Thick airfoil designs for the root of the 10MW INNWIND.EU wind turbine

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Abstract.

The main objective of the “INNWIND.EU” project is to investigate and demonstrate innovative designs for 10-20MW offshore wind turbines and their key components, such as lightweight rotors. In this context, the present paper describes the development of two new airfoils for the blade root region. From the structural point of view, the root is the region in charge of transmitting all the loads of the blade to the hub. Thus, it is very important to include airfoils with adequate structural properties in this region. The present article makes use of high-thickness and blunt trailing edge airfoils to improve the structural characteristics of the airfoils used to build this blade region. CENER’s (National Renewable Energy Center of Spain) airfoil design tool uses the airfoil software XFOIL to compute the aerodynamic characteristics of the designed airfoils. That software is based on panel methods which show some problems with the calculation of airfoils with thickness bigger than 35% and with blunt trailing edge. This drawback has been overcome with the development of an empirical correction for XFOIL lift and drag prediction based on airfoil experiments. From the aerodynamic point of view, thick airfoils are known to be very sensitive to surface contamination or turbulent inflow conditions. Consequently, the design optimization takes into account the aerodynamic torque in both clean and contaminated conditions. Two airfoils have been designed aiming to improve the structural and the aerodynamic behaviour of the blade in clean and contaminated conditions. This improvement has been corroborated with Blade Element Momentum (BEM) computations.

1. Introduction and state-of-the-art

The wind energy industry is working to reduce the Levelized Cost of Energy (LCOE). With this objective, two of the main trends that are being followed are the design of larger wind turbines and the integrated optimization of every component in the system. The “INNWIND.EU” project investigates and demonstrates innovative designs for large wind turbines of rated capacities between 10 MW and 20 MW and their key components. The project will also develop methodologies for assessing innovative designs at turbine and subsystem levels. The integrated wind turbine concept will be supported by innovations and demonstrations of the key components of the 20 MW wind turbine.

As blades become larger, some challenges are being faced by R&D departments. On the aerodynamic side, with the increasing tip speed, blades are working under flow conditions beyond the limits studied previously such as high Reynolds and Mach numbers. Moreover, aerodynamicist are looking for shape optimization and new design concepts to obtain maximum...
power production and maximum load reduction. On the structural side, blades’ structure has to withstand very high loads that require innovative structural solutions.

In this paper, the authors have dealt with the blade root region which design is very complex because it is tightly constrained by the structural requirements as it withstands the loads of the blade. The airfoil sections from which the blade geometry is created usually require big areas and moments of inertia. Therefore, the root region has traditionally shown low aerodynamic properties. The objective of the designed airfoils is to enhance both the aerodynamic properties (generated torque . . . ) and the structural behaviour (area, moments of inertia . . . ).

The aerodynamic design of airfoils for wind turbine blades is a very challenging field because it allows to tailor the aerodynamic properties of the section making them suitable for specific design requirements. In general, wind turbine airfoils are designed to operate at high lift-to-drag ratio, to have smooth behaviour in out-of-rated conditions and to maintain high structural properties. For example, Risø designed a family of airfoils based on a simplex method[1] and Grasso[2] used a gradient-based method for his designs.

The airfoils used in existing wind turbine blade root regions have been studied to characterize the state-of-the-art of root region airfoils. In general, these airfoils are characterized by high thickness and blunt trailing edges mainly because this region has to transmit all the blade loads to the hub. To the best of the authors knowledge, there are few airfoils publicly available with the described characteristics such as the Göttingen (GÖE), Wortmann (FX), Delft (DU) and NREL-SANDIA (FB) airfoils. Two of these families have been chosen to define the state-of-the-art: the Delft university [3] and the Wortmann airfoils [4]. They have been chosen due to their fitness to the objectives (focused on wind energy industry use) and to the technical specifications (high Reynolds numbers) of the “INNWIND.EU” project. Figure 1 shows the typical aerodynamic characteristics of these airfoils in comparison with thinner airfoils with sharp trailing edge (DU95-W-180 and FX84-W-175). DU airfoils are relatively thick but they keep the trailing edge gap below 2%. However, the FX family exhibits quite large trailing edge. These experimental results describe how high-thickness blunt-trailing-edge airfoils have a higher slope of the $\alpha - C_L$ curve and a higher level of drag coefficient ([5] and [6]).

During the design process, the aerodynamic characteristics of this kind of airfoils have to be evaluated. The aerodynamic motor of the CENER airfoil design tool is XFOIL. It is based on the panel-method theory which is not suitable for the calculation of high-thickness and blunt trailing edge airfoils. Actually, XFOIL makes use of empirical correlations to account for blunt trailing edge effect. These correlations were validated for trailing edge gaps much smaller than the ones found in literature [7]. That is the reason to develop a correction for the prediction of the aerodynamic characteristics based on XFOIL calculations. This empirical correction has been done with the same experimental data that were used to define the state-of-the-art.

As a summary of this work, the method used by CENER for airfoil design will be described focusing on the correction of XFOIL prediction of the high-thickness blunt-trailing-edge airfoils. Afterwards, the design objectives have been chosen and the result of the optimization process will be presented including an estimation of the effect of the new airfoils on the annual energy production (AEP).

2. Description of the airfoil design tool

The design method is based on an evolutionary algorithm which makes use of Darwin’s laws of evolution to modify a group of airfoil geometries towards the achievement of an objective. It works iteratively creating a new airfoil “generation” from the previous one based on the principles described below.

According to genetic theory, two parents of a living species transmit a mixture of their genetic characteristics to their children (this is the so called “crossover” process). In addition, Darwin’s theory suggests that the better the adapted an individual is to the environment, the more prone
it is to reproduce and so to transmit its properties to the following generation (it is usually known as the “natural selection” process). As a consequence, species improve their characteristics over generations because only the best adapted individuals are able to reproduce.

In relation with airfoil design, the degree of adaptation to the environment is measured with a mathematical function called the “objective function”. This function assigns a mark to an airfoil as a function of its aerodynamic and structural characteristics. In the same way as living species, the airfoil that best fits the objective function will be the most disposed to pass on its characteristics to the following generation. This way, airfoil characteristics get better as generations pass.

The main idea of Darwin’s theory is the already stated “natural selection” concept. However, genetic theory also suggests other events in evolution that allow the change in characteristics over generations. An example of these events is “mutation” that describes the sudden change in an specific characteristic in an individual of the new generation that is not inherited from its parents. This operation is also included in the genetic algorithm implemented in the airfoil design tool.

Airfoils have to be defined by a certain list of parameters (which are equivalent to the characteristics of the living beings) to apply the laws of evolution (crossover, selection and mutation). In this case, these parameters are the control points of the Bezier curves that define the geometry (one curve for the thickness and another one for the camber). These Bezier curves are forth and fifth order and account for a total of twelve control parameters.

Moreover, as it was introduced before, an objective function has to be defined to evaluate the performance of every airfoil to calculate how likely it is to transmit its characteristics to the following generation. Any characteristic coming out from the aerodynamic or the structural motors or a mixture of them can be used as input for the objective function. The specific
objective function used for the current design will be described in the following sections.

As an outline, CENER’s airfoil design tool is conformed by several modules. Each one of these modules develops one function. This configuration gives an interesting flexibility to the tool because any functionality can be changed just reprogramming the module that deals with it. This is the list of the components:

**Optimization module:** Applies the laws of evolution to the control points (the points that define the airfoil geometry) to create a new generation. Its decisions are based on the value of the objective function of each airfoil

**Geometric module:** Generates an airfoil geometry from the control points

**Aerodynamic motor:** Calculates the aerodynamic properties of an airfoil (lift and drag coefficients, transition location . . .)

**Structural motor:** Calculates structural properties from airfoil geometries (moment of inertia, area . . .)

**Evaluator module:** Evaluates the airfoil performance by applying the objective function to the aerodynamic and the structural motors’ output

In this case, the functions of the “Optimization module” and the “Aerodynamic motor” are carried respectively by DAKOTA [8] and XFOIL [9]. Further information can be found in previous papers published by CENER [10].

### 3. XFOIL correction for high-thickness blunt-trailing-edge airfoils

XFOIL is used as the aerodynamic motor of the design tool. The theoretical background of panel methods makes them non-suitable for the calculation of finite-trailing-edge airfoils because the Kutta condition cannot be applied at the trailing edge. However, these codes are usually modified to, somehow, calculate this kind of airfoils.

XFOIL is able to provide results for these airfoils, however, the quantitative prediction does not fit the experimental data. In general, it provides good results for the lift coefficient of low-thickness and pointed trailing edge airfoils but it is known to overpredict the lift curve slope for thick airfoils with thick trailing edge. For both types of airfoils, XFOIL underpredicts the drag coefficient showing bigger deviations the thicker the airfoil trailing edge.

Accordingly, an empirical correction has been developed to modify the output given by XFOIL in order to make a better comparison of airfoils. The objective is not to create a panel software able to calculate blunt-trailing-edge airfoils. Instead, the objective is to avoid introducing the error in XFOIL prediction into the optimization process. For example, if the design objective was to reduce the drag coefficient, the optimization algorithm without the correction would not try to reduce the trailing edge because the drag prediction of large trailing edge airfoils is highly underestimated. It would result in a thick-trailing-edge airfoil that in real life would have much higher drag coefficient than expected.

Figures 2a and 2b show an example of how the correction works. This correction reduces the slope of the XFOIL prediction by means of rotating the $C_L - \alpha$ curve using $\alpha = 0^\circ$ as rotating origin and multiplies the drag coefficient by a constant factor. This factor has been obtained around the maximum efficiency point and has been applied to the rest of the $C_D - C_L$ curve.

The characteristics of the DU97W350 airfoil (t/c=18% and TGap/c=0) make it suitable for the calculation with XFOIL, thus, the correction barely modifies the slope and it slightly increases the drag prediction (around 18%). On the other hand, the DU97W350 is relatively thick with blunt trailing edge. Consequently, the slope is significantly modified and the drag coefficient increases as well.

This correction has been developed based on the airfoils described in the introduction (the Delft and the Wortmann collections). Those experiments have been used to evaluate how XFOIL
prediction deviates from experiments. The \( C_L - \alpha \) slope has been measured at the linear region of the curve (around \( \alpha = 0^\circ \)) and the drag used in the comparisons has been selected around the maximum efficiency point. It has been found that XFOIL shows bigger differences the bigger the airfoil trailing edge. Those deviations are shown in figures 3a and 3b.

Unfortunately, due to the limited amount of experiments for this kind of airfoils, the effect of the trailing edge cannot be separated from other effects that have been unavoidably included in the correction (usual drag underprediction of panel methods . . . ).

The data used to create the correction includes airfoils with thickness from 18%c to 66%c and trailing edge gap from 0%c to 27%c at Reynolds number from 1.5e6 to 4e6. The Reynolds numbers are not as high as the ones encountered in the original “INNWIND.EU” blade design, however, authors have not been able to find experiments at higher Reynolds numbers.

4. Design method and objectives

The high loads present in the blade root require that the airfoils in this region provide good structural behaviour. For this reason, high-thickness and blunt-trailing edge airfoils are used for the current design. The parameters that define the structural behaviour of an airfoil are, for example, the area and the moments of inertia with respect to the “x” and the “y” axes.

The contribution of this region of the blade to the power coefficient of the wind turbine is very small, nevertheless, it is important to include aerodynamic properties in the optimization function to obtain airfoils with better aerodynamic characteristics than the original ones. The aerodynamic target is to increase the generated power. To do so, there are two options: increase the lift coefficient or decrease the drag coefficient. A possible reduction of the drag coefficient does not seem to be very effective to improve the aerodynamic behaviour because these airfoils will intrinsically have a high drag coefficient due to the geometrical constraints imposed by the structural requirements (high-thickness and blunt trailing edge). For this reason, the objective of the design is to obtain the maximum lift coefficient at the design point.

When an airfoil is designed to be used in wind turbines, it is important to consider the behaviour at normal operating conditions, but it is also important to evaluate the characteristics in out-of-rated operating points. In this case, the airfoil has been optimized at rated conditions. However, out-of-rated conditions have been also considered when analyzing the airfoil behaviour. The angles of attack at rated conditions have been obtained from previous simulations of the
original “INNWIND.EU” blade with the code “FAST” [11]. The optimization was done at an angle of attack of 10° at Re9e6 and Re11e6 for the t/c=50% and t/c=40%, respectively.

Surface irregularities, turbulent instabilities present in the wind and contamination of the blade surface (by insect impacts, oil from maintenance . . . ) make transition happen at an earlier chord position. Moreover, thick airfoils are known to be very sensitive to this phenomena [12]. Therefore, special care has been taken to enhance the performance under the so called “contaminated conditions” which aim to represent the effect of the previously cited phenomena. The “eN” transition method [13] predicts the transition location over the airfoil based on the degree of amplification of the instabilities present in the flow. The “Ncrit” parameter defines the amplification threshold that triggers transition. Physically the “Ncrit” parameter is used to quantify the effect of surface contamination and inflow turbulence. For the clean case Ncrit=9 has been used. The way of simulating the contamination phenomena is to undertake calculations with the parameter Ncrit=0.1.

These design requirements are translated into the following optimization objectives:

- Optimize structural characteristics by using thick airfoils and thick trailing edges.
- Maximize the airfoil lift coefficient for the design angle of attack in both clean and contaminated conditions.

5. Results

Two airfoils have been designed to improve the behaviour of the root blade region of the 10MW “INNWIND.EU” rotor, according to the previous methodology. The main objectives are maximize the lift coefficient, improve the “contaminated” behaviour and provide good structural properties, as it was stated in section 4.
These two airfoils have thickness-to-chord ratios equal to 50% and 40%, respectively. The aerodynamic characteristics of each airfoil are compared with the official blade root airfoils of the “INNWIND.EU” project. The presented curves have been corrected with the methodology described in section 3.

5.1. 50% airfoil

Figure 4 shows the geometric shape of the new 50%-thick airfoil compared to the original one. This airfoil was obtained after computing 96 generations of 50 members each.

The thick trailing edge \((T_{Egap}/c = 20\%)\) provides good structural behaviour. Specifically, the enclosed area increases 11% and the moments of inertia with respect to the “x” and the “y” axis increase 9% and 48%, respectively (table 2).

When averaging the clean and contaminated behaviour at the design point, the lift provided by the new airfoil is 56% higher than the coefficients of the original airfoil in the “INNWIND.EU” blade (figure 5a). On the other hand, the new airfoil has a higher drag coefficient than the original airfoil and so the new airfoil is around 30% less efficient in average at the design point (figure 5b). Notice that the maximum efficiency shows a large drop. However, previous simulations show that the airfoil is working around \(\alpha = 10^\circ\) so the efficiency drop is not that severe. Moreover, the efficiency in contaminated conditions has grown.

In both clean and contaminated conditions, the stall happens at higher angles of attack with respect to the original airfoil. This provides a margin of safety for out-of-rated conditions that can take place during gust or other special operating conditions.

![Figure 4: Geometry of the 50% thick airfoils](image-url)
Figure 5: t/c=50%. Re9e6. Solid line clean (Ncrit=9), dashed line contaminated (Ncrit=0.1)

5.2. 40% airfoil
The 40%-thick airfoil shows the same behaviour as the previous one: 21% higher lift, low sensitivity to roughness and around 60% lower efficiency than the original airfoil, in average at the design point. Regarding the structural behaviour, the enclosed area increases 12% and the moments of inertia with respect to the “x” and the “y” axis increase 9% and 63%, respectively. Tables 1 and 2 gather some performance data of the designed airfoils with respect to the original ones. This airfoil was obtained after computing 52 generations of 50 members each.

Figure 6: Geometry of the 40% thick airfoils
Figure 7: t/c=40%. Re11e6. Solid line clean (Ncrit=9), dashed line contaminated (Ncrit=0.1)

Table 1: Aerodynamic characteristics at the design point

|                      | t/c=50% | t/c=40% |
|----------------------|---------|---------|
|                      | original| new     | original| new     |
| \((C_{L_{clean}} + C_{L_{contaminated}})/2\) | 1.25    | 1.95    | 1.66    | 2.01    |
| \((C_{L}/C_{D_{clean}} + C_{L}/C_{D_{contaminated}})/2\) | 21      | 14      | 61      | 26      |

Table 2: Structural characteristics

|                      | t/c=50% | t/c=40% |
|----------------------|---------|---------|
|                      | original| new     | original| new     |
| TEgap/c (%)          | 7       | 20      | 5       | 16      |
| \(A/c^2\)            | 0.3167  | 0.3518  | 0.2478  | 0.2784  |
| \(I_{xx}/c^4\)       | 0.0044  | 0.0048  | 0.0022  | 0.0024  |
| \(I_{yy}/c^4\)       | 0.0163  | 0.0242  | 0.0123  | 0.0201  |

As a back-of-envelope calculation, some Blade Element Momentum (BEM) calculations have been performed to check how the annual wind energy production changes with these new airfoils. A reference wind turbine model was described in the “INNWIND.EU” project. This model has been use as a base. To account for the different airfoils, the polar curves included in the model were substituted by the new ones calculated and corrected during the present work for both the original and the new airfoils. Two calculations were performed with the original airfoils, one of them in clean configuration and the other one in contaminated configuration. Afterwards, the root airfoils were replaced by the airfoils designed in the present paper. Again, a clean and a contaminated configuration were calculated. Calculations were performed for a Weibull wind distribution at an average wind speed of 10m/s and a shape factor equal to 2.
results are shown in table 3 according to equation 1. Even though blade root region does not have an influential effect on annual energy production, a very small increase in both clean and contaminated configurations is observed.

Table 3: $\Delta AEP$ in the “INNWIND.EU” wind turbine

|                      | $\Delta AEP$ (%) |
|----------------------|------------------|
| Clean conditions     | 0.07             |
| Contaminated conditions | 0.05            |

$\Delta AEP(\%) = \frac{AEP_{\text{new}} - AEP_{\text{original}}}{AEP_{\text{original}}} \cdot 100$ (1)

6. Conclusions and future work
In this study, two new root airfoils (thickness equal to 40% and 50% respectively) were designed under the scope of the “INNWIND.EU” project. During this project, a more extensive description of this work was reported in [14].

Prior to the design process, the state-of-the-art has been characterized studying the available airfoils with large thickness and blunt trailing edge. These airfoils provide a higher $\alpha - C_L$ slope and a higher drag coefficient than the airfoils used for the blade tip region (which are thin and with small trailing edge gap). However, there is still a need of experimental data of airfoils with high thickness and blunt-trailing-edge, specially at Reynolds numbers above three millions.

Panel methods provide inaccurate results for that kind of airfoils. During the study, this problem has been overcome with the development of an empirical correction of the XFOIL prediction of high-thickness and blunt-trailing-edge airfoils.

Two airfoils for the root region of the “INNWIND.EU” blade have been designed. The main characteristics of the new airfoils is that they have high lift and low sensitivity to surface contamination. At the same time, they provide good structural behaviour increasing the enclosed area and the moment of inertia with respect to both axis.

The performance of the airfoils within the “INNWIND.EU” blade has to be evaluated using the BEM theory. The results show that the contribution of these airfoils to the torque generated by the wind turbine is very small. Despite the fact that the new blade geometry has not been optimized, a small increase in energy production has been observed. As a consequence, it would be interesting to include the designed airfoils in an optimization process including the whole blade. Moreover, the new geometries design show that there is a big margin for structural properties improvement without penalizing the aerodynamic behaviour.

It would be interesting to characterize the airfoils behaviour with 2D CFD calculations to confirm the properties predicted by XFOIL and the correction developed. Moreover, the complexity of the flow in the blade root region requires that further steps are performed in the optimization process. For example, it would be interesting to analyze how the root region works under rotational effects. It could be done with 3D CFD computations. There are also unsteady effects that could modify the properties of the present airfoils, some Unsteady Reynolds Averaged Navier Stokes (URANS) computations could clarify this point.

Nomenclature

A Area enclosed by the airfoil [$m^2$]
c Airfoil chord [m]
$C_D$ Drag coefficient [-]

$C_L$ Lift coefficient [-]

$C_{L}/C_D$ Airfoil efficiency [-]

$\partial C_L/\partial \alpha$ Slope of the linear region of the $\alpha - C_L$ curve (around $\alpha = 0^\circ$) [1/$^\circ$]

$I_{xx}$ Moment of inertia respect an axis parallel to “x” [m$^4$]

$I_{yy}$ Moment of inertia respect an axis parallel to “y” [m$^4$]

$N_{crit}$ Logarithm of the disturbances amplification factor from the eN transition method [-]

$t$ Airfoil thickness [m]

$TE_{gap}$ Trailing edge gap [m]

**Greek letters**

$\alpha$ angle of attack [$^\circ$]

**Subscripts**

experiments Data from experiments

clean Clean conditions

contaminated Contaminated conditions

new Refers to the airfoils designed in the present work

original Refers to the original “INNWIND.EU” design

xfoil Data from XFOIL calculation

**Abbreviations**

AEP Annual Energy Production

BEM Blade Element Momentum theory

CENER National Renewable Energy Center of Spain

CFD Computational fluid dynamics

LCOE Levelized Cost of Energy

R&D Research and development

URANS Unsteady Reynolds Averaged Navier Stokes

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