometry.

Table 1 summarizes the differences between the original NACA airfoil and the modified version. The chord Reynolds number based on mean aerodynamic chord was $3.24 \cdot 10^6$ for the full size plane at cruise and 322,000 for the 1:5 scale model at the dynamically scaled cruise condition. To understand and analyze the effect of this factor 10 change in Reynolds number on the airfoil's aerodynamics, two different analysis were run on the 2D wing section of the airfoil. By using a 2D section, 3D effects such as finite aspect ratio, taper, or fuselage interference could be excluded.

Table 1 - Geometric parameters of original and modified naca 64_3-618 airfoil used in Super Ximango aircraft

	NACA 64_3-618	Mod. NACA 64_3-618
Max. thickness	17.979%	18.343%
Max. thickness location	35.4%	36.3%
Max. camber	0.03034%	0.02964%
Max. camber location	55.0%	51.6%
Leading edge radius	0.02191%	0.02264%
Trailing edge angle	5.13°	3.82°

5.1 Analysis of Ximango Airfoil at Full Size and Low Reynolds Number Conditions

Using XFoil we first analyzed the airfoil for the full size (*Re*=3.24·10^4) and the 1:5 scale (*Re*=322,000) cruise conditions (Fig. 1). The full size wing has boundary layer trips (zig-zag tape) at 53% chord on the upper side and 54% chord on the lower side of the airfoil. In the XFoil predictions for the full size airfoil transition was forced at the same locations. The most obvious difference in the predicted lift curves for the two Reynolds numbers is the lower $C_{l,Max}$ for the model Reynolds number. For the model Reynolds number and without the trips, the boundary layers remain laminar over a large portion of the airfoil and the friction drag should, therefore, be low. However, XFoil predicts laminar separation bubbles near the maximum thickness location which slightly lowers the slope of the lift curve (Fig. 1a), increases drag (Fig. 1b), and changes the moment coefficient (Fig. 1c). For obtaining aerodynamic similarity we want to match the slope of the lift curve for a <8° and achieve a similar stall behavior.

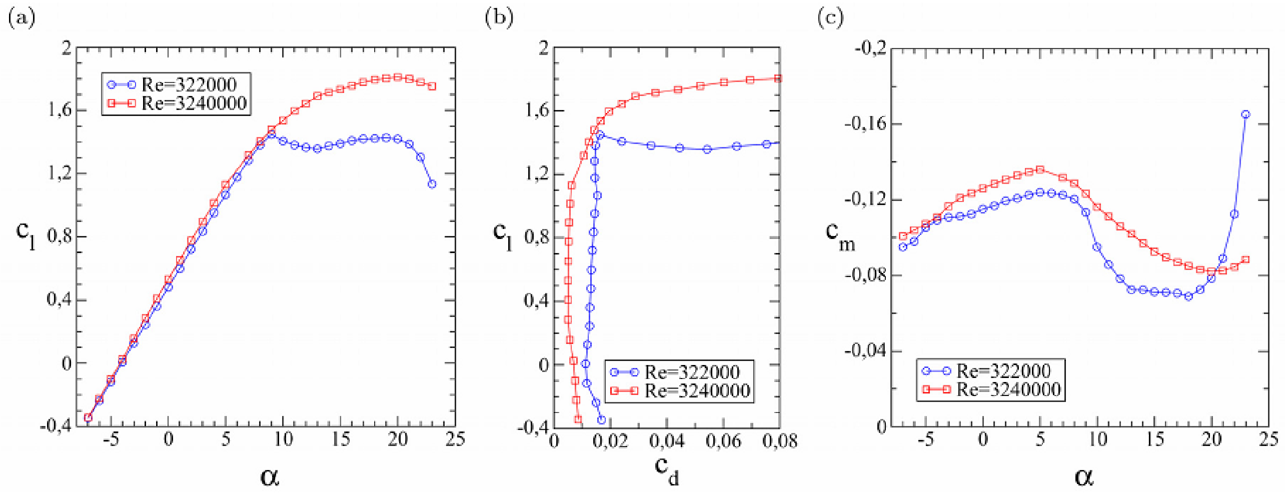

Figure 3 - XFoil Prediction of (a) lift curves, (b) drag polars and (c) moment coefficients, for the NACA64_3-618 airfoil, at full size and 1:5 scale cruise condition

5.2 Optimization Goals

The objective of the optimization process was to find an airfoil geometry that has the same aerodynamic behavior of the original full size airfoil, while operating at a lower Reynolds number. It was required that the Lift and Moment coefficients curves were matched in the angle of attack range of operation of the original airfoil. In order to evaluate the quality of new airfoils, they were analyzed in the same range of angle of attack as the original airfoil, and the resultant curve was best fitted to the original one by allowing the airfoil to have an different zero lift angle of attack, as the incidence of the wing can be changed in the scaled model.

$$F = \left(\int_{AOA_{min}}^{AOA_{max}} |\Delta C_L(\alpha \pm \alpha_0)| d\alpha \right) \cdot \left(\int_{AOA_{min}}^{AOA_{max}} |\Delta C_M(\alpha \pm \alpha_0)| d\alpha \right)$$

$$\Delta C_L(\alpha \pm \alpha_0) = C_{L_{Scaled}}(\alpha \pm \alpha_0) - C_{L_{Fullscale}}(\alpha \pm \alpha_0)$$

$$\Delta C_M(\alpha \pm \alpha_0) = C_{M_{Scaled}}(\alpha \pm \alpha_0) - C_{M_{Fullscale}}(\alpha \pm \alpha_0)$$

The final objective of the genetic algorithm was set to minimize the value of the above function.

5.3 Results

The optimization process starts with the pre-selection of the best airfoil among others in a database. It was clear that only some airfoils were indicated for this application, as the requirements of high lift coefficients at a low-Reynolds number are critical for the airfoil performance.

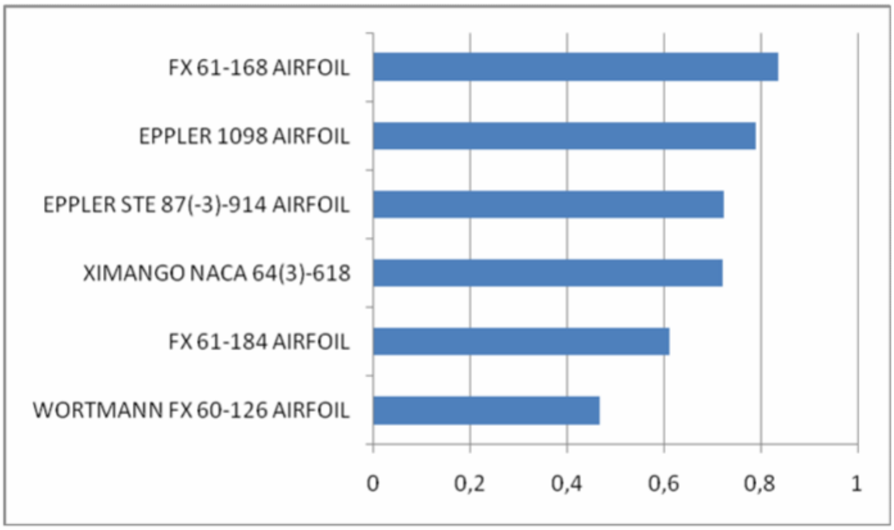

Figure 4 - Initial fitness evaluation

Based on the initial fitness evaluation of airfoils, the Wortmann FX 60-126 was selected as a start for the parametric modification genetic algorithm. In order to evaluate the effect of starting with a different airfoil in the convergence of the optimization, a 300 generations run case was made, and is clear that starting already with a local minima leads to a better convergence history than worse airfoils.

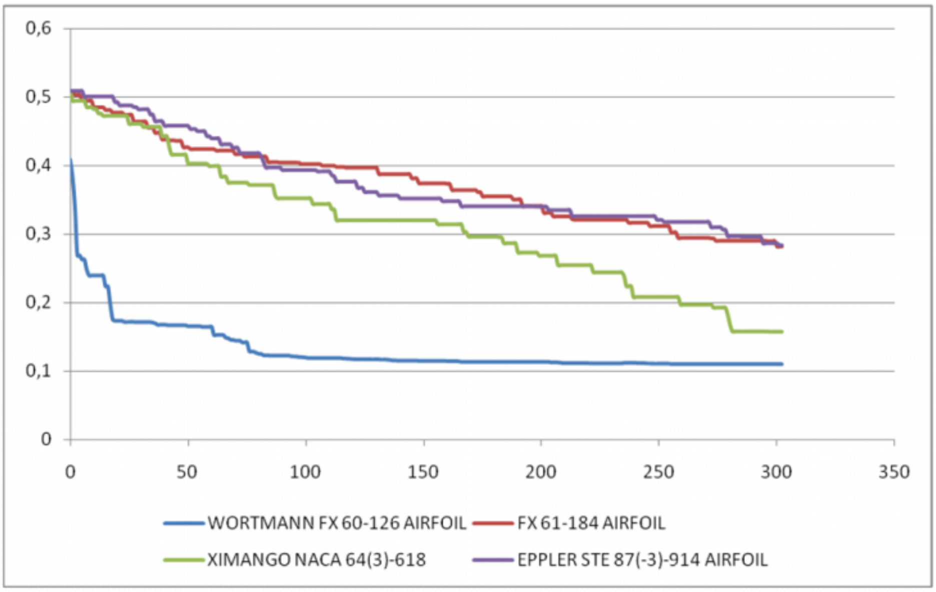

Figure 5 - Optimization history – Test case for different initial airfoils

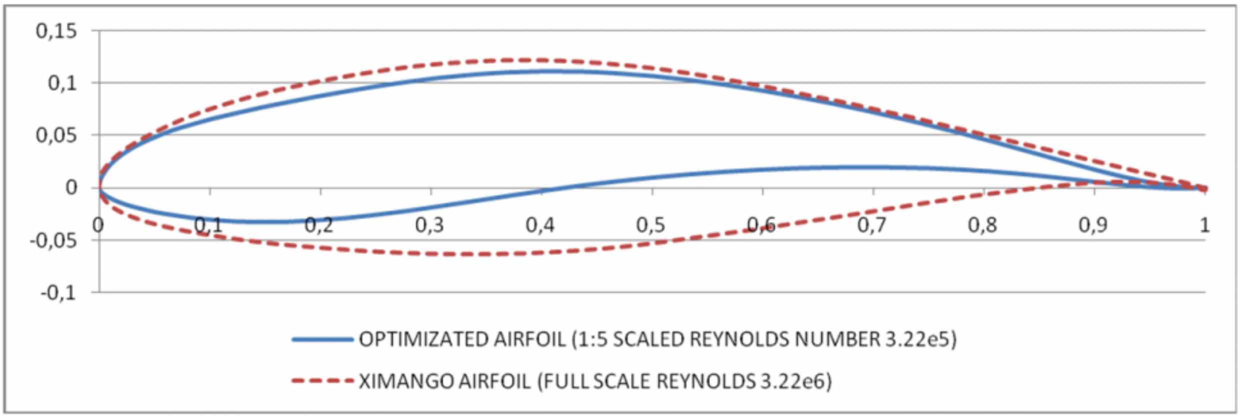

Figure 6 - Scaled Airfoil after the optimization process

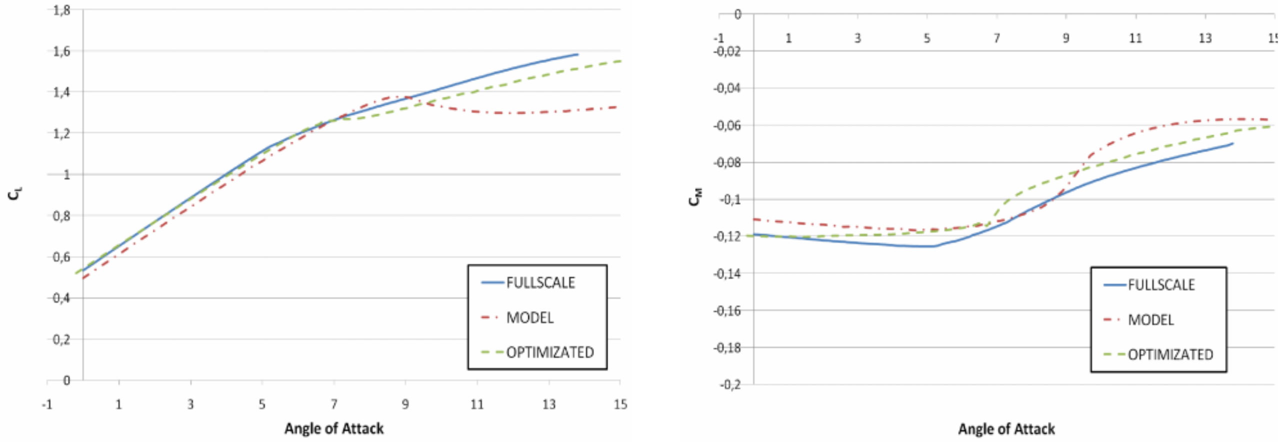

Figure 7 - Lift and Moment coefficients vs Angle of Attack, for the fullscale, model and optimized airfoils, showing the improved results after the optimization

6. CONCLUSION

The optimization results were fairly satisfactory and are likely to generate a methodology for aerodynamic scaling of airfoils. Some specificities of each project, however, must be considered before the airfoil can be implemented, and some validation of the results using wind tunnels is highly recommended. The use of other CFD methods for the evaluation of airfoils could lead to different results, but probably at a higher computational cost that may not justify its use. Although XFoil boundary layer extension (that is fundamental for the airfoil performance) may not be perfectly predicted, in the scope of this work, however, the evaluation method is secondary, and further works with different CFD codes are encouraged both for research and aircraft development.

Perhaps, the most important result of this work is the analysis the optimization technique, which may also be employed for wing and aircraft optimization as a whole, given an efficient and representative parameterization.

7. REFERENCES

Fasel, H. F., Heine, B., Mack, S. et al (2008). Aerodynamic Scaling of General Aviation Airfoil for Low Reynolds Number Application. *AIAA 38th Fluid Dynamics Conference and Exhibit*. AIAA 2008-4410. *American Institute of Aeronautics and Astronautics*.

Bernstein, A. V., Kouleshov, A. P., Sviridenko, Y. N., & Vyshinsky, V. V. (2007). Fast Aerodynamic Model for Design Technology. *West-East High Speed Flow Field Conference* .

Désidéri, J.-A., & Janka, A. (2004). Multilevel Shape Parametrization for Aerodynamic Optimization - Application to Drag and Noise Reduction of Transonic/Supersonic Business Jet. *European Congress on Computational Methods in Applied Sciences and Engineering* .

Drela, M. (2008). XFOIL 6.97 Software Manual.

Heine, B., Mack, S., Kurz, A., Gross, A., & Fasel, H. F. (2008). Aerodynamic Scaling of General Aviation Airfoil for Low Reynolds Number Application. *AIAA Journal* .

Lutz, T., Würz, W., & Wagner, S. (201). *Numerical Optimization and Wing Tunnel Testing of Low Reynolds Number Airfoil.* University of Stuttgart, Institute for Aerodynamics and Gas Dynamics, Stuttgart - Germany.

Lyrio, J. A., Cavalcanti, J. M., Mattos, B. S., Fico Junior, N. G., & Paglione, P. (2006). Wing and Airfoil Optimized Design of Transport Aircraft. *11th Brazilian Congress of Thermal Sciences and Engineering - ENCIT 2006* .

Raymer, D. P. (2002). *Enhancing Aircraft Conceptual Design Using Multidisciplinary Optimization.* Doctoral Thesis, Kungliga Tekniska Högskolan - Royal Institute of Technology, Department of Aeronautics.

Regis, A. L., & Mattos, B. S. (2004). Wing Structural Weight Evolution with the Cruise Mach Number of a Commercial Transport Aircraft. *American Institute of Aeronautics and Astronautics* .

Rodriguez, D. L., & Sturdza, P. (2006). A Rapid Geometry Engine for Preliminary Aircraft Design. *American Institute of Aeronautics and Astronautics*.

Correa, L. G. N., Entz, R. M. U., Oliveira, R. F., Medeiros, M. A. F. (2009). Methods for Preliminary Airfoil Optimization. *American Institute of Aeronautics and Astronautics - AIAA*

Oliveira, R. F., Abdalla, A. M., Belo, E. M. (2008). Genetic Optimization Applied in Conceptual and Preliminary Aircraft Design. *The 2008 International Conference on Genetic and Evolutionary Methods. GEM4680*

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