Genetic Algorithms in Wind Turbine Airfoil Design

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One key element in the aerodynamic design of wind turbines is the use of specially tailored airfoils to increase the ratio of energy capture to the loading and thereby to reduce cost of energy. This work is focused on the design of a wind turbine airfoil by using numerical optimization. Firstly, the optimization approach is presented; a genetic algorithm is used, coupled with RFOIL solver and a composite Bezier geometrical parameterization. A particularly sensitive point is the choice and implementation of constraints; in order to formalize in the most complete and effective way the design requirements, the effects of activating specific constraints are discussed. A numerical example regarding the design of a high efficiency airfoil for the outer part of a blade by using genetic algorithms is illustrated and the results are compared with existing wind turbine airfoils. Finally a new hybrid design strategy is illustrated and discussed, in which the genetic algorithms are used at the beginning of the design process to explore a wide domain. Then, the gradient based algorithms are used in order to improve the first stage optimum.

Nomenclature

α = angle of attack [deg]
α_{des} = design angle of attack [deg]
c = airfoil chord [m]
C_d = airfoil drag coefficient [-]
C_{dmin} = minimum airfoil drag coefficient [-]
C_f = skin friction coefficient [-]
C_l = airfoil lift coefficient [-]
$C_{l\alpha}$ = slope of the lift curve [deg^{-1}]
C_{lmax} = maximum airfoil lift coefficient [-]
$C_{mc/4}$ = airfoil moment coefficient referred to the quarter of chord [-]
F = objective function [-]
g = inequality constraints [-]
h = equality constraints [-]
H = boundary layer shape factor [-]
L/D = aerodynamic efficiency [-]
X = design variables [-]
X^L = lower bounds for the design variables [-]
X^U = upper bounds for the design variables [-]
w_i = weight i^{th} objective function
p_i = coefficient to make of the same order all the objective functions

av_{ij} = actual value of the j^th^ constrained characteristic at the i^th^ objective function evaluation
cw_j = weight of the j^th^ constraint
pc = coefficient to make of the same order the constraints and the objective functions

I. Introduction

Design of airfoils specifically suited for wind turbine blade applications is important in the continuing development of wind turbines. New airfoils families [1-4] for wind turbines are developed because of the intrinsic requirements in terms of design point, off-design capabilities and structural properties.

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, mid and tip parts where the root part is mainly determined from structural considerations. In contrast, the tip part is determined from aerodynamic considerations.

This work is focused on the design of a wind turbine dedicated airfoil for the tip region of the blade, by using numerical optimization.

II. Numerical Optimization Approach

Especially when multiple requirements, concerning different disciplines are involved in the design process, it can be convenient to use multidisciplinary design optimization (MDO) approach. In the most general sense, numerical optimization [5, 6] 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:

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

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

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

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 and equation 4 defines the region of search for the minimum. The bounds defined for each degree of freedom by equation 4 are referred to side constraints.

A. Geometry Description

One of the most important ingredients in numerical optimization is the choice of design variables and the parameterization of our system in using these variables. In order to reduce the number of necessary parameters to take into account to describe the airfoil's shape, but without loss of information about the geometrical characteristics of the airfoil, several mathematical formulations were proposed in literature [7]. In the present work, a composite third order Bezier is used. Basically, the airfoil is divided in four parts and for each part, a third order Bezier curve is used to describe the geometry. The advantage of this choice is the possibility to conjugate the properties of Bezier functions in terms of regularity of the curve and easy usage, with a piecewise structure that allows also local modifications to the geometry. The complete description can be found in [8, 9] and an example is reported in Fig.1.

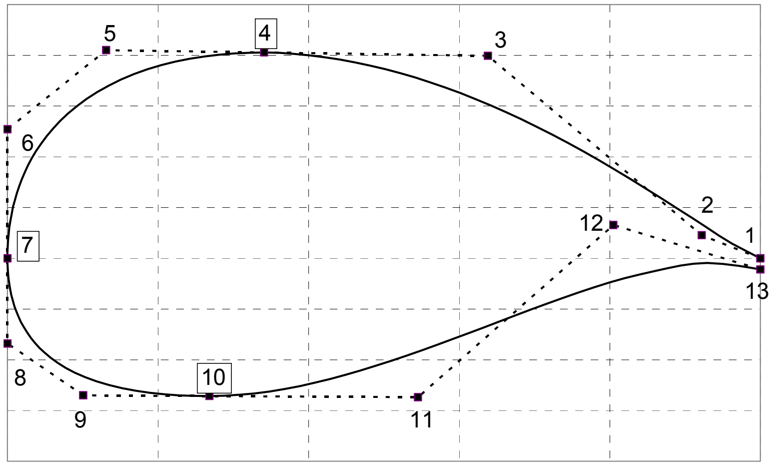

Figure 1: Geometry parameterization example.

B. Optimization Algorithm

The choice of optimization algorithm is very important because the final results are usually dependent on the specific algorithm in terms of accuracy and local minima sensitivity. In this work, Genetic Algorithm (GA) developed by Caroll [10, 11] is used for the optimization process. The main reason of this choice is the capability of GA to explore wide, non-linear and discontinuous domains and be less sensitive to the initial configuration, especially when compared to gradient-based algorithms (GBA). In addition to this, GBA are more accurate, but also more sensitive to local optima for complex domains. Due to the multidisciplinary context, GA were preferred at this stage, even if with less accuracy than GBA. In the implemented GA, several evolutionary mechanisms are included and here, briefly summarized.

1. Selection

Tournament Selection scheme is used: random pairs are selected from the population and the most fit of each pair is allowed to mate. Each pair of mates create 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.

2. Crossover

In this work uniform crossover is chosen where each bit has a probability for a crossover with the second parent, so it's possible to obtain every combination of the two parents.

3. Mutation

In order 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 mutation and creep mutation are used. In jump mutation one or more child'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 creep mutation one or more child's parameters have a probability to be incremented up or down from the relative parent value.

4. Elitism

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

5. MicroGA

The MicroGA is a method to improve the performance of genetic algorithms used in this work and derived by the studies of Goldberg and Krishnakumar [12] to explore the use of small population sizes in genetic. Small populations can lead to too rapid convergence, so the re-generation of random population members helps to ensure diversity during the search process and so to avoid local minima.

C. Objective Function Evaluation

Since the optimization process requires many evaluations of the objective function and the constraints before an optimum design is obtained, the computational costs cannot be neglected, as well as the accuracy of the results.

RFOIL [13] is a modified version of XFOIL [14] 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. The following figures illustrate a comparison with experimental data [15] for the NACA-$63_3$418 airfoil. The Reynolds number is 6 million and the transition is free.

It should be noted that the RFOIL prediction for the stall region is well described and very close to the experimental data; in XFOIL results, only the deviation from the linear zone is described but not the stall. For the drag curve, XFOIL and RFOIL are very close to each other for small values of C_l, but for high C_l, XFOIL is under predicting. In ref [13], an additional drag of 10% is suggested to correct the RFOIL data; by adding this factor, a very good agreement is found also for the drag coefficient. In order to have more realistic predictions, this 10% drag penalty is added during the optimization process and for all the numerical analyses.

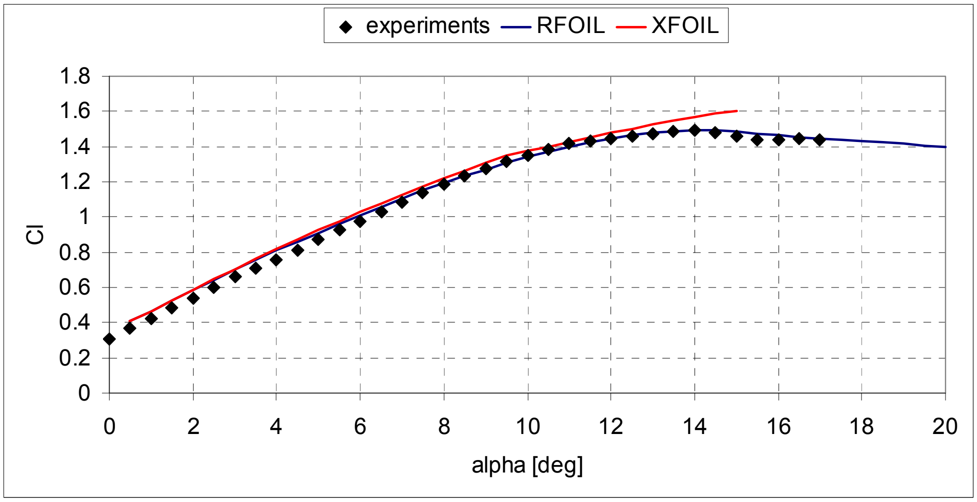

Figure 2: Lift curve for the NACA-$63_3$418 airfoil; comparison between XFOIL and RFOIL with experiments [15]. Reynolds number 6 million, free transition.

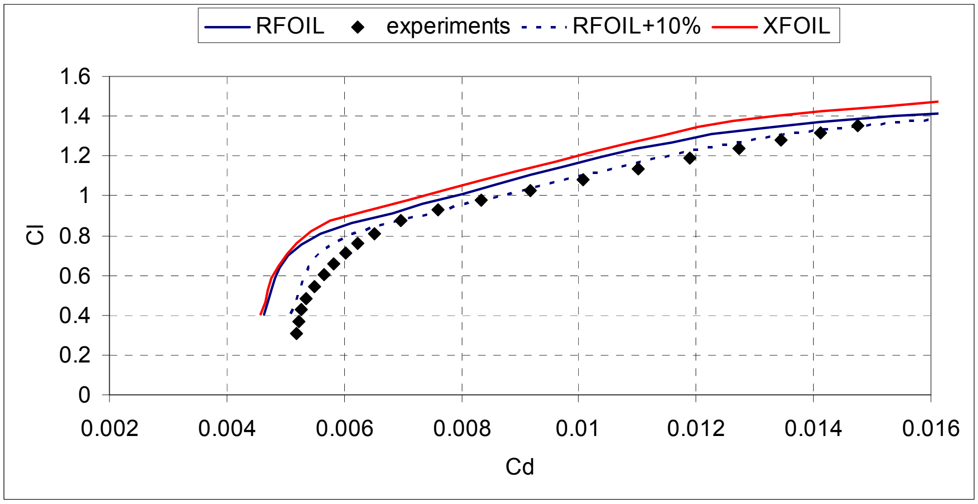

Figure 3: Drag curve for the NACA-$63_3$418 airfoil; comparison between XFOIL and RFOIL with experiments [15]. Reynolds number 6 million, free transition.

D. Constraints

Two different methods to handle constraints have been investigated in the present work.

In the first method, a fixed penalty value is assigned to the objective function if at the least one of the constraints is not respected.

In the second method, for each violated constraint, the penalty value assigned to the objective function is proportional to the difference between the actual value for the specific characteristic and the corresponding constraint. In particular, the objective function has the following expression:

$$\sum_{i=1}^{nobj}\{F_i * w_i * p_i + \sum_{j=1}^{nc}[(av_{ij} - c_j)/|c_j| * cw_j] * pc\} \qquad (5)$$

III. Design of tip region airfoil

The design of a new airfoil for the tip region of the blade is presented in this section. The airfoil is designed to maximize the aerodynamic efficiency at 6 degrees of angle of attack, a Reynolds number of 6 million, a Mach number of 0.2.

Eight degrees of freedom are actively used, which correspond to the ordinates of the control points 2, 3, 5, 6, 8, 9, 11, 12 (see Fig. 1). The control points 4 and 10 are automatically controlled by the algorithm in order to ensure smoothness properties between different Bezier curves.

A. Geometrical Constraints

Usually, for Mega-Watt class wind turbines, the thickness at the tip is between 15% and 18% of the chord; here, a minimum value of 18% is prescribed.

A minimum trailing edge thickness of 0.25% of the chord is required to ensure airfoil's feasibility from manufacturing point of view.

B. Aerodynamic Constraints

In [9], in order to limit the blade torsion, a minimum value for $C_{mc/4}$ of -0.08 is prescribed. This value comes from a comparative analysis on experimental data [3,15] for existing airfoils realistically usable for this class of turbines. To avoid possibility of abrupt stall and converge to a solution in which a Stratford style recompression is not present (it can lead to a not gradual evolution in transition location), the design is performed by fixing transition at 0.02c on the suction side and 0.1c on the pressure side.

Two different aerodynamic constraints are imposed to control the airfoil behaviour at the stall. To control the stall angle, the separation point is imposed to be beyond the 80% of the chord at $\alpha=\alpha_{des}+\Delta\alpha$ where $\Delta\alpha$ can be chosen by the user. This also guarantees robustness in airfoil performance in case of gust.

To control the kind of stall, the absolute value of the slope beyond the stall angle is imposed to be less than a chosen value.

C. Results

Fig. 4 illustrates the evolution of the aerodynamic efficiency with the number of generations. The steps of the curve are typical of genetic algorithms.

In Fig. 5, the geometries of the best elements at the 30th, 60th and 100th generations are compared with the airfoils of the first generation and in Fig. 6, their efficiency curves are compared with the efficiency curve of the NACA-$63_3$418.

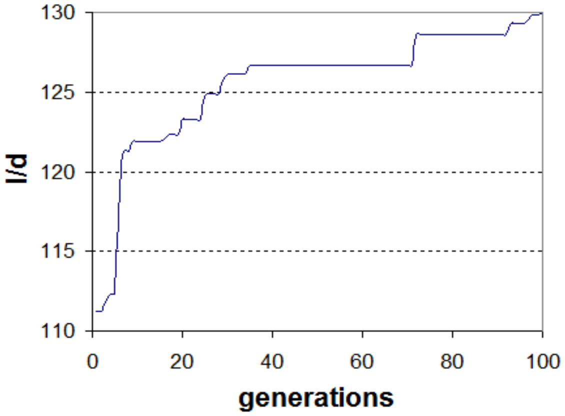

Figure 4: Evolution of the objective function (l/d) with the number of generations.

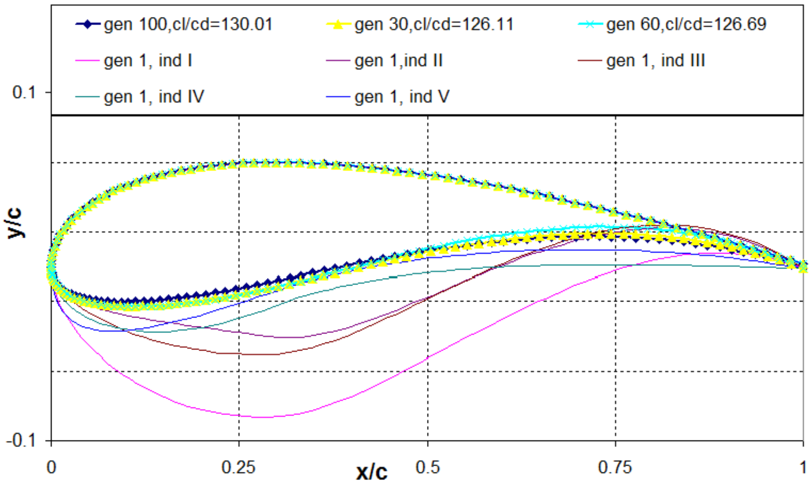

Figure 5: Best element at the 30th, 60th and 100th generations compared with the airfoils of the first generation.

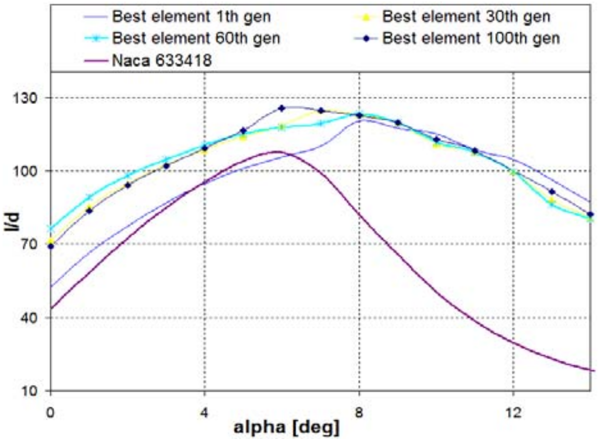

Figure 6: Efficiency curves of the best elements at the 30th, 60th and 100th generations compared with NACA-$63_3$418 airfoil.

Figures 4, 5 and 6 refer to an example without any constraints. The effect of imposing constraints has been investigated and it can be noticed in Fig 7, where an optimized airfoil obtained with and without constraint on the moment coefficient (C_m) is illustrated. In order to improve the aerodynamic efficiency, the airfoil should be cambered, but at the same time, the moment coefficient is increasing and consequently, the torsion of the blade is also increased. The result is consistent with the expectations since without constraint, the geometry can be much more cambered and the efficiency is also higher (l/d=184 without constraint, l/d=162.7 with constraint).

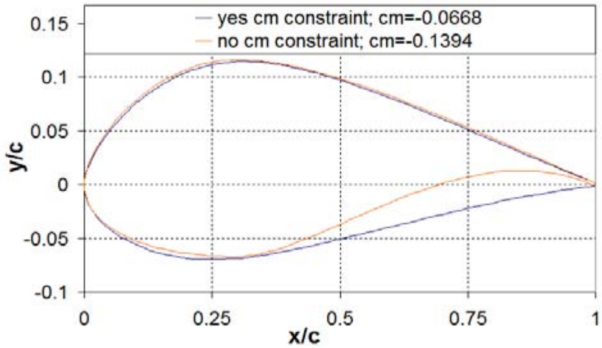

Figure 7: Comparison between an optimized airfoil with and without Cm constraint.

As mentioned in the previous section, two different methods to handle constraints have been implemented and a comparison between the results obtained in the two cases is shown in Fig 8.

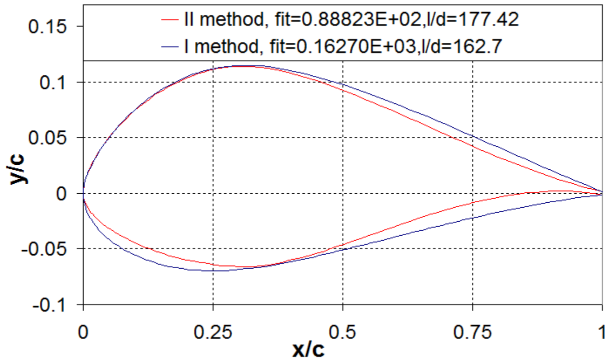

Figure 8: Comparison between optimized airfoils obtained with two different methods to handle constraints.

By using the second method, a penalty value that is proportional to the violation of the constraints, is assigned to the objective function. This method gives an higher efficiency, but it needs more evaluations of the objective function that means higher computational costs; for this reason, the first method, in which a fixed penalty is assigned, was used in the rest of the work.

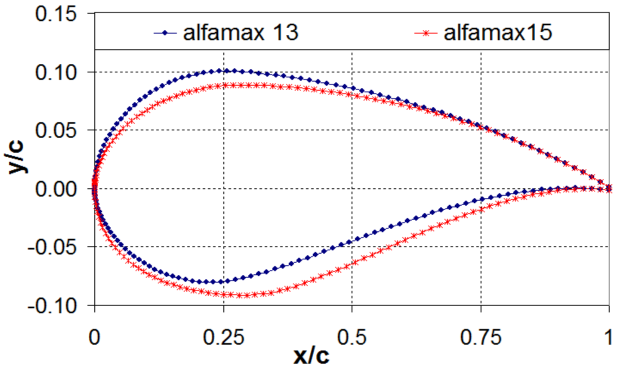

Figure 9: Comparison between the airfoil obtained with stall constraint equal to 13 and 15 degrees.

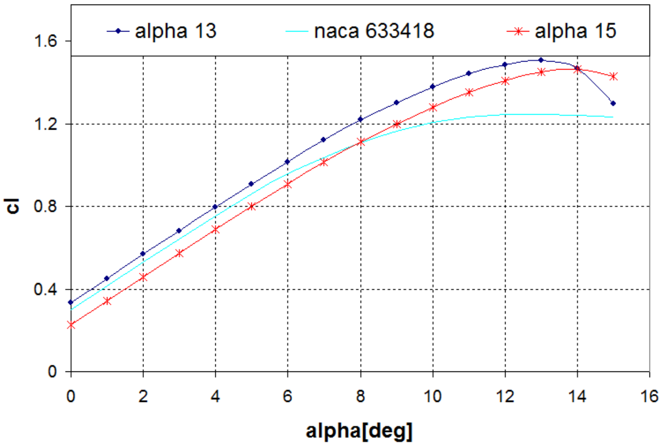

Figure 10: Comparison between lift curves of the airfoil obtained with stall constraint equal to 13 and 15 degrees.

In Fig. 9, the effect of activating the two constraints on stall is shown. In order to see the effects of these constraints, the optimization process has been performed two times. In both cases, a minimum angle of attack for stall equal to 11 degrees is prescribed.

In addition to this condition, the slope of the lift curve in post stall region is imposed to be less than -0.2 deg^{-1} ; this value comes from some comparisons between experimental data [15]. In one case, this constraint is assigned at 13 degrees of angle of attack, in the second case at 15 degrees. As consequence, the airfoil cannot stall before 11 degrees of angle of attack and the stall cannot more pronounced than the assigned value for the specific angle.

Also in this case, the results are in line with the expectations. In order to avoid separation, the geometry optimized including the higher value of stall angle has a flatter suction side surface, but at the same time, due to the fact that the minimum airfoil thickness is 18%, the pressure side is lower than the other geometry. As global consequence, the airfoil optimized to avoid stall at 15 degrees is less cambered, so the lift curve is lower.

IV. Hybrid scheme approach

One of the aims of the present work is to compare the results obtained by using GA, GBA and hybrid method.

AIRFOIL	EFFICIENCY (cl/cd)	TIME COST (sec)
Hybrid (Genetic+Gradient) Initial geometry = 59th generation	176.013 (initial l/d=110.234)	118.50 sec (grad)+14sec(gen)= 132.5 sec
Hybrid (Genetic+Gradient) Initial geometry= 100th generation	176.013 (initial l/d= 147.771)	119.44 sec (grad)+88 sec(gen)= 207.44 sec
Hybrid (Genetic+Gradient) Initial geometry= 200th generation	169.964 (initial l/d=162.699)	173.56 sec (grad)+372 sec(gen)= 545.56 sec
Gradient	171.013	117.09 sec
Genetic	162.699	372 sec

Table 1: Comparison between the three optimization methods.

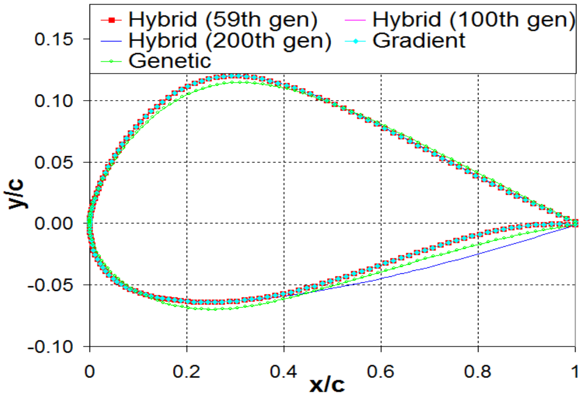

Figure 11: Optimized airfoils with the three methods

In the hybrid method developed in this work, GA is used at the beginning of the design process to explore a wide domain; then, due to the higher accuracy, GBA is used in order to improve the first stage optimum. Table 1 shows the results in terms of computational time and aerodynamic efficiency obtained by using only GA, only GBA or a combination of the two in which, the initial geometry for the GBA is the best element coming from different generation of GA.

V. Conclusions

By using genetic algorithms, a family of airfoils that improves the aerodynamic efficiency has been obtained. Further developments can be done by adding more constraints in the design process.

Genetic algorithms have been compared to the gradient-based ones in terms of objective function improvement and calculation time. Gradient based algorithms gave better results and the demand in computational time is less than for genetic algorithms. Nevertheless, gradient based methods can be very sensitive to the initial condition. A viable approach to obtain a more robust design strategy, is a combination of the two algorithms. The preliminary results are promising and show that a hybrid scheme can provide better results than genetic algorithms and save computational time.

Despite these good results, wind tunnel tests are recommended to validate predictions. Especially for the stall behaviour, the numerical predictions, and consequently the MDO process used in this work, need to be verified.

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Genetic Algorithms
In Wind Turbine Airfoil Design

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Abstract

One important element in the aerodynamic design of wind turbines is the use of specifically tailored airfoils to increase the ratio of energy capture to the loading and thereby to reduce cost of energy.
Due to the intrinsic requirements of the new wind turbines in terms of design point, off-design capabilities and structural properties, new airfoil families are needed.
Especially because of the increase of computational resources, numerical optimization approach is becoming more and more attractive for design purposes.

The present work is focused on the design of wind turbine airfoils by using numerical optimization.

Objectives

- The aim of the work is to investigate the potentialities of the genetic algorithms, also in combination with other methods, in order to develop a more complete and robust strategy to design new, high aerodynamic efficiency airfoils.

- Particular attention is given to the design requirements to find the most effective way to include them in the design process.

Method

Optimization algorithm

Genetic Algorithm (GA) developed by Caroll [1, 2] is used for the optimization process. In particular, the MicroGA method (derived from Goldberg and Krishnakumar [3]) is used to explore the use of small population sizes in genetic.

Evolutionary mechanisms included: Selection, Crossover, Mutation (creep and jump mutation), Elitism.

Geometry description

A composite third order Bezier curve parameterization is used [4, 5].

- The airfoil is divided in four parts and for each part, a third order Bezier curve is used to describe the geometry.
- In this work, eight degrees of freedom are actively used (ordinates of the control points 2, 3, 5, 6, 8, 9, 11, 12).
- To guarantee smoothness properties between the different Bezier curves, the control points 4 and 10 are automatically controlled by the algorithm.

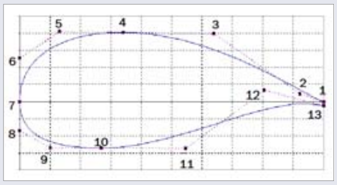


Fig. 1: Geometry parameterization

Aerodynamic solver

RFOIL [6] is used for aerodynamic evaluations.

It is a modified version of XFOIL [7] improving accuracy in stall prediction and enabling to include rotational effects on airfoil characteristics.

Constraints

Two different methods to handle constraint violation are investigated.

- *Fixed value:* a fixed penalty value is assigned to the objective function.
- *Proportional value:* the penalty value assigned to the objective function is proportional to the difference between a specific characteristic and the corresponding constraint.

Specific constraints on the following characteristics are included:

- Airfoil thickness
- Thickness at the trailing edge
- Leading edge radius
- Pitching moment about the quarter-chord point ($Cm_{c/4}$)
- Maximum lift coefficient angle of attack
- Slope of the lift curve beyond stall

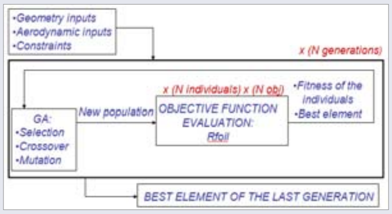


Fig. 2: Logic flow of the code

Results

Case study

Aerodynamic efficiency (l/d) optimization of an airfoil for the outer part of a blade compared with existing wind turbine airfoils. (Optimization at Alpha= 6 deg, Re=6000000, M=0.2)

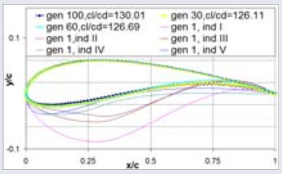


Fig.3: Best element at 30th , 60th ,100th generation compared to elements of the first generation.

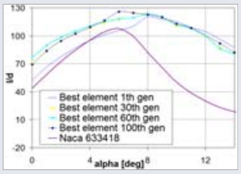


Fig. 4: l/d of the best element at 30th ,60th ,100th generation compared to NACA 63_3418.

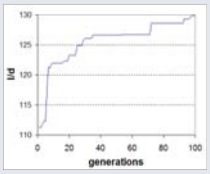


Fig. 5: Trend of the fitness (l/d) with the increasing of the generations.

Fig. 6: Comparison between the geometry of the optimized airfoil with and without pitching moment (Cm) constraint (Cm>-0.08).

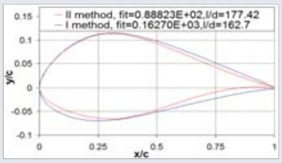


Fig. 7: Comparison between the geometry of the optimized airfoil obtained with the two methods to handle the constraints.

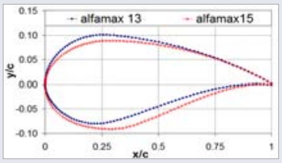


Fig. 8: Optimized airfoil for different angles of the stall constraint.

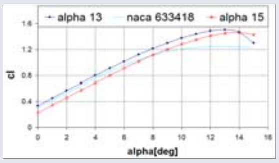


Fig. 9: Lift curve of the optimized airfoil for different angles of the stall constraint.

Hybrid scheme approach

- Combination of genetic and gradient-based algorithms to obtain high accuracy and low sensitivity to local solutions.
- Genetic algorithms are used to explore wide domains. Gradient-based algorithms are used to improve the first stage optimum.

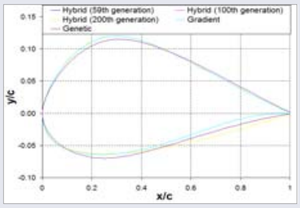
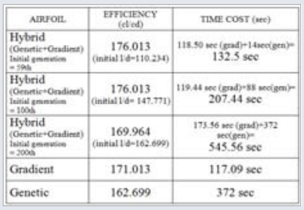


Fig. 10: Comparison of the methods: optimal airfoils



AIRFOIL	EFFICIENCY (cl/cd)	TIME COST (sec)
Hybrid (Genetic+Gradient) Initial generation = 59th	176.013 (initial l/d=110.234)	118.50 sec (grad)+14sec(gen)= 132.5 sec
Hybrid (Genetic+Gradient) Initial generation = 100th	176.013 (initial l/d= 147.771)	119.44 sec (grad)+88 sec(gen)= 207.44 sec
Hybrid (Genetic+Gradient) Initial generation = 200th	169.964 (initial l/d=162.699)	173.56 sec (grad)+372 sec(gen)= 545.56 sec
Gradient	171.013	117.09 sec
Genetic	162.699	372 sec

Fig. 11: Comparison of the methods: aerodynamic efficiencies

Conclusions

The comparisons show that the usage of genetic algorithms helps to achieve better airfoil's performance at an affordable computational cost.

Comparisons between hybrid scheme and single-algorithms results show that the hybrid scheme is effective to achieve high accuracy and low sensitivity to local minima.

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