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Development of Thick Airfoils for Wind Turbines

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One important element in the aerodynamic design of wind turbines is the use of specially tailored airfoils to increase the ratio of energy capture and reduce the cost of energy. This work is focused on the design of thick airfoils for wind turbines by using numerical optimization. A hybrid scheme is proposed in which genetic and gradient-based algorithms are combined together to improve the accuracy and the reliability of the design. First, the requirements and the constraints for this class of airfoils are described; then, the hybrid approach is presented. The final part of this work is dedicated to illustrate a numerical example regarding the design of a new thick airfoil. The results are discussed and compared to existing airfoils.

Nomenclature

c	=	airfoil chord, m
C_d	=	airfoil drag coefficient
$C_{d\,\mathrm{min}}$	=	minimum airfoil drag coefficient
C_f	=	skin friction coefficient
C_l	=	airfoil lift coefficient
$C_{l\,\mathrm{max}}$	=	maximum airfoil lift coefficient
$C_{l\alpha}$	=	slope of the lift curve, deg^{-1}
$C_{\mathrm{mc}/4}$	=	airfoil moment coefficient referred to the quarter of chord
F	=	objective function
k	=	weighting parameter
L/D	=	aerodynamic efficiency
r	=	local radius, m
W	=	sectional moment of resistance
α	=	angle of attack, deg

Introduction

THE design of airfoils specifically suited for wind turbine blade applications is important in the continuing development of wind turbines. Because of the intrinsic requirements in terms of design point, off-design capabilities, and structural properties, new airfoils dedicated to wind turbine applications have been developed [1–4]. However, most of these airfoils were designed for the outer part of the blade where the aerodynamic requirements have a higher priority compared to the structural ones.

Nowadays, the design of geometries with relatively large trailing-edge thicknesses (blunt trailing edge or flat-back airfoils) have become popular in order to improve the airfoil's lift performance. From a numerical point of view, this class of geometries is challenging, due to their intrinsic characteristics and the lack of experimental data to validate the numerical predictions. Also, the fact that aerodynamic performance should be conjugated together with structural properties makes the problem even more attractive from the design point of view.

In the last decades, multidisciplinary design optimization became a more and more attractive and effective approach instead of the traditional methodologies during the design process. This is due to the rapid increase in computational resources normally available but also to the fact that the algorithms are more efficient and robust, giving the opportunity to the designers to include several disciplines in their procedures.

In the next section, the requirements for this class of airfoils are presented; then, the used approach is explained. Finally, the design of the new airfoil is described, and the results are discussed.

Airfoils for the Inner Part of the Blade

Airfoil characteristics include both aerodynamic and structural requirements. For the inner part of the blade, the structural requirements have a higher priority than for the sections in the outer part of the blade. To guarantee the needed structural strength and stiffness, the airfoils at the root have large values of moment of resistance; this means large values of thickness and sectional area. In this perspective, flat-back airfoils are helpful to improve the structural properties.

From the aerodynamic point of view, the most important parameter for the tip region is the aerodynamic efficiency, L/D. To obtain good turbine performance, the aerodynamic efficiency should be as high as possible, but at the same time, other considerations should be taken into account.

For the inner part of the blades, the lift coefficient C_l itself is very important as well as the stall behavior. This is because, in normal operating conditions, the local angle of attack can be quite high. Good values of $C_{l\,\mathrm{max}}$ and good stall characteristics can help to keep high aerodynamic performance and prevent structural problems for the blade.

Another consideration is related to the presence of gusts. The local angle of attack can rapidly change, and so there should be a "safety" margin between the design angle of attack and the stall angle in order to avoid that the airfoil works in stall or across the stall region, which can lead to fatigue problems.

Also, wind turbines should be efficient in dirty conditions as well; this means that the sections need to be insensitive to roughness.

For the outer part of the blade, the connection between the aerodynamic performance and the structural response of the blade (i.e., blade torsion) is a crucial element during the design; for the inner part, this connection should be still taken into account, even if with a lower priority. A complete discussion about the requirements for wind turbine airfoils can be found in [5] by the present author.

Design Approach

Hoerner [6,7] and van Dam et al. [8] proposed a way to generate thick airfoils with blunt trailing edges (by systematically cutting part of the trailing-edge region according to Hoerner or by smoothly increasing the thickness at the rear part of the airfoil according to van Dam et al.). However, in general, both procedures cannot be used as a design procedure in the sense that the characteristics of the final airfoil cannot be fully controlled, and these characteristics are really dependent on those of the initial geometry. As mentioned, for this class of airfoils, the structural characteristics play an important role

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for their real usage, and so a cut-and-dry approach can lead to suboptimal solutions.

In the present work, a numerical-optimization-based approach has been used in order to have an efficient design method able to deal with the multiple requirements coming from different disciplines.

Optimization Scheme

Nowadays, several algorithms are available for optimization, belonging to different categories depending on the mathematical formulation. Usually, evolutionary algorithms are less sensitive to local minima, but they are time consuming, and constraints have to be included as a penalty term to the objective function. On the other hand, gradient-based algorithms (GBAs) can lack in global optimality but allow multiple constraints and are more robust, especially for problems in which a large number of constraints are prescribed. In this research, a hybrid scheme has been implemented in which genetic algorithms (GAs) and GBAs are combined together to improve the accuracy and the reliability of the design.

GAs are used at the beginning of the design process in order to explore a large domain with fewer problems regarding local optima. The optimal solution found by the GA is then used as initial configuration for the GBA that aims to reach a more accurate optimal solution in a smaller design space. Despite the fact that a single design procedure can be implemented in which automatically the result of a GA is further improved by a GBA, the two algorithms are kept independent from each other. Separate runs are necessary to complete a single design. The reason of this choice is that a GBA can be sensitive to the initial geometry, and a suboptimal solution from a GA could lead to a better final solution. One of the goals of the present work is also to investigate what is the best combination of GAs and GBAs in order to have the best final solution but also to reduce the computational time.

The GBA implemented in this work is the sequential quadratic programming method [9], with the gradients approximated by finite differences.

Regarding the GA, the algorithm developed in [10] has been preferred. Several evolutionary mechanisms are included and here briefly summarized. The complete description of the algorithm and the parameters can be found in [10].

Selection

The tournament selection scheme is used. In practice, random pairs are selected from the population, and the most fit of each pair is allowed to mate. Each pair of mates creates a number of offspring that have some mix of the two parents' chromosomes according the method of crossover. The process continues until a new generation of n individuals is created.

Crossover

Uniform crossover is chosen in which each bit has a probability for a crossover with the second parent, and so it is possible to obtain every combination of the two parents.

Mutation

To prevent the solution from local optima, a new individual point in the solution space is created by altering one of the bits of an individual. In the present research, both jump mutations and creep mutations are used. In a jump mutation, one or more children's chromosomes have a probability to be subjected to a mutation not depending on either parent. In particular, a child's parameter is randomly selected, and then its value is changed by a random amount chosen within a prescribed range. In a creep mutation, one or more children's parameters have a probability to be incremented up or down from the relative parent value.

Elitism

To guarantee convergence, the chromosome set of the best parent is reproduced in the succeeding generation.

MicroGA

One of the unique characteristics of used GA is the so-called "microGA"; it is a method to improve the performance of the GA used in this work and derived by the studies presented in [11] to explore the use of small population sizes in genetics. Small populations can lead to too a rapid convergence, and so the regeneration of random population members helps to ensure diversity during the search process and avoid local minima.

For the implementation of the constraints in a GA, a zero value is assigned to the objective function in case at least one constraint is violated.

Geometry Parameterization

Several descriptions have been developed to describe parameterize the geometry of an airfoil [12]. Here, a composite cubic Bezier parameterization is used, based on the development done by the present author [13]. The design variables of this parameterization are the coordinates of the control points (see Fig. 1). With reference to Fig. 1, the airfoil is divided in four parts (from control point 1 to 4, 4 to 7, 7 to 10, and 10 to 13); each part is described by a separate cubic Bezier curve, plus special conditions assigned to the control points 4, 7, and 10, in order to guarantee the continuity of the shape and its derivatives. The advantage of this choice is the possibility to conjugate the properties of Bezier functions in terms of the regularity of the curve and ease of usage, with a piecewise structure that also allows local modifications.

Objective Function Definition and Evaluation

Aerodynamic efficiency has been used as an aerodynamic performance parameter to be improved, together with the sectional moment of resistance W for the structural part of the problem. These two requirements conflict with each other; in fact, the aerodynamic efficiency pushes the design to thin geometries, whereas the structural requirements would prefer thick shapes. The two objectives are combined together in the form of a weighted linear combination [see Eq. (1)]; this means that the final shape is also function of the relative importance of the aerodynamics compared to the structures. A nondimensional parameter k is used to define the relative importance of the two contributions to the global objective function. To create a family of new airfoils and to investigate the effect due to the value of k, the optimization process has been repeated several times by changing the value of the parameter k:

$$F = k(L/D) + (1 - k)W \tag{1}$$

where k is a weighting parameter varying between 0 and 1. For values close to 1, the aerodynamic efficiency is predominant; for values close to 0, instead, the structural requirements are predominant.

The sectional moment of inertia is related to the moment of inertia I and the distance from the outside of the object concerned to its major axis e [see Eq. (2)]:

$$W = I/e \tag{2}$$

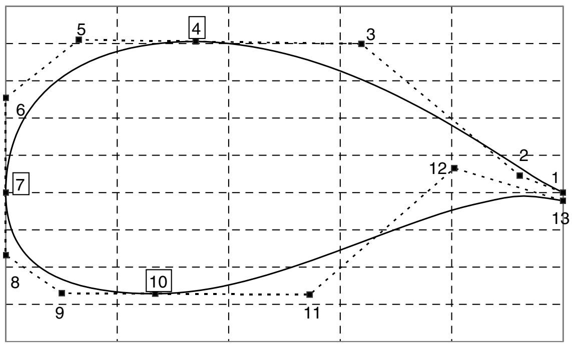

Fig. 1 Sketch of the parameterization.

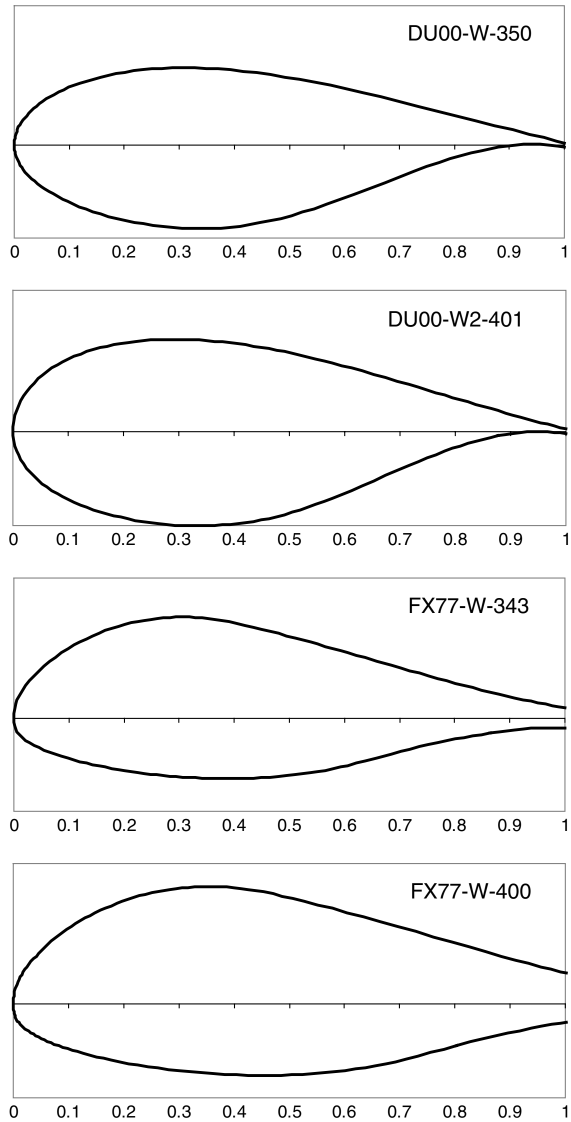

Fig. 2 Airfoils selected for the validation.

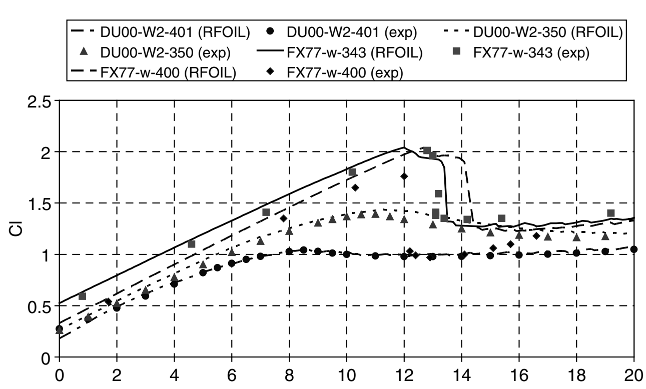

Fig. 3 Validation for thick airfoils: lift curve. Reynolds number: 3.0×10^6. Experimental data from [4,16].

In this work, the internal layout (i.e., the presence and shape of the spar) is not considered but only the external skin modeled as thin skin (or shell). W depends only on the airfoil's geometry, but an aerodynamic solver has been necessary to evaluate the aerodynamic efficiency (and some aerodynamic constraints; see the next section for details).

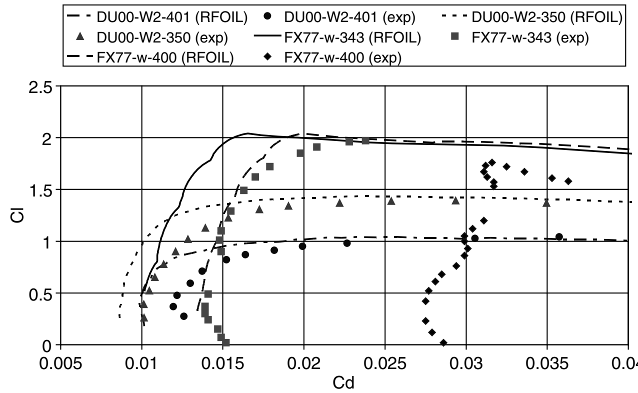

Fig. 4 Validation for thick airfoils: polar curve. Reynolds number: 3.0×10^6. Experimental data from [4,16].

To do this, the RFOIL [14] code has been used. RFOIL is a modified version of XFOIL [15], in which a more accurate modeling for the stall region has been implemented, together with the capability to predict the effect of rotation on the airfoil characteristics. During the design, the rotational effects are not part of the problem; nevertheless, RFOIL is used instead of XFOIL because of its higher accuracy at the stall. In the last section, in which the results are discussed, some considerations focused on the rotational effects are addressed.

To assess the accuracy of RFOIL for this particular class of geometries, DU00-W2-350, DU-00-W2-401, FX77-W-343 [16], and FX77-W-400 (Fig. 2) airfoils have been used as references to validate the numerical predictions. The Delft University (DU) airfoils have been tested at Delft University; the FX airfoils instead at Stuttgart University. All the tests have been performed at a Reynolds number of 3.0×10^6, except for the FX77-W-400 airfoil (4.0×10^6).

For the DU airfoils, the agreement in terms of lift performance is very good (Figs. 3 and 4); in terms of drag, an underestimation of around 13% has been found, which is in line with the results of previous validations done on thinner geometries. Looking at the FX airfoils, the lift curve is quite well described, at least for the general shape of the curve. For the FX77-W-400, there is an overestimation of the maximum lift coefficient and consequently of the angle of stall, but the abrupt shape of the stall is anyway captured. In terms of drag, the underestimation is higher, especially for the 40% airfoil. The reason of that can be related to the lack of accuracy in the presence of large trailing-edge thicknesses.

Design of New Thick Airfoils

Definition of the Requirements and Constraints

The design of new airfoil for the inner part of the blade is presented in this section. The goal of the optimization process is to maximize the aerodynamic efficiency and the moment of resistance at the same time. As final result, a family of airfoils should be expected, with the relative thickness increasing depending on the structural needs.

The Reynolds number during the design is 3.0×10^6 (intended to be representative of a MegaWatt class wind turbine), and the design angle of attack is 6 deg. The design is performed by imposing the transition at 1% of the chord on the suction side and 10% for the pressure side. The reason of that is to obtain airfoils that exhibit a good insensitivity to the roughness by driving the design process to geometries without a large extent of laminar flow. In fact, performing the optimization in free transition could lead to better aerodynamic performance in terms of efficiency at the design point but with a high probability of stronger losses in case of rough conditions and sensitivity to the angle of attack.

From geometrical point of view, a minimum airfoil thickness of 35% of the chord and a minimum thickness at the trailing edge of 1% of the chord have been prescribed. The constraint related to the trailing-edge thickness has been assigned to take into account manufacturing requirements; an upper bound for this variable is not prescribed, in order to be able to explore flat-back solutions.

In addition to these geometrical constraints, several aerodynamic constraints have been defined. As discussed in Sec. II, the effect of aerodynamic performance on structural deformations should be taken into account; in particular, the torsion of the blade has a strong impact on the selection of the materials and costs. Also, considering that several airfoils are installed on the same blade, the aerodynamic properties of the single airfoils should not differ too much between each other (see [5]). For these reasons, a maximum value for the moment coefficient $C_{\mathrm{mc}/4}$ equal to -0.15 has been assigned at the design condition (angle of attack of 6 deg).

Special attention should be paid to the stall performance of these airfoils, due to the fact that the sections at the root of the blade work at a high angle of attack. The stall condition and the airfoil's separation point movement must be part of the core requirements. In fact, good $C_{l\,\max}$ values should be achievable, in conjunction with soft stall and poststall characteristics. Also, a margin between the design condition and the stall condition should be kept to take into account the angle-of-attack change due to gusts. In [5], an explicit constraint on the position of the separation point was used; in this research, however, a different approach has been preferred.

A drop in C_l between 15 and 16 deg smaller than 0.3 has been implemented as constraint. The threshold value has been selected after comparison of the experimental data from [17] for four-, five-, and six-digit National Advisory Committee for Aeronautics (NACA) airfoils. Despite the fact that these airfoils were not designed for wind turbines, some of them are used in reality. In this context, they are anyway a good guideline to define "abrupt" stall (i.e., NACA five-digit airfoils).

Design Variables

Fifteen design variables have been actively used in this case, corresponding to (see Fig. 1) control points 2, 3, 5, 9, 11, and 12 in both directions and control points 1, 6, 8 only in the vertical direction. Control point 7 is fixed, whereas control points 4 and 10 are adjusted automatically by the algorithm to ensure the smoothness of the shape.

It should be noticed that keeping free the control point 1, it allows the optimization scheme to search also in the space of blunt trailing-edge airfoils. One of the drawbacks of the solution proposed by Hoerner [7] to generate thick airfoils is the fact that the chord is not anymore horizontal, affecting the real angle of attack. To avoid this problem, the control point 13 is mirrored according to the value of the control point 1.

In Table 1, the values for upper and lower bounds are listed. According to these values, airfoils with thicknesses varying from 10 up to 50% of the chord can be explored. The trailing-edge thickness can increase to up to 20% of the chord.

Preliminary Tests

Preliminary investigations have been performed separately on GAs and GBAs. In this paragraph, some of the results found in these tests are illustrated. A simplified version of the optimization problem presented in the previous section has been used; the objective function is just the aerodynamic efficiency at an angle of attack of 6 deg. It should be also underlined that looking only at one parameter is not enough to decide about the quality of an airfoil because many characteristics, often conflicting with each other, should be evaluated. Usually a good airfoil is a combination of several characteristics. However, in this context, the interest is focused on the response of the algorithms more than the real airfoil design problem. All the tests have been performed on a machine with Centrino-Duo processor (CPU at 2 Ghz).

Genetic Algorithm

As mentioned, the GA used has the special microGA scheme. The tests have been focused on evaluating the effects of such scheme with respect to the traditional scheme; also, the influence of the population size, number of generations, and children per pair have been considered. Population sizes of 5 and 10 individuals have been used, evolving up to 400 generations with and without the microGA scheme. With microGA, only one child is allowed per pair; instead, without it, one and two children are allowed.

Finally, both a complete set of constraints and a reduced one have been used; in particular, the constraints about the stall have been deactivated. The idea was to use a subset of constraints in the GA to reduce the computational time, whereas in the GBA, the refinement is always performed with the full set of requirements. In principle, this could save some time and force the GBA to change the solution (avoiding local optima) to satisfy the whole set of conditions. Table 2 summarizes some of the results of these tests performed on the reduced set of constraints.

With reference to the table, the solutions for configurations B, C, and E are the most promising; however, the airfoils generated for B and E did not show a completely regular shape on the suction side, leading to a very sharp stall. Also, they are the most expensive in terms of computational costs. From the design process, however, this result can be avoided only by adding extra constraints on the stall, thus using the complete set of constraints. With the complete set, the average computational time is increased because the simulations take longer, and the difference in results is reduced, due to the effect of the extra constraint. However, the trend does not change, and the configuration C is still the best (Table 3). It should be stressed that the fact that the stall is not assigned explicitly does not mean that the stall is sharp.

According to the tables, very small populations with one child per pair produce better values. Figure 5 illustrates the evolution of the configurations in case of an incomplete set of constraints.

Table 1 Bounds for the design variables

Design variable number	Control point[1][a]	Lower bound	Upper bound
1	2h	0.7	0.8
2	3h	0.4	0.5
3	5h	0.09	0.15
4	9h	0.09	0.15
5	11h	0.4	0.5
6	12h	0.7	0.8
7	1v	0	0.1
8	2v	0.03	0.2
9	3v	0.08	0.25
10	5v	0.08	0.25
11	6v	0.03	0.1
12	8v	−0.1	−0.02
13	9v	−0.25	−0.02
14	11v	−0.25	0.04
15	12v	−0.1	0.09

[a]"h" denotes the horizontal direction, "v" the vertical direction.

Table 2 Summary of results for preliminary tests on the GA (not complete set of constraints)

Design variable number	MicroGA	Population	Children	Time, min	L/D
A	yes	5	1	25	55.48
B	yes	10	1	130	68
C	no	5	1	43	62.1
D	no	5	2	30	52.4
E	no	10	1	150	60

Table 3 Summary of results for preliminary tests on the GA (complete set of constraints)

Design variable number	MicroGA	Population	Children	Time, min	L/D
A	yes	5	1	110	55.7
B	yes	10	1	130	55.7
C	no	5	1	170	56

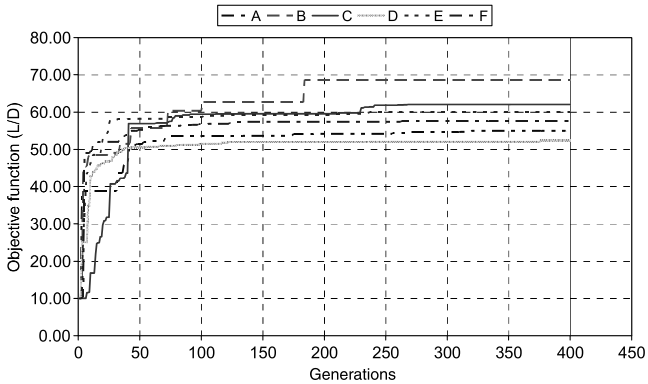

Fig. 5 Best individual evolution.

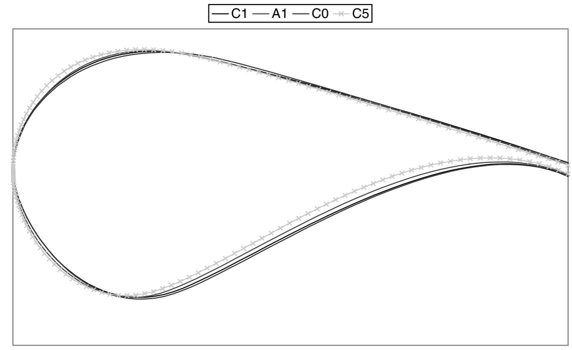

Fig. 6 Comparison between the airfoil geometries.

Gradient-Based Algorithm

The aim of the tests performed on the GBA was to assess the sensitivity of the algorithm to the initial solution and the sensitivity to local optima. Also, in order to have confidence in the hybrid optimization scheme, it was important to understand the response of the GBA depending on the GA individual used as baseline.

The configuration C has been used as reference, and several optimizations with the GBA have been performed by changing the generation in which to consider ending the GA process. The best individuals from the generations 4, 25, 50, 100, 200, and 400 have been used; the results are shown in Table 4.

In Fig. 6, Comparing the "C" solutions, it can be observed that the GBA is able to improve more when the starting point is at the beginning of the GA optimization; this is mostly due to the fact that the GBA has more freedom with respect to the local optima found with the GA. For C3, C4, and C5, the GBA is not able to move from the initial solution. Looking at the time, this increases according to the generation of the initial solution, and so the GBA needs more time to find an improving path. According to these results, it is convenient to run the GBA after few iterations of the GA in order to reduce the computational time and obtain an optimal result. In the table, a solution obtained with the microGA scheme has also been used to perform the GBA, obtaining a very good solution. The indication coming from these analyses is that the best hybrid combinations are the ones corresponding to the fewest full GA generations or full microGA optimizations before starting the GBA. In both cases, the computational time can be significantly reduced.

Table 4 Summary of results for preliminary tests on the GBA

Design variable number	GA generation	L/D			T, s
		GA	GBA	Δ, %	
A1	400	55.48	60	8.15	453
C0	4	10	58	480	652
C1	25	31.7	60	89.27	767
C2	50	56.9	56.9	0	935
C3	100	59.4	59.42	0.034	125
C4	200	59.6	59.62	0.034	128
C5	400	62	62.05	0.081	121

Table 5 Settings used for genetic algorithms

Feature	Setting
Selection	Tournament
Crossover	Uniform
Mutation	Jump and creep
Elitism	Active
MicroGA	Active
No. of parents	2
Population size	5
Generations	200

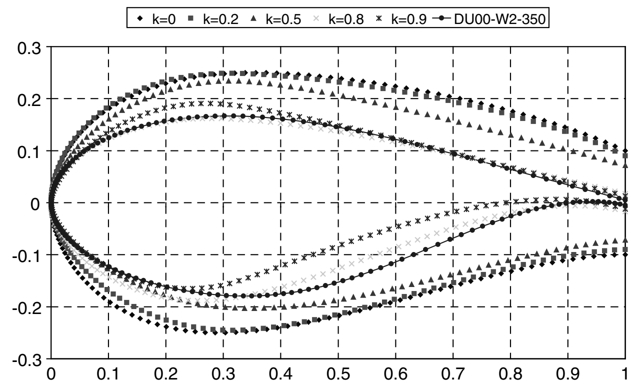

Fig. 7 New geometries for different values of the weighting factor.

Design of Thick Airfoils

In the present work, five individual populations have been used, evolving for 200 generations. A summary of the used GA features can be found in Table 5.

A family of new thick airfoils has been obtained by changing the relative importance of the aerodynamic requirements with respect to the structural requirements. The thickness varies between 50% of the chord for the geometries in which the structural requirements were predominant (values of the k parameter close to 0) to 35% of the chord for the configurations in which the aerodynamic efficiency was predominant (values of the k parameter close to 1). All the geometries exhibited blunt trailing edges, with larger values for the thicker airfoils. These first indications are consistent with the expectations because maximizing the moment of resistance means increasing the internal volume and vice versa for the aerodynamic efficiency. Figure 7 shows some of the developed geometries; Figs. 8–12 illustrate their aerodynamic characteristics.

Lift Performance

In Figs. 8 and 9, also the lift characteristics of the DU00-W2-350 airfoil are illustrated, in free and fixed transition. Compared to this geometry, the new airfoils for $k = 0.8$ and $k = 0.9$ exhibit a higher value of $C_{l\,\max}$ and, in general, better lift performance, with a large extension of the linear part of the lift curve. This is positive to reduce fatigue problems due to gusts. In particular, the geometry for $k = 0.8$ has also good stall characteristics with a value of $C_{\mathrm{mc}/4}$ close to the one of the reference geometry. The airfoils have been compared also in fixed transition; in this case, the performances of the new airfoils are evidently better than the reference geometry. The strange behavior of the DU00-W2-350 airfoil should be noticed, found in [18] during wind-tunnel tests.

In the same figures, also the airfoils for low values of the k parameter are illustrated, in which the structural requirements are predominant. These airfoils are characterized by a large trailing-edge thickness; as consequence of the validation performed, RFOIL underpredicts the C_d for large trailing-edge thicknesses, and

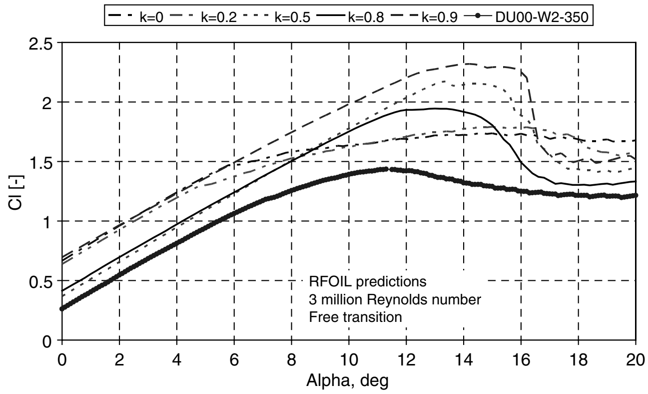

Fig. 8 Lift curve for the new airfoils compared to the DU00-W2-350 airfoil.

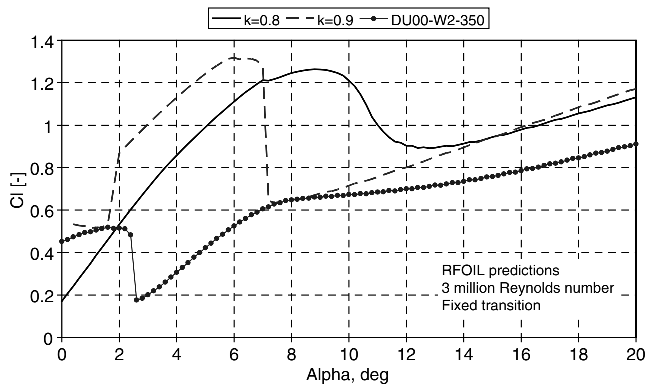

Fig. 9 Lift curve for the new airfoils compared to the DU00-W2-350 airfoil.

higher-order computational fluid dynamics tools could be better suited for such a problem. However, for these geometries, the aerodynamic performance is not important in itself because they mostly maximize the moment of resistance.

Aerodynamic Efficiency Performance

Figures 10 and 11 illustrate the aerodynamic efficiency of the new geometries compared to the reference airfoils. The individuals optimized for efficiency ($k = 0.8$, $k = 0.9$) have better performance than the DU00-W2-350 in design and off-design conditions (in particular, $k = 0.9$ has a higher efficiency over the entire range of angles of attack). Especially in the fixed transition, there is a significant drop in efficiency of the reference geometry, whereas for the new airfoils, the response in more robust against roughness. The dip in the lift curve of the DU00-W2-350 in fixed transition affects also the efficiency; the new geometries have regular behavior.

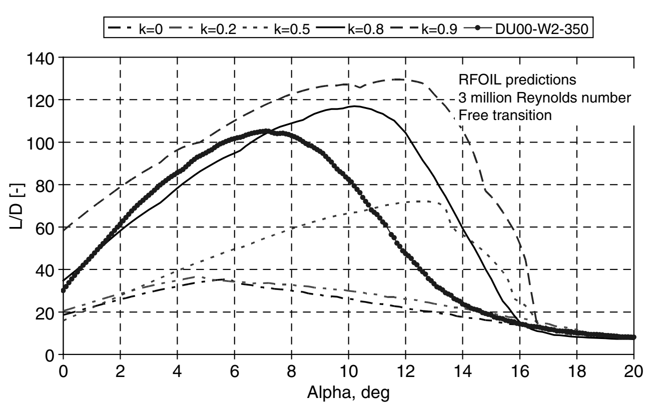

Fig. 10 Efficiency curve for the new airfoils compared to the DU00-W2-350 airfoil.

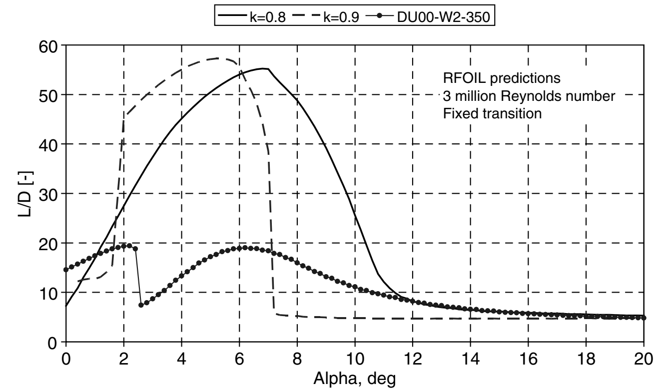

Fig. 11 Efficiency curve for the new airfoils compared to the DU00-W2-350 airfoil.

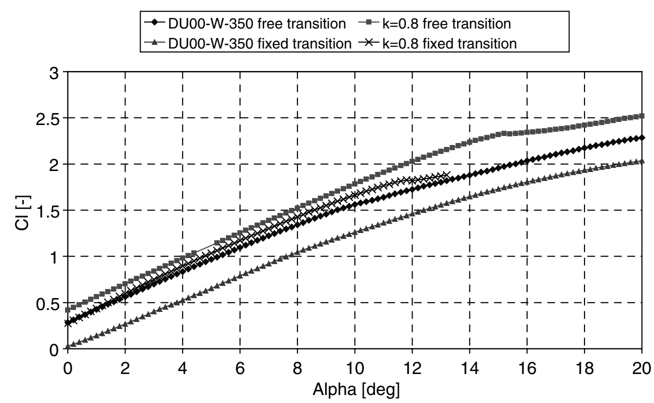

Fig. 12 Lift curve in presence of rotational effects. Reynolds number $= 3 \times 10^6$, free transition, $c/r = 0.248$.

Rotational Effects

During the design, the rotational effects have not been taken into account, but at the root, these effects cannot be neglected. Figure 12 shows the comparison between the lift curves in the presence of rotational effects. These effects have been included in RFOIL [19]. According to this formulation, the main parameter controlling the rotational effects is the ratio between the local chord and local radius; a value of 0.248 for c/r has been assigned. Both in free and in fixed transitions, the new airfoil has a better performance than the reference geometry. This is also due to the higher lift performance of the new airfoil.

Optimization Scheme

In terms of optimization process, the combination of the GA and the GBA in a hybrid scheme produced good results, improving the reliability of the design and contributing to save computational time. In fact, in almost all the cases analyzed, the usage of the GBA after the GA made it possible to achieve a better final solution. For some configurations, however, the GBA was not able to change the solution coming from the GA, meaning that probably the interaction between the two algorithms can still be improved.

Conclusions

A hybrid optimization scheme making use of genetic algorithms (GAs) and gradient-based algorithms (GBAs) has been developed and applied to design a new family of airfoils dedicated to the root region of the wind turbine blade. Both aerodynamic and structural requirements have been included in the optimization process, and specific constraints have been implemented to control the stall behavior.

According to the numerical predictions, the results are promising, showing that the new airfoils have feasible shapes, consistent with the assigned requirements and with good performance. Despite these good results, however, wind-tunnel tests are mandatory to validate the numerical predictions, especially at the stall, in which the numerical accuracy can be lower.

For this class of airfoils, the rotational effects play an important role; in the next development, they will be included in the design process.

Regarding the hybrid approach, the results showed that the combination of genetic and GBAs can be beneficial to improve the accuracy and robustness of the design and to reduce the computational time. However, improvements in the implementation of the constraints in GAs and, in general, a better communication between the two algorithms can lead to higher quality results.

References

[1] Tangler, J. L., and Somers, D. M., "NREL Airfoil Families for HAWT's," *Proceedings WINDPOWER'95*, AWEA, Washington, D.C., 1995, pp. 117–123.

[2] Björk, A., "Coordinates and Calculations for the FFA-W1-xxx, FFA-W2-xxx and FFA-W3-.xxx Series of Airfoils for Horizontal Axis Wind Turbines," Aeronautical Research Institute of Sweden, Rept. FFA-TN-1990-15, Stockholm, Sweden, 1990.

[3] Fuglsang, P., and Bak, C., "Design and Verification of the New Risø-A1 Airfoil Family for Wind Turbines," AIAA Paper 2001-0028, 2001.

[4] Timmer, W. A., and van Rooij, R. P. J. O. M., "Summary of the Delft University Wind Turbine Dedicated Airfoils," AIAA Paper 2003-0352, 2002.

[5] Grasso, F., "Usage of Numerical Optimization in Wind Turbine Airfoil Design," *Journal of Aircraft*, Vol. 48, No. 1, 2011, pp. 248–255. doi:10.2514/1.C031089; also AIAA Paper 2010-4404, 2010.

[6] Hoerner, S. F., "Base Drag and Thick Trailing Edge," *Journal of the Aeronautical Sciences*, Vol. 17, No. 10, Oct. 1950, pp. 622–628.

[7] Hoerner, S. F., and Borst, H. V., *Fluid-Dynamic Lift*, Hoerner Fluid Dynamics, Brick Town, NJ, 1985, pp. 3.19–3.22.

[8] van Dam, C. P., Mayda, E. A., and Chao, D. D., "Computational Design and Analysis of Flatback Airfoil Wind Tunnel Experiments," Sandia National Laboratories, Rept. SAND2008-1782, Albuquerque, NM, March 2008.

[9] Schittkowski, K., "NLPQLP: A New Fortran Implementation of a Sequential Quadratic Programming Algorithm—User's Guide, Version 1.6," Dept. of Mathematics, Univ. of Bayreuth, Bayreuth, Germany, 2001.

[10] Yang, G., Reinstein, L. E., Pai, S., Xu, Z., and Carroll, D. L., "A New Genetic Algorithm Technique in Optimization of Permanent 125-I Prostate Implants," *Medical Physics*, Vol. 25, No. 12, 1998, pp. 2308–2315. doi:10.1118/1.598460

[11] Krishnakumar, K., "Micro-Genetic Algorithms for Stationary and Non-Stationary Function Optimization," *SPIE: Intelligent Control and Adaptive Systems*, Vol. 1196, Philadelphia, 1989, pp. 289–296.

[12] Samareh, J. A., "Survey of Shape Parameterization Techniques for High-Fidelity Multidisciplinary Shape Optimization," *AIAA Journal*, Vol. 39, No. 5, 2001, pp. 877–884. doi:10.2514/2.1391

[13] Grasso, F., "Multi-Objective Numerical Optimization Applied to Aircraft Design," Ph.D. Dissertation, Dipartimento Ingegneria Aerospaziale, Univ. of Naples "Federico II," Naples, Italy, Dec. 2008.

[14] van Rooij, R. P. J. O. M., "Modification of the Boundary Layer Calculation in RFOIL for Improved Airfoil Stall Prediction," Delft Univ. of Technology, Rept. IW-96087R, Delft, The Netherlands, Sept. 1996.

[15] Drela, M., *XFOIL 6.94 User Guide*, Aeronautics and Astronautics Dept., Massachusetts Inst. of Technology, Cambridge, MA, Dec. 2001.

[16] Althaus, D., *Stuttgarter Profilkatalog II: Niedriggeschwindigkeit-sprofile*, Vieweg & Sohn Braunschweig, Stuttgart, Germany, 1996 (in German).

[17] Abbott, I., and Von Doenhoff, A., *Theory of Wing Sections*, Dover, New York, 1958, pp. 309–687.

[18] van Rooij, R. P. J. O. M., and Timmer, W. A., "Rougness Sensitivity Considerations for Thick Rotor Blade Airfoils," AIAA Paper 2003-0350, 2003.

[19] Snel, H., Houwink, R., van Bussel, G. J. W., and Bruining, A., "Sectional Prediction of 3D Effects for Stalled Flow on Rotating Blades and Comparison with Measurements," *Proceedings of the European Community Wind Energy Conference*, H.S. Stephens & Associates, Felmersham, Bedford, 8–12 March 1993, pp. 395–399.

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