Airfoil family design for large offshore wind turbine blades

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Abstract. Wind turbine blades size has scaled-up during last years due to wind turbine platform increase especially for offshore applications.

The EOLIA project 2007-2010 (Spanish Government funded project) was focused on the design of large offshore wind turbines for deep waters. The project was managed by ACCIONA Energía and the wind turbine technology was designed by ACCIONA Windpower. The project included the design of a wind turbine airfoil family especially conceived for large offshore wind turbine blades, in the order of 5MW machine. Large offshore wind turbines suffer high extreme loads due to their size, in addition the lack of noise restrictions allow higher tip speeds. Consequently, the airfoils presented in this work are designed for high Reynolds numbers with the main goal of reducing blade loads and maintaining power production.

The new airfoil family was designed in collaboration with CENER (Spanish National Renewable Energy Centre). The airfoil family was designed using a evolutionary algorithm based optimization tool with different objectives, both aerodynamic and structural, coupled with an airfoil geometry generation tool. Force coefficients of the designed airfoil were obtained using the panel code XFOIL in which the boundary layer/inviscid flow coupling is interacted via surface transpiration model. The design methodology includes a novel technique to define the objective functions based on normalizing the functions using weight parameters created from data of airfoils used as reference.

Four airfoils have been designed, here three of them will be presented, with relative thickness of 18%, 21%, 25%, which have been verified with the in-house CFD code, Wind Multi Block WMB, and later validated with wind tunnel experiments. Some of the objectives for the designed airfoils concern the aerodynamic behavior (high efficiency and lift, high tangential coefficient, insensitivity to rough conditions, etc.), others concern the geometry (good for structural design, compatibility for the different airfoil family members, etc.) and with the ultimate objective that the airfoils will reduce the blade loads. In this paper the whole airfoil design process and the main characteristics of the airfoil family are described. Some force coefficients for the design Reynolds number are also presented.

The new designed airfoils have been studied with computational calculations (panel method code and CFD) and also in a wind tunnel experimental campaign. Some of these results will be also presented in this paper.

1. Introduction

In this paper the process for the design of a new wind turbine airfoil family is described. For the first wind turbine blades existing aeronautical airfoils were used (some of them are still used nowadays). It was in the early mid 1980’s when specifically designed airfoils for wind
energy applications were designed. Wind turbine airfoils differ from traditional aviation airfoils in choice of higher design lift point, wider off-design capabilities and more demanding structural properties. Airfoils with smooth post stall are also very interesting. Nowadays most of the wind turbine manufacturers design or buy new designs for their blades in order to achieve several goals: increase performance, reduce loads, help the structural design, etc.

Some previous works can be found in the literature regarding airfoil design. Tangler and Sommers [1] developed some of the first wind turbine dedicated airfoil families, as well as Timmer and Van Rooij [2], Hill and Garrad [3] and Chaviaropoulos et al [4]. Most of these airfoil designs were developed by use of inverse design methods. In 2001, Riso National Laboratory [5] presented the design of the wind turbine airfoil family RISO-A-XX using a direct design method. In this case the optimization algorithm is a simplex algorithm that uses XFOIL for the aerodynamics calculations. In 2010 Grasso [6] presented a gradient based algorithm coupled with RFOIL.

The present work is focused on the design of a wind turbine airfoil family specific for large offshore wind turbines blades and high Reynolds numbers. The main design goal of the new airfoil family is to get similar production and reduce loads regarding to reference airfoils. First, the description of the method will be presented as well as the main characteristics and requirements of the airfoil family. The novel definition of the objective functions used in the optimization process is presented. Next, results from the design process and comparison with CFD calculations and experiments are shown. The experimental campaign was performed in the DNW-HDG high pressure wind tunnel at Gottingen for high Reynolds numbers and it was under the scope of the EOLIA project. Finally, the conclusions of this work will be summarized.

2. Description of the method

The airfoil design methodology developed by CENER is based on a evolutionary algorithm optimization tool linked to a geometric module to generate the airfoil geometries and to the code XFOIL [8] to perform the force coefficients calculations. The airfoils are designed for a specific application, so the main characteristics of the blade and wind turbine for which the airfoil is conceived should be known in advance. More specifically, a definition of the main characteristics of the airfoil to be designed is needed. These are mainly the Reynolds number, the airfoil thickness and performance. One of the most challenging parts of designing an airfoil is deciding which are the objectives the airfoil is designed for. The objective function could cover a wide range of aerodynamic characteristics, such as design lift coefficient, minimum drag coefficient or insensitivity to contamination. In addition structural facts are used to define the objective function to allow the structural design to obtain suitable airfoils that hold the blade structure.

A general description of the design process is:

- The geometric module will create an airfoil geometry using a parametrization.
- The objective functions are generated by means of normalized parameters based on existing airfoils in order to direct the result towards a specific point.
- The optimization tool will use evolutionary algorithms to find the airfoil that suites better the requirements of the objective function. For this purpose the panel code XFOIL is used to evaluate the aerodynamic characteristics of the airfoil.
- The airfoil resulting from the optimization loop will be characterized using either XFOIL or the in-house CFD code WMB. WMB is used in the process to verify the XFOIL results and support the wind tunnel tests.

**Geometric Module**

A mathematical formulation based in Bezier curves is used to describe the airfoil’s shape. Fourth and fifth order Bezier curves are used, with up to twelve control parameters available.
The geometric module used during the airfoil design process generates the airfoil geometries that will be evaluated with XFOIL.

**Optimization algorithm**

The optimization algorithm used in this work is based in evolutionary algorithms. The Dakota optimizing tool [7] is the motor of the optimization process.

Evolutionary algorithms are based on Darwin’s theory in which the best population member survives. The algorithm starts with a randomly selected population of design points in the parameter space, where the values of the design parameters form a genetic string that uniquely represents each design point in the population. The algorithm then follows a sequence of generations, where the best design points in the population (those airfoil geometries having low objective function values) are considered to have the best characteristics and are allowed to survive and reproduce. Finally, the evolutionary algorithm identifies the best airfoil geometry that minimizes the objective function of the optimization problem.

As an example of convergence time, one of the designed airfoils is obtained after 11,000 evaluations of a compound objective function that evaluates four single aerodynamic and structural functions in 8 cores with a CPU speed of 2493 MHz with an average of 50 seconds per evaluation and a total time for this specific case of 150 hours.

**Panel code XFOIL**

XFOIL is an interactive program developed by Mark Drela [8] from the MIT used for the design and analysis of subsonic isolated airfoils. It consists of a collection of menu-driven routines which perform various useful functions such as a viscous or inviscid analysis of an existing airfoil, airfoil design or redesign and drag polar calculation. The boundary layer and wake are described with two-equation lagged dissipation integral boundary layer formulation and transition criterion. The boundary layer/inviscid flow coupling is interacted via surface transpiration model.

In CENER’s airfoil design tool XFOIL is linked to the optimization algorithm to provide force coefficient calculations for the different flow conditions.

**WMB description**

WMB (Wind Multi Block) [9] is a CFD method developed and validated by CENER and the University of Liverpool for wind turbine aerodynamics analysis (2D and 3D). It is capable of solving the compressible Unsteady Reynolds Averaged Navier-Stokes (URANS) flow equations on multi-block structured grids using a cell-centered finite-volume method for the spatial discretization. Moving and deforming grids can be calculated using WMB and aeroelastic analysis of structures such as wind turbine blades are analyzed based on modal representation.

WMB has the capacity to study both fully turbulent and transitional flows around airfoils. In addition airfoils with distributed roughness on the surface can be calculated using WMB.

In this study $k-\omega$ Baseline turbulence model and $e^N$ for the transitional calculations are used.

3. Characteristics of the airfoil family

In this section the novel technique used to create the objective function is presented.

The requirements for blade sections in a wind turbine blade can be contradictory if they come from the different disciplines involved in the design of a wind turbine. From a purely lift oriented unique aerodynamic point of view a high-lift, low-drag, thin airfoil with a laminar boundary layer over a wide range of angles of attack may be desirable, while from a structural point of view a thick airfoil with thick trailing edge allows for better elastic and strength properties of the blade. From a manufacturing point of view a blade shape with small variations of slope along the contour may be a clear objective to help saving costs in tooling and process definitions.

Nevertheless, the approach followed here has been to focus the design on the aerodynamic requirements for the airfoils and introduce other requirements either as constraints to the optimization problem or as a properly weighted additional term to the objective function.
A number of individual objective functions have been defined, each one aiming to fulfill one or more requirement. For example, one possible requirement for an airfoil placed near the tip of the blade is to have a high lift to drag ratio at the design angle of attack. This would be expressed as $F_1 = (c_l/c_d)|_{\alpha_1}$. Other possible requirement for an airfoil is to have a high tangential force coefficient (chordwise) at a range of angles of attack. This would be expressed as $F_2 = c_t|\alpha$.

The blending function $FF_i$ is defined after a comparison of the performance of some reference airfoils in that particular $F_i$. The reference airfoils are well-known public airfoils similar to the airfoil to be designed, for example airfoils of the same relative thickness, or airfoils designed in an intermediate step of this project. The definition points of the weight function serve to twist the desired result towards a particular direction: if the behavior of a particular reference airfoil $R_1$ regarding $F_i$ is considered interesting the value $F_i(R_1)$ is given a high $FF_i$, and so on. Another use of $FF_i$, complemented with weighting function values, is to make as uniform as possible the scales of all the $F_i$. An example is shown in figure 1.

![Figure 1. Piecewise linear weight function $FF_i$ used to modulate the effect of a certain objective function $F_i$.](image)

Once the specific objective functions are created the compound objective function is defined as:

$$F = \sum_i v_i FF_i,$$  \hspace{1cm} (1)

$v_i$ are new weight parameters used to emphasize the importance of each of the individual objective functions.

The optimization problem set up is complete with the definition of the desired range of variation for the design variables and the constraints imposed to the solutions. The airfoils in this family have been designed with the constraint that the moment coefficient around the quarter-chord point at zero-lift shall be above a certain level $c_{m0}$, slightly different for every airfoil in the family. This coefficient is usually negative in the attached flow regime, and the constraint helps in both reducing the pitching moment and, indirectly, in preventing the maximum camber of the airfoil from taking on too high values.

Other general conditions are specified, as the Reynolds numbers and the expected behavior of the boundary layer.

The optimization problem can be stated as

$$\max_x F(x) \quad \text{with}$$

$$x \in D, \quad \text{subject to}$$

$$g(x) < 0.$$  \hspace{1cm} (2)
In the framework of this design method it is difficult to introduce global blade or even wind turbine design goals. On the one side the calculated flow is two dimensional and nice objective functions like (minimum) cost of energy or annual energy yield do not appear in the problem. On the other hand estimates of those global variables built up from the two dimensional available quantities are very difficult to formulate and often rely upon crude approximations that somehow invalidate the use of an involved mathematical method as the present one.

Some of these estimates have been tested, however, but at the end they have been discarded either because of their low capacity to represent the true global quantity, or because the fact that the design of airfoils *per se* can be quite useful and complemented if necessary with some additional analysis.

The ACCIONA Windpower airfoil family presented here, of 18%, 21% and 25% relative thickness are named, respectively, AWA18-1, AWA21-1 and AWA25-1. The main design target of the airfoil family is to maintain the same production as reference airfoils but having some characteristics that contribute to reduce the wind turbine loads.

3.1. Design of AWA18-1

This airfoil is expected to be placed in the outer region of the blade. The individual objective functions defined for this airfoil are:

- **$F_1$** High chordwise force coefficient at a design angle of attack. Maximizing this coefficient will improve the torque generating capacity of the airfoil, which is quite desirable for a *thin* airfoil placed towards the tip of the blade since it leads to slender blades in the blade tip region.

- **$F_2$** Low sensitivity to roughness. The flow is calculated in clean and rough conditions at a range of angles of attack. The results are plotted in the $c_l - c_d$ plane, and the distance from the clean to the rough points $\|DR(\alpha)\|$ are calculated. $F_2$ is the maximum of that function. This low sensitivity to roughness is required in the angle of attack range -12° to 20°.

- **$F_3$** Structural capacity. The skin moment of inertia $I_{xx}$ as calculated by XFOIL is used to measure this feature.

- **$F_4$** Low lift-related loads. Minimizing the normal force coefficient in clean and rough conditions will improve the performance of the airfoil regarding the loads on the wind turbine caused by a high lift coefficient. This requirement is opposite to that of $F_1$ and is employed to compensate for an excess of lift in the designed airfoil and consequently reduce blade loads.

Using these objective functions, $F_1$ to $F_4$, four blending functions are defined using data from reference airfoils of the same thickness as explained in section 3, the normalized functions are called $FF_1$ to $FF_4$.

Using the normalized objective functions the compound function that enters the optimization process of AWA18-1 is defined as:

$$ F = v_1 \times FF_1 + v_2 \times FF_2 + v_3 \times FF_3 + v_4 \times FF_4 $$

3.2. Design of AWA21-1

This airfoil is designed to be placed in the mid region of the blade, and shares some of the requirements for AWA18-1. Consequently the same individual objective functions are included in its design ($F_1$ to $F_4$), although with different set of parameters and weighting. In addition a couple of objective functions are taken into account:

- **$F_5$** Controlled low negative pressure gradient in the suction side at a design angle of attack to avoid laminar separation. A discrete relative variation of pressure coefficient in the suction side is calculated and $FF_5$ limits its value in the range of the reference airfoils.
Controlled transition point motion towards the leading edge as the angle of attack increases in order to have a smooth transition from laminar to turbulent flow and have more compatibility between the airfoil family members.

The compound objective function for this airfoil is defined as:

\[
F = v_1 \ast FF_1 + v_2 \ast FF_2 + v_3 \ast FF_3 + v_4 \ast FF_4 + v_5 \ast FF_5 + v_6 \ast FF_6
\]

Note that the values of \(v_i\) and \(FF_i\) are different for every airfoil designed.

3.3. Design of AWA25-1

This airfoil is intended to be placed closer to the blade root than the former two airfoils. Consequently the requirements regarding to forces either torque-related or thrust-related are less strict and the relative weight of the structural requirements are higher than before. Now two individual objective functions have been used in the design of AWA25-1, the same \(F_2\) used before and an objective function regarding the airfoil aerodynamic performance \(F_7 = (c_l/c_d)|_{c_l=c_1}\).

The objective function for this airfoil is defined as:

\[
F = v_2 \ast FF_2 + v_7 \ast FF_7
\]

with \(FF_2\) and \(FF_7\) being the normalized functions coming from \(F_2\) and \(F_7\).

4. Results

The three airfoils in this family were designed to be as compatible among them as possible. The geometry of AWA18-1 and AWA21-1’s upper sides is quite the same as shown in figure 2, what ensures a smooth transition from one shape to the other in a wind turbine blade. In addition, it is important to outline that the airfoil family presented here has aerodynamic compatibility. An example of this is shown in figure 9, in which the transition point location variation with the angle of attack is similar for both airfoils AWA18-1 and AWA21-1.

Figure 2. The three airfoils presented here, AWA18-1 (——), AWA21-1 (- - - -) and AWA25-1 (······).

In the following sections some aerodynamic results are shown for AWA18-1 as well as some more general studies for this airfoil.

4.1. Aerodynamic data for AWA18-1

In this section WMB results for the AWA18-1 are shown comparing with the results obtained from XFOIL during the design process. In the following figures 3 to 7 lift and pressure coefficients are plotted for clean and turbulent flow for CFD code WMB and panel code XFOIL.
for $Re = 7 \cdot 10^6$. With this comparison it is verified that the panel code used in the optimization process produces good results in the linear region and how it behaves when separated flow is present. As it can be seen in the lift plots, AWA18-1 has a smooth post stall region.

**Figure 3.** Lift coefficient for AWA18-1, Clean, $Re = 7 \cdot 10^6$. WMB ——, XFOIL - - - -

**Figure 4.** Pressure coefficient for AWA18-1, Clean, $Re = 7 \cdot 10^6$, $\alpha = 4^\circ$. WMB ——, XFOIL - - - -

**Figure 5.** Lift coefficient for AWA18-1, Fully Turbulent, $Re = 7 \cdot 10^6$. WMB ——, XFOIL - - - -

**Figure 6.** Pressure coefficient for AWA18-1, Fully Turbulent, $Re = 7 \cdot 10^6$, $\alpha = 4^\circ$. WMB ——, XFOIL - - - -

In figure 7 the effect of having clean or fully turbulent flow around the airfoil is presented for the WMB calculations. The requirement included in the objective function of low sensitivity to roughness ($F_2$) is verified.
4.2. Comparison with reference airfoils

The 18% airfoil, AWA18-1, is compared next with two of the airfoils taken as reference for comparison: ref1 is a result of a previous iteration and ref2 is a TU-DELFT public airfoil of that relative thickness. The behavior of the three airfoils is quite similar, but the final design choice was AWA18-1 due to some improvements over its competitors.

AWA18-1 was better than the two reference airfoils regarding the sensitivity to roughness. In figure 8 the performance of \(\|DR\|\) defined before with respect to the angle of attack is plotted for the three airfoils. Although the objective function was designed taken into account only the maximum value of \(\|DR\|\) in a wide range of angles of attack it can be seen in the figure that AWA18-1 response is below the other airfoils for \(\alpha \geq 0\) up to stall region and therefore this airfoil is less sensitive to roughness than the other airfoils.

The performance of the 18% relative thickness airfoil designed in this work (AWA18-1) is...
Table 1. Summary of airfoil aerodynamic characteristics. Relative values using ref2 as reference. Re = 6 · 10^6.

|        | L/Dmax | CL/L/Dmax | C_Lmax |
|--------|--------|-----------|--------|
| AWA18-1 | 0%     | +3%       | -18%   |
| ref2   | 0%     | 0%        | 0%     |

compared with the performance of the TU-Delft airfoil of the same thickness used as reference in this work (ref2). Relative values are presented in table 1. These results show that the design objectives for AWA18-1 are achieved: same values for the airfoil production magnitudes and reduction for the loads magnitudes.

The 21% airfoil included an objective function F6 stated in section 3.2 which accounted for a controlled evolution of the transition point in the upper side as the angle of attack increased. In the figure 9 it can be seen that AWA21-1 behaves in a similar way to AWA18-1 and better than the previous iteration ref1 since the transition from laminar to turbulent is smoother.

Figure 9. Variation of the transition point in the upper side with angle of attack in the clean configuration. AWA21-1 (○), ref1 (△) and AWA18-1 (▽). The behavior of AWA21-1 is similar to that of AWA18-1 and smoother than that of ref1, a previous iteration.

5. Comparison with measurements
5.1. Wind tunnel description
A wind tunnel experimental campaign was performed under the scope of the EOLIA project in spring 2010 in the DNW-HDG High Pressure Wind Tunnel at Gottingen. The HDG is a closed circuit type low speed wind tunnel. It can be pressurized up to 100 bar in order to achieve high Reynolds Numbers. The speed range is 3.5 to 35 m/s. The turbulence level increases with speed (and therefore with Reynolds) from 0.2% to 0.6%. The test section size is 0.6 × 0.6 m and 1 m length.

5.2. Experimental results vs CFD for AWA18-1
In the following figures a comparison between the WMB calculations and the test in HDG wind tunnel is shown for the 18% airfoil thickness designed in this work. The tests were performed for Reynolds number 3, 6 and 9 million. For the lift coefficient curves, the XFOIL results are also included. Figures 10 to 15 show lift coefficients for the whole range of angles of attack and pressure coefficients for a certain angle. As it can be seen good agreement between experiments
and calculations in achieved for the three Reynolds numbers. Comparison between XFOIL and WMB show the expected over prediction of lift coefficient in the post stall region in the XFOIL results. In addition, the smooth post stall region obtained in the experiments is verified with the CFD calculations.

![Figure 10. Lift coefficient for AWA18-1, Re = 3 \cdot 10^6, WMB ——, XFOIL - - - -and HDG wind tunnel ▽](image1)

![Figure 11. Pressure coefficient for AWA18-1, Re = 3 \cdot 10^6, \alpha = 4^\circ . WMB ——, HDG wind tunnel ▽](image2)

![Figure 12. Lift coefficient for AWA18-1, Re = 6 \cdot 10^6. WMB ——, XFOIL - - - -and HDG wind tunnel ▽](image3)

![Figure 13. Pressure coefficient for AWA18-1, Re = 6 \cdot 10^6, \alpha = 4^\circ . WMB ——, HDG wind tunnel ▽](image4)

6. Conclusions

In this study a new airfoil family was designed under the scope of the EOLIA project (2007-2010). The airfoils were designed with specific aerodynamic and structural requirements using an evolutionary algorithm based tool coupled with a geometric module and the panel code XFOIL. The objective functions are created using normalized parameters based on existing airfoils in order to direct the result towards an specific point.
The airfoils were studied in detail using the CFD compressible code WMB and the results were completed with an experimental campaign in the HDG pressurized wind tunnel for high Reynolds numbers. Good comparison levels are achieved for WMB and the panel code XFOIL used during the design process. Comparison between WMB and tests is also satisfactory for both the linear and post stall regions.

The 18% relative thickness airfoil AWA18-1 has low sensitivity to roughness and a smooth post stall region. The main goal of the design process, that is reducing loads with the same power production, is also verified comparing with the reference airfoil.

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