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Abstract. In order to maximize the ratio of energy capture and reduce the cost of energy, the selection of the airfoils to be used along the blade plays a crucial role. Despite the general usage of existing airfoils, more and more, families of airfoils specially tailored for specific applications are developed. The present research is focused on the design of a new family of airfoils to be used for the blade of one megawatt wind turbine working in low wind conditions. A hybrid optimization scheme has been implemented, combining together genetic and gradient based algorithms. Large part of the work is dedicated to present and discuss the requirements that needed to be satisfied in order to have a consistent family of geometries with high efficiency, high lift and good structural characteristics. For each airfoil, these characteristics are presented and compared to the ones of existing airfoils. Finally, the aerodynamic design of a new blade for low wind class turbine is illustrated and compared to a reference shape developed by using existing geometries. Due to higher lift performance, the results show a sensitive saving in chords, wetted area and so in loads in idling position.

1. Introduction

In order to maximize the ratio of energy capture and reduce the cost of energy, the selection of the airfoils to be used along the blade plays a crucial role. In the modern wind turbines, some airfoils for aeronautical applications (i.e. NACA 63xxx and NACA64xxx) are still quite used; however, due to the particular requirements in terms of design/off design properties and structural properties, there is an increased interest in develop dedicated airfoils for wind turbines. Starting from the mid-1980s, quite some work has been done at NREL [1], FFA [2], Delft University [3], Risoe [4].

The target design characteristics for the airfoils have been updated during the years and tailored to the specific type of power control and the need for off design operation. The desirable airfoil characteristics can be divided into structural and aerodynamic properties, and the wind turbine blade can be divided into the root, middle, and tip parts, where the root part is mainly determined from structural considerations. In contrast, the tip part is determined from aerodynamic considerations.

Some research about airfoils design has been done by the present author [5-7], focused both on tip and thick geometries. Starting from the results of those works, the present work is focused on the design of a family of new airfoils and analyze their impact on the performance of the blade. In this context, family of airfoils is intended as a group of geometries with consistent characteristics. Along the same blade, several geometries are used; to obtain good performance it is necessary that the airfoils have not only good individual properties, but also that they show similar behavior.

In the next paragraph, the design approach is illustrated; then the characteristics of the new geometries are presented and finally their effect on turbine performance are discussed.

2. Airfoil design approach

Numerical optimization is used in this work. In the most general sense, numerical optimization solves the nonlinear, constrained problem to find the set of design variables, X_i, i=1, N, contained in vector X, that will:

$$\text{Minimize } F(X) \qquad (1)$$

subject to:

$$g_j(X) \leq 0 \qquad j = 1, M \qquad (2)$$

$$h_k(X) = 0 \qquad k = 1, L \quad (3)$$

$$X_i^L \leq X_i \leq X_i^U \qquad i = 1, N \quad (4)$$

Equation 1 defines the objective function which depends on the values of the design variables, X. Equations 2 and 3 are inequality and equality constraints respectively (equality constraints can be written as inequality constraints and included in equation 2), and equation 4 defines the region of search for the minimum.

2.1. Optimization scheme

Several algorithms have been developed to perform numerical optimization. Depending on the specific problem to be solved, one algorithm is more suitable than another one. In the present paper, a hybrid scheme is used in which genetic algorithms (GA) are combined with gradient based algorithms (GBA). GA are usually less sensitive to local optima but also less accurate in reach the optimal solution; instead the GBA are quite accurate but they can be affected by the initial solution and local optima. GA are used at the beginning of the design to explore wide domains, while GBA are used as refinement. A more complete discussion can be found in [8].

2.2. Geometrical parameterization

The airfoil is described by using a parameterization [9] through 4 Bezier polynomials of the third order. The design variables are the positions (horizontal and vertical) of the control points of the polynomials (see Figure 1).
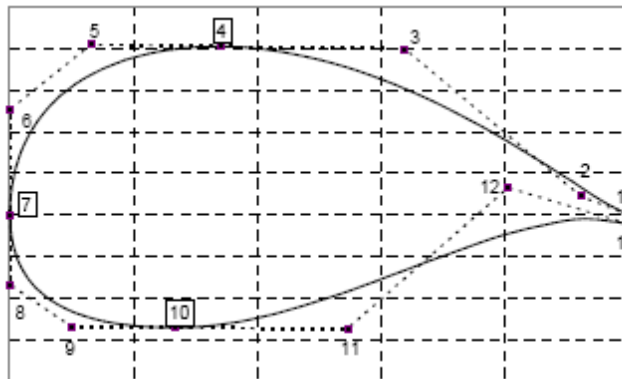

Figure 1 Sketch of the airfoil parameterization.

2.3. Aerodynamic solver

Here, the RFOIL [10] numerical code is used. RFOIL is a modified version of XFOIL [11] featuring an improved prediction around the maximum lift coefficient and capabilities of predicting the effect of rotation on airfoil characteristics. Regarding the maximum lift in particular, numerical stability improvements were obtained by using the Schlichting velocity profiles for the turbulent boundary layer, instead of Swafford's. Furthermore, the shear lag coefficient in Green's lag entrainment equation of the turbulent boundary layer model was adjusted and deviation from the equilibrium flow has been coupled to the shape factor of the boundary layer. From the validation results, 10% of under-prediction has been found for the drag (see ref. 5). In order to compensate this inaccuracy, 10% penalty is added to RFOIL drag predictions.

3. Design of new airfoils

A family of 6 new airfoils (named ECN-G2-xx) has been developed with the percentage thickness ranging between 18 and 40 percent. The main objective of the design was to obtain airfoils with high aerodynamic efficiency (*L/D*); however, beside this, also other considerations have been included during the development. Since the new geometries have to be suitable for low wind class turbines, not only *L/D* should be high, but the lift coefficient (C_l) and the maximum lift coefficient (C_{lmax}) should also be high to produce enough lift in low wind conditions. As discussed in [5], high lift airfoils can lead to a reduction in chord distribution that is beneficial to limit the extreme loads in parking conditions and the load fluctuations in case of gust. On the other hand, abrupt stall should be avoided and a safety margin between design condition and separated flow region should be ensured to protect the airfoils from working in separated flow during gusts (that could lead to fatigue problems for the blade). In order to prevent abrupt stall, the location of the transition should move gradually when the angle of attack changes. Sometimes high efficiency airfoils have large extension of laminar flow; this helps to have low values of drag coefficient (C_d) but at the same time, can mean that the geometry is sensitive to the roughness so the performance can significantly decrease.

In the present work, the design has been performed in fixed transition conditions in order to have a good robustness against roughness. Also, the airfoils have been optimized for relatively large values of angle of attack in order to obtain high lift performance.

In terms of constraints, the same set of constraints has been prescribed in order to have consistent properties along the blade. In particular, a minimum value for leading edge radius and trailing edge thickness have been assigned, the first to ensure a quite round shape for the airfoils, the second to avoid manufacturing problems. Together with the geometrical constraints, an aerodynamic constraint on the moment coefficient ($C_{mc/4}$) has been used. On one side, this helps to include the torsion of the blade during the design; at the same time, the airfoils are consistent with each other also from aerodynamic point of view.
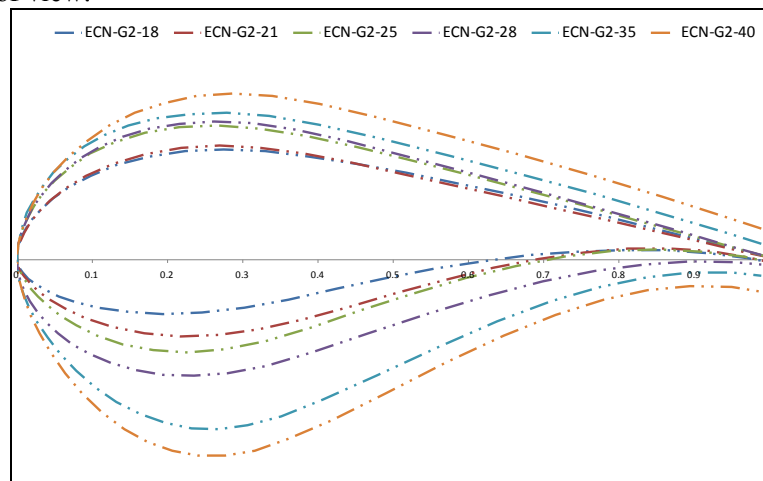

Figure 2 Sketch of the new ECN-G2-xx airfoils.

In Figure 2, a sketch of the new airfoils is shown (the geometries have been deformed to protect the confidentiality of the data), while figures 3 - 6 show the performance in terms of lift curves and the efficiency curves for clean and dirty conditions. The data are compared to the ones related to NACA 63_3618 and FFA-W-280 airfoils. The Reynolds number is 4 million; in accordance to what mentioned in section 2, the drag coefficient is increased by 10 percent.
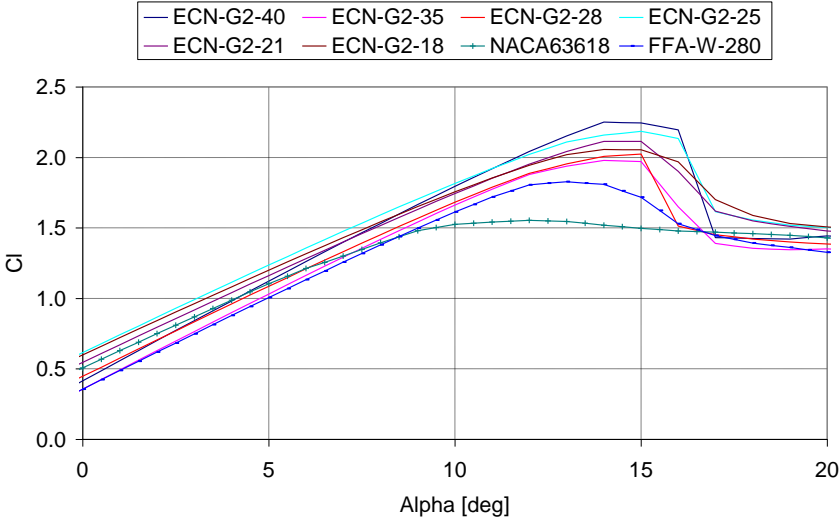

Figure 3 Lift curves. Comparison between the new geometries with NACA63$_3$618 and FFA-W-280. RFOIL predictions: 4 million Reynolds number, free transition.
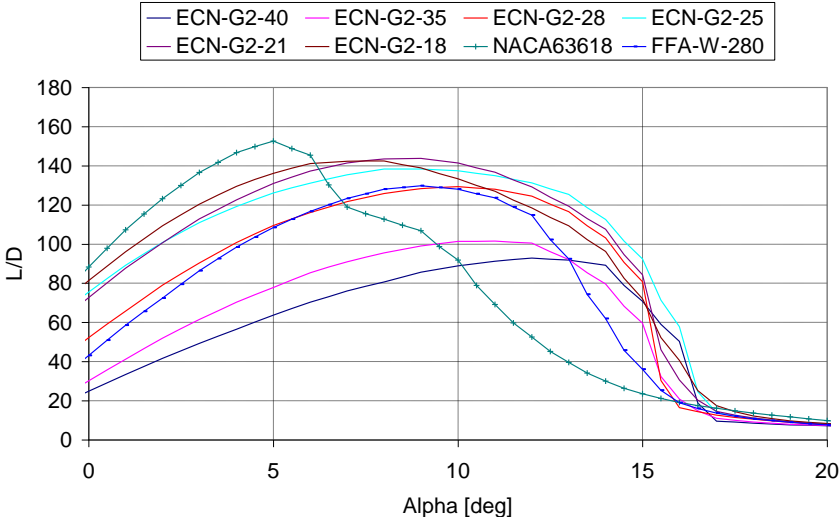

Figure 4 Efficiency curves. Comparison between the new geometries with NACA63$_3$618 and FFA-W-280. RFOIL predictions: 4 million Reynolds number, free transition.

All the new airfoils exhibit high lift performance with good extension of the linear part of the lift curve and not abrupt stall. In terms of efficiency, all of them have good off design performance and relatively good values of efficiency. Compared to the NACA 63_3618, the ECN-G2-18 has better lift characteristics with the linear region of the curve extended almost up to the stall. Looking at the efficiency, the NACA airfoil has slightly better performance but the new geometry keeps its maximum value over a wide range of angles of attack. Due to fixed transition the performance of the airfoils

decrease; however, the new airfoil maintains better lift performance and higher efficiency in design and off-design conditions. Regarding the FFA-W-280 airfoil, the ECN-G2-28 has very similar characteristics in terms of efficiency but slightly better lift properties.
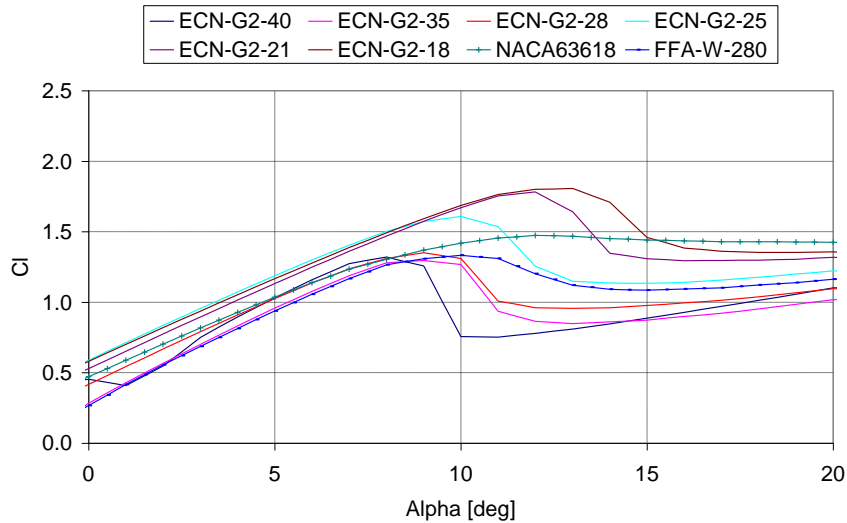

Figure 5 Lift curves. Comparison between the new geometries with NACA63₃618 and FFA-W-280. RFOIL predictions: 4 million Reynolds number, fixed transition (1% on suction side, 10% on pressure side).
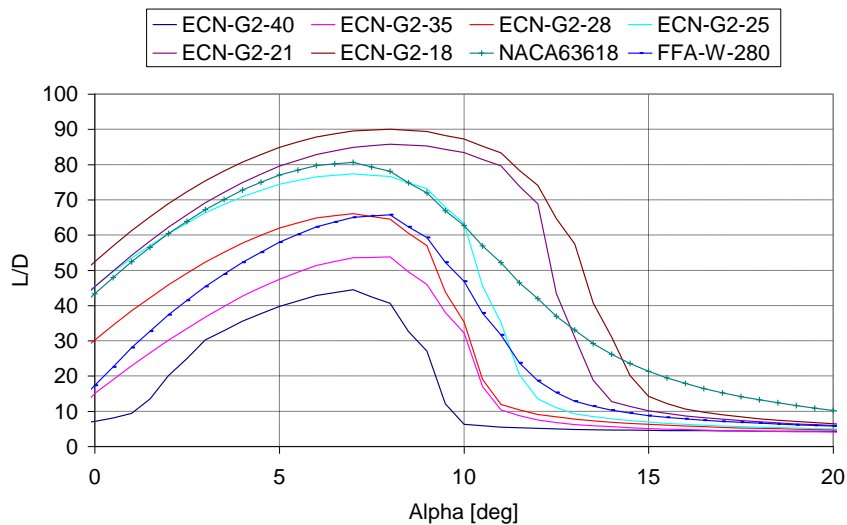

Figure 6 Efficiency curves. Comparison between the new geometries with NACA63₃618 and FFA-W-280. RFOIL predictions: 4 million Reynolds number, fixed transition (1% on suction side, 10% on pressure side).

4. Impact of the new airfoils on blade design

In order to estimate the impact of the new airfoils on the wind turbine performance, a case study has been considered in which a 24 meter radius blade for 600kW IEC class3 turbine has been used for comparisons. A combination of NACA 63₃6xx and FFA-W-xxx airfoils is installed on the reference blade (named RWT). Starting from the new airfoils, a new blades have been designed (named G1) with the constraint to have yield production not lower than the reference geometry. The ECN software BOT [12][1] has been used. BOT is based on Blade Element Momentum (BEM) theory and is capable

to automatically optimize chord and twist distributions along the blade in order to maximize the annual yield production. Figure 7 and Figure 8 show the comparisons between the geometries in terms of chord and twist distribution.

Table 1 Comparison reference blade (RWT) and the new design (G1).

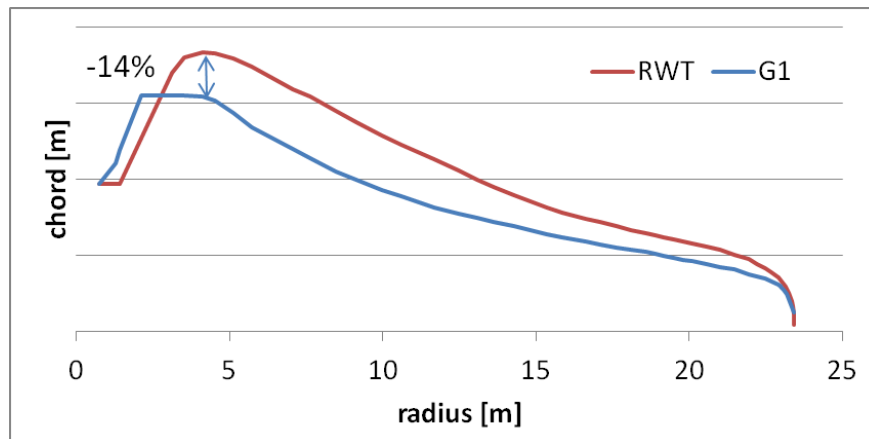|	RWT	G1	Δ [%]
Yield [GWh/yr]:	2.191	2.194	0.10
P_{rated} [kW]:	600.0		-
$C_{pmax (mech)}$[-]:	0.5112	0.5128	0.32
Axial force [kN]:	83.7	82.3	-1.74
Root flap bend. Mom. [kNm]:	394.8	399	1.24
Root flap bend. Mom. (idling) [kNm]:	501.11	403.16	-19.55
Wetted area [m^2]:	53.22	43.13	-18.96
Aspect ratio [-]	10.31	12.72	23.4

Figure 7 Comparison between chord distributions of the new blade (G1) and the reference (RWT).
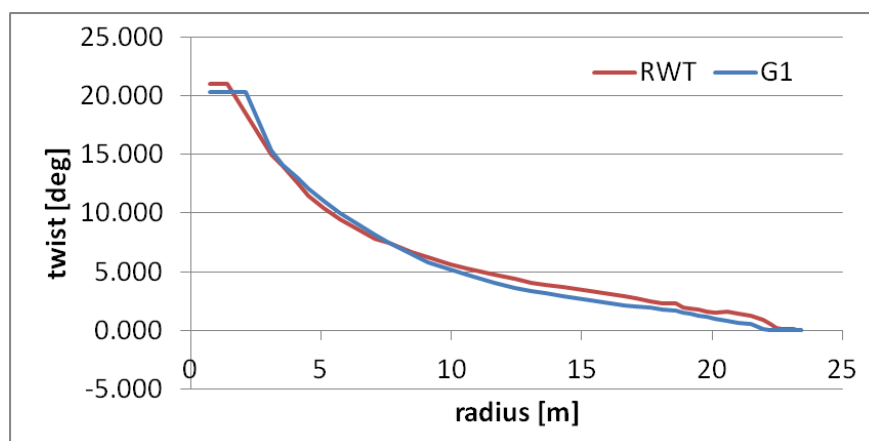

Figure 8 Comparison between twist distributions of the new blade (G1) and the reference (RWT).

Due to airfoil high lift performance, G1 blade is visibly more slender than the RWT. This means that the wetted area is less (-19%, see Table 1) so some savings is expected in terms of material for the skin and weight of the blade. Also, the reduction in maximum chord (-14%) could lead to reduce problems for transportation.

Looking at the global performance (Table 1), the maximum power coefficient (Cp_{max}) is improved with the new blades, while the annual yield is almost the same.

The reduction in chord can be beneficial in regards of extreme loads in idling case. In order to quantify the reduction in root bending moment, a simple calculation has been made integrating the contribution due to the force produced by the individual sections. Due to the 90 degrees blade pitch angle, the aerodynamic force is purely drag; the blade is considered like a flat plate and based on the aspect ratio (AR), a value of drag coefficient (C_d) of 1.296 has been considered for the RWT and 1.33 for G1 blade [13]. Also, the surface considered is the plan area. The survival wind speed prescribed by IEC standard for class 3 is used (52.5 m/s). The root flap bending moment decreases of almost 20 percent.

5. Conclusions

The design of new airfoils for low wind class turbines has been discussed, as well as the effects of such new airfoils on the design of a new blade. The new family of airfoils shows similar properties in terms of general shape and aerodynamic properties; in particular, all the geometries exhibit large leading edge radius and high lift performance. The first feature makes the geometries less sensitive to roughness, the second one leads to slender blades. The effects due to the new airfoils have been studied by designing a blade with new airfoils and comparing it with a reference geometry. Beside the same annual energy production, the new blade has less wetted area and reduced root flap bending moment in idling case.

In order to validate the results however, wind tunnel tests for the new airfoils are necessary.

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