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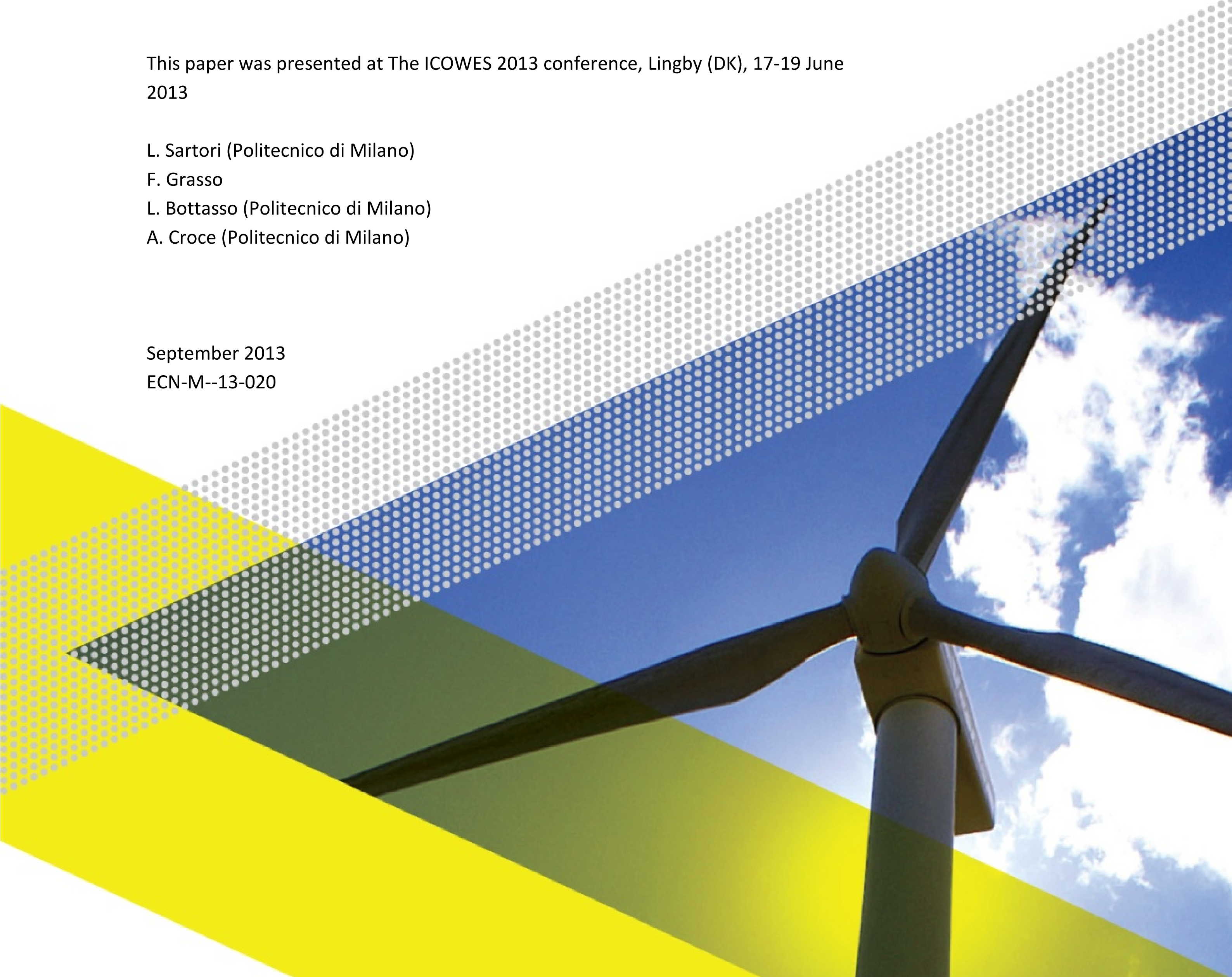

INTEGRATION OF AIRFOIL DESIGN DURING THE DESIGN OF NEW BLADES

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ABSTRACT

Despite the fact that the design of a new blade is a multidisciplinary task, often the different disciplines are combined together at later stage.

Looking at the aerodynamic design, it is common practice design/select the airfoils first and then design the blade in terms of chord and twist based on the initial selection of the airfoils. Although this approach is quite diffused, it limits the potentialities of obtaining optimal performance.

The present work is focused on investigating the benefits of designing the external shape of the blade including the airfoil shapes together with chord and twist.

To accomplish this, a design approach has been developed, where an advanced gradient based optimization algorithm is able to control the shape of the blade. The airfoils described in the work are the NACA 4 digits, while the chord distribution and the twist distribution are described through Bezier curves. In this way, the complexity of the problem is limited while a versatile geometrical description is kept.

After the details of the optimization scheme are illustrated, several numerical examples are shown, demonstrating the advantages in terms of performance and development time of integrating the design of the airfoils during the optimization of the blade.

INTRODUCTION

The design of a new rotor is a multidisciplinary task. The aerodynamics plays a crucial role, but of course an efficient structural design is also important to reduce the weight, while supporting the loads generated during the lifetime of the wind turbine. In regards of the general objective to decrease the cost of energy associated with the turbine, the aero-elastic behavior of the turbine cannot be neglected, as well as the role of the control strategies.

The present work is considering only of the aerodynamic side of this complex problem. Despite this, an important and innovative aspect is included, that is the integration of the airfoil design with the optimization of the chord and twist distributions.

Very often, the airfoils are selected in advance by using specific databases (i.e. ECN tool ATG), based on general requirements and experience of the designers. On one side this approach is convenient if the data related to the airfoils are experimental. This reduces also the uncertainties attached to the design. The airfoil aerodynamic characteristics play a fundamental role in designing the external shape of the blade, especially if a tool based on Blade Element Momentum (BEM) theory is used, where the 2D performance of the airfoils are a needed input that drives the optimization itself. The usage of existing, well known airfoils is also beneficial from structural point of view, since the internal layout should not reserve any surprise, once the shapes are investigated. The drawback of such approach is the limitation in terms of innovative solutions that can be obtained and design flexibility in regards of specific requirements.

In alternative, new airfoils can be designed depending on the actual requirements of the turbine. Starting from the middle 1980’s, quite some work has been done to develop new airfoils specifically designed for wind turbines[1-4]. Specific studies[5-10] have been performed on airfoil design also at ECN. The main advantage of designing new airfoils is the possibility to address specific requirements in very effective way. On the other hand, extra expertise is required to develop new airfoils and ensure that the properties of the airfoils are gradually changing along the blade. From the design point of view, the right connection between airfoil performance and rotor performance is needed, since the design of new airfoils has the goal to improve the airfoil performance and , as consequence, the performance of the blade.

The novelty and the challenge of the present work is to explore the possibility of designing the external shape of the blade in just one design process that involves the design of the proper airfoils depending on the region of the blade and the optimization of chord and twist distribution. The main advantage is that the airfoils are designed directly based on rotor performance/requirements.

In the next paragraph the design approach, that is based on numerical optimization, is illustrated. Particular attention is paid in regards of the evaluation of the objective function and the geometrical parameterization; this is because the difficulty behind this integration is to combine the modeling of airfoils and blade.

Finally, some examples are presented to show the potentialities of this design scheme.

INTEGRATED DESIGN APPROACH

As mentioned in the introduction, the challenge of the present work is to be able to design an optimal blade including the 2D part (airfoils) and the 3D part (chord-twist distribution) at the same time. This implies a design approach that is robust, general and flexible.

The design scheme implemented in this work is based on multidisciplinary design optimization (MDO). In the most general sense, numerical optimization[11,12] solves the nonlinear, constrained problem to find the set of design variables, X_i, i=1, N, contained in vector $\boldsymbol{X}$, that will:

Minimize $F(X)$ (eq.1)

subject to:

$$g_j(X) \leq 0,\ j=1,M \quad \text{(eq.2)}$$

$$h_k(X)=0,\ k=1,L \quad \text{(eq. 3)}$$

$$X_i^L \leq X_i \leq X_i^U,\ i=1,N \quad \text{(eq. 4)}$$

Equation 1 defines the objective function which depends on the values of the design variables, $\boldsymbol{X}$. Equations 2 and 3 are inequality and equality constraints respectively, while equation 4 defines the region of search for the minimum. The bounds defined for each degree of freedom by equation 4 are referred as side constraints. As it can be seen, the methodology is very general and able in principle to describe in a compact, efficient way problems with complex, interconnected sub components.

The FFSQP algorithm[13] has been implemented, that is a sequential quadratic programming (SQP) gradient based algorithm. The gradients have been approximated by finite differences.

Looking at the optimization process, different approaches are possible to combine the optimization of the airfoils with the optimization of the blade.

One option is to keep separate the design of the airfoils from the design of the blade. In this way, the design procedure is formed by two sub-optimization processes focused on airfoil and blade design. In practice, this would result in a complete optimization process of the airfoil(s) for each change in chord/twist.

Alternatively, the design process could be a so called “all in once” approach, where the optimization process is just one, including both the airfoils and the blade at the same time. From the implementation point of view, a single data structure is necessary in this case, containing degrees of freedom for both aspects of the design.

Decide in advance what is the best approach is hard. Depending on the specific problem, one procedure can be more convenient than the other one, in regards of quality of the optimal solution, computational time, robustness of the process. In this paper, the second approach has been preferred , mainly due to the interest of having a single design process dealing with the complete problem and trying to distinguish the roles/effects of the different sub-components.

Objective function evaluation

In order to evaluate the quality of the design produced by using this integrated approach, the performance of the rotor such the Cp_{max} and the annual energy production (AEP) have been used as objective functions.

The open source code WT_Perf[14] developed by NREL, has been implemented in the design procedure. WT_Perf is based on BEM theory, so the aerodynamic properties of the airfoils are a needed input. In the design scheme then, also a 2D solver is necessary to generate these input. XFOIL[15,16] panel code has been used, coupled with Viterna-Corrigan[17] analytical model to extend the numerical data between -180 and 180 degrees.

Geometrical parameterization

The selection of the most convenient degrees of freedom for the problem in exam, plays a crucial role in order to obtain an efficient and robust design scheme. In this case in particular, two parameterizations are needed: one for the airfoils and another for the blade. Looking at the design procedure from a computational point of view, it would be convenient to reduce as much as possible the total number of parameters to keep low the complexity of the problem. On the other hand, from the design perspective, being able to control the geometrical characteristics in details would be highly desirable.

Regarding chord and twist distributions these have been described through variable order Bezier curves. The main property of this approach is the fact that the shape of the curve is controlled by the position of few control points, as sketched in figure 1.

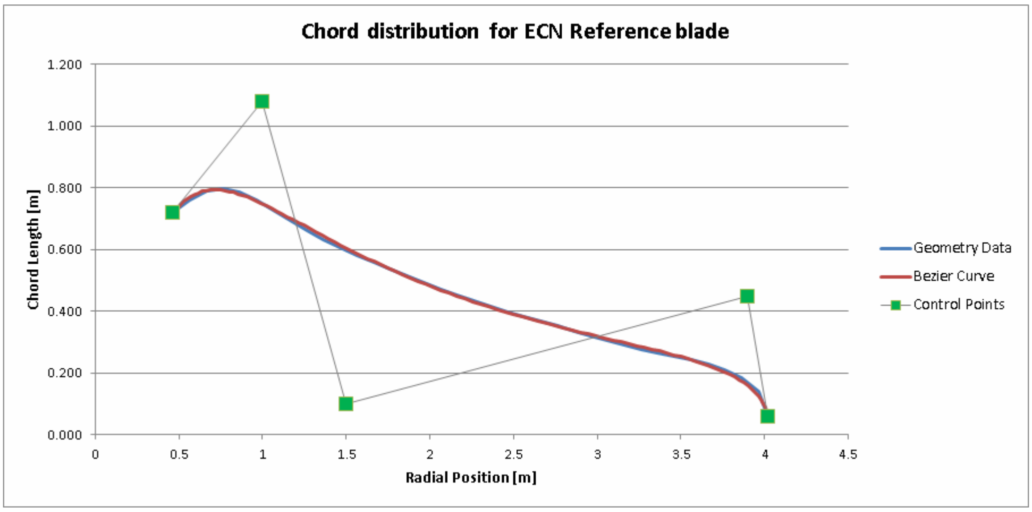

Figure 1 Example of chord distribution, by using fourth order Bezier curves.

The same approach could be conveniently used to describe the shape of the airfoils, as discussed by Samareh[18] and developed by Grasso[10]. However, a simplified approach has been preferred, that makes use of the geometrical parameterization of the NACA 4 digits airfoils. These geometries are described by a set of three equations related to the thickness distribution and the camber distribution.

$$y_t(x) = \frac{t}{0.2}c\left[0.2969\sqrt{\frac{x}{c}} - 0.1260\left(\frac{x}{c}\right) - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right]$$

(eq. 5)

$$y_c = \begin{cases} m\frac{x}{p^2}\left(2p - \frac{x}{c}\right) & for \quad 0 \le x \le pc \\ m\frac{c-x}{(1-p)^2}\left(1 + \frac{x}{c} - 2p\right) & for \ pc \le x \le c \end{cases}$$

(eq. 6)

The parameters that control the shape of the airfoils are the airfoil thickness (t), the maximum camber (m) and the chord wise location of the maximum camber (p). The complete description can be found in Abbott[19].

Although the usage of such class of airfoils limits the space of solutions that can be explored during the design, there are several advantages connected to this choice. It has been already mentioned the crucial role of the number of degrees of freedom in regards of the computational complexity of the design problem; for this parameterization, only three parameters are needed for each airfoil. The second and more important aspect is connected to the geometrical properties of the airfoils generated; due to the analytical description, any set of three parameters leads to a smooth shape. Especially in this first attempt to couple airfoil design and blade design, this fact allows to skip many checks on the regularity of the airfoil geometries, reducing the computational time and the number of trial unfeasible designs eliminated during the process.

NUMERICAL EXAMPLES

In this paragraph, several examples regarding the integrated airfoil/blade design are illustrated. The reference geometry has been a two blade rotor developed at ECN for marine applications, equipped with NACA 4418 airfoil (see table 1).

Table 1: Main characteristics of the reference blade.

Rotor radius [m]	4.022
Design water speed [m/s]	1.5
Rotor speed [RPM]	24.93
Pitch angle [deg]	-1.3
AEP [GWh/year]	0.018
Cp_{max} [-]	0.438

Also, for all the examples, a rectangular blade with zero twist, equipped with NACA 4418, airfoil has been used as baseline.

In terms of degrees of freedom, fourth order Bezier curves have been selected for the twist and chord distributions. Regarding the airfoils, the thickness has been kept constant to 18%. This is due to the absence in the current design scheme, of structural constraints; without these, very preliminary tests showed the tendency to reduce as much as possible the thickness of the airfoils in order to reduce the drag. The implementation of a simple structural model in further development, is expected to counter balance this trend and provide a more realistic solution.

Example 1: chord, twist and two airfoils to maximize the Cp

The objective of the test is to design a blade where the Cp_{max} is optimized, changing the chord and twist distributions and the camber characteristics of two airfoils installed along all the blade. Figures 2 and 3 show the optimal distributions for the chord and the twist.

Looking at the results, the Cp improves significantly compared to the baseline, but also in regards of the above mentioned reference blade, the Cp has larger value. It should be noticed that the baseline is a rectangular blade without any twist, so a very low Cp should be expected.

In figure 4, the comparison between the shapes of the airfoils is illustrated. As it can be seen, the optimal airfoils are quite different in terms of camber line, since they are more aft loaded. In figure 5 and 6, the aerodynamic characteristics of the airfoils, calculated with XFOIL, are shown. It should be noticed that both the new airfoils have better lift and efficiency performance.

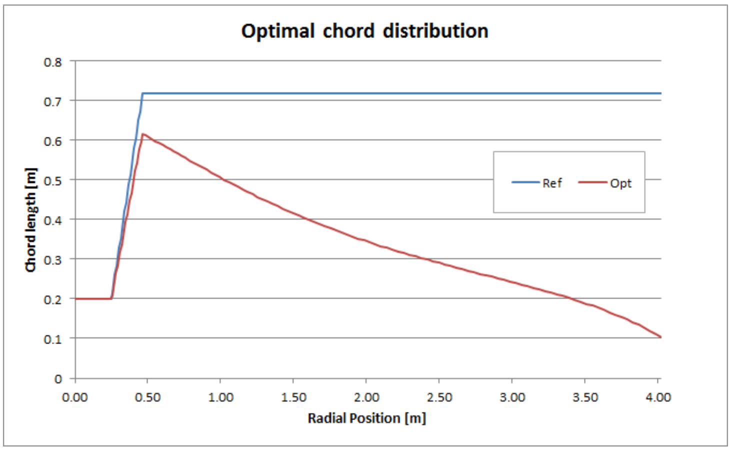

Figure 2 Optimal chord distribution.

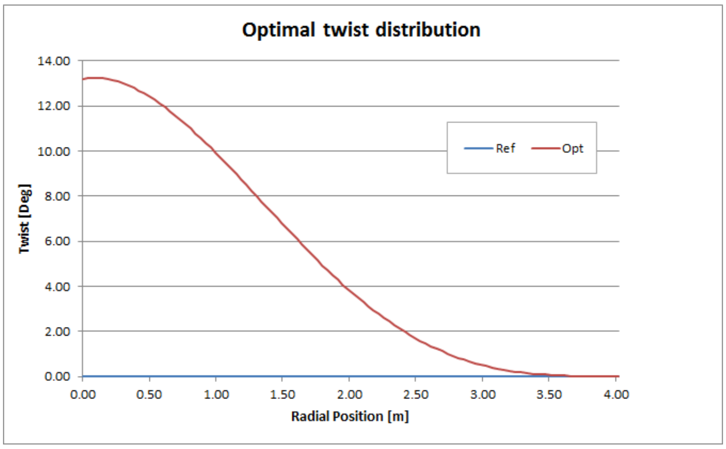

Figure 3 Optimal twist distribution.

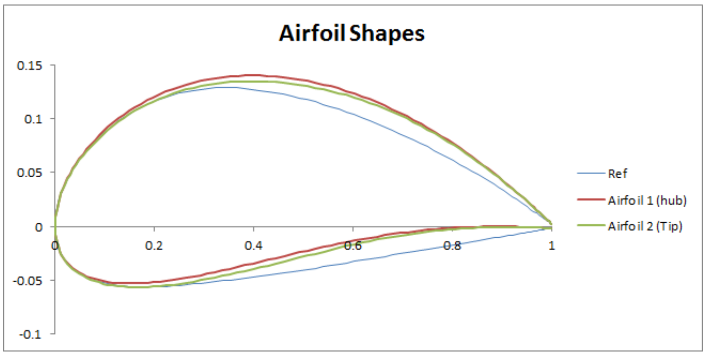

Figure 4 Optimal airfoil shapes.

Blade	Cp	Airfoil 1	Airfoil 2	Time [sec]
Baseline	0.2249	4418	4418	-
Opt	0.4531	6518	5518	8675.2

Table 2 Summary of the optimization process.

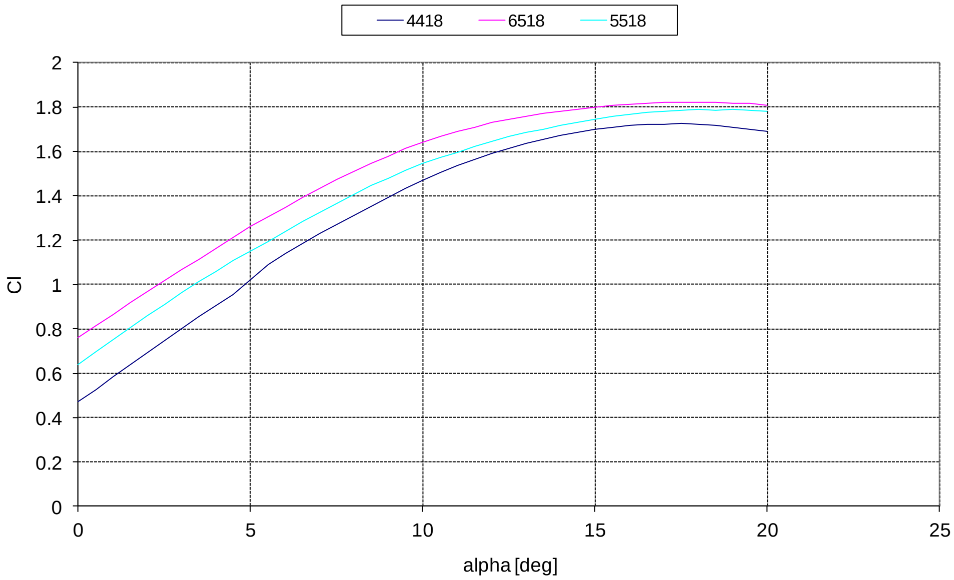

Figure 5 Lift curves of the airfoils involved during the design. XFOIL predictions. Free transition, 2 millions Reynolds number.

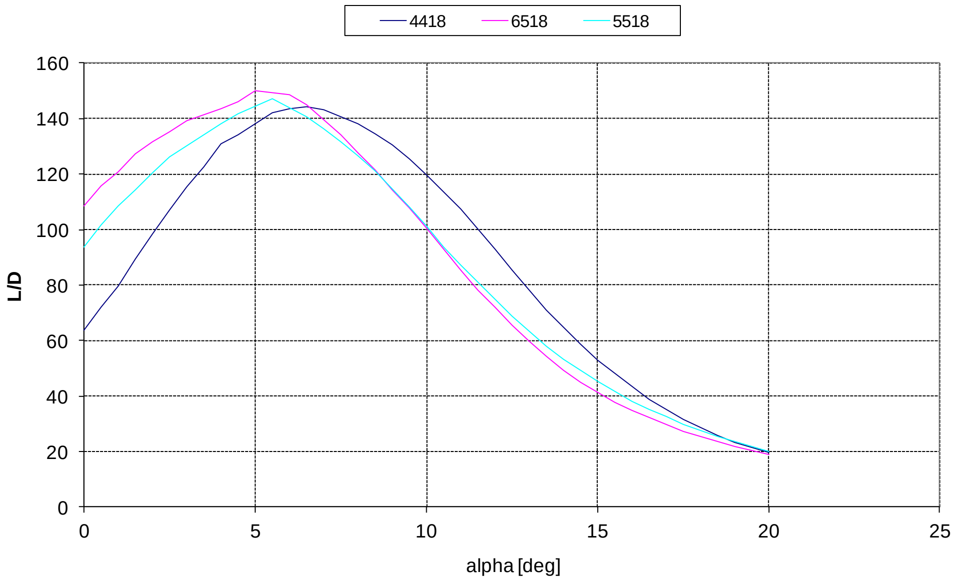

Figure 6 Efficiency curves of the airfoils involved during the optimization. XFOIL predictions. Free transition, 2 millions Reynolds number.

Example 2: chord, twist and three airfoils to maximize the Cp

The same test illustrated in the first example has been performed by increasing the number of airfoils along the blade, in order to check the robustness of the design procedure. As it can be observed, both the chord and twist distribution are still smooth, the airfoils are consistent with each other and the performance of the blade are improved.

Blade	Cp	Airfoil 1	Airfoil 2	Airfoil 3	Time [sec]
Baseline	0.2249	4418	4418	4418	-
Opt	0.4534	6518	5518	5518	19286

Table 3 Summary of the optimization process.

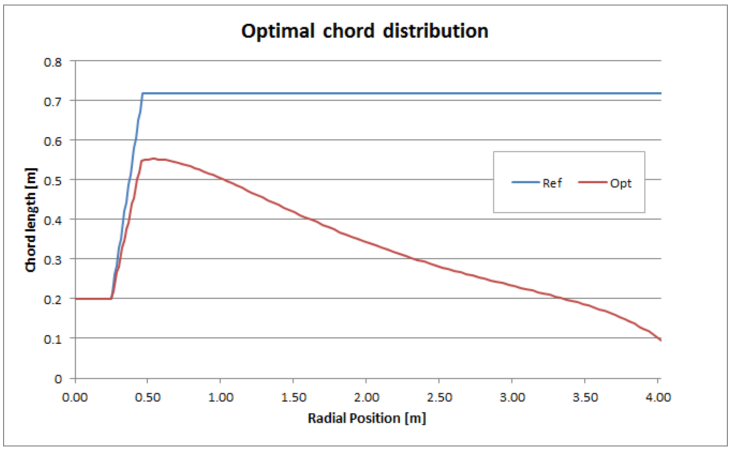

Figure 7 Optimal chord distribution.

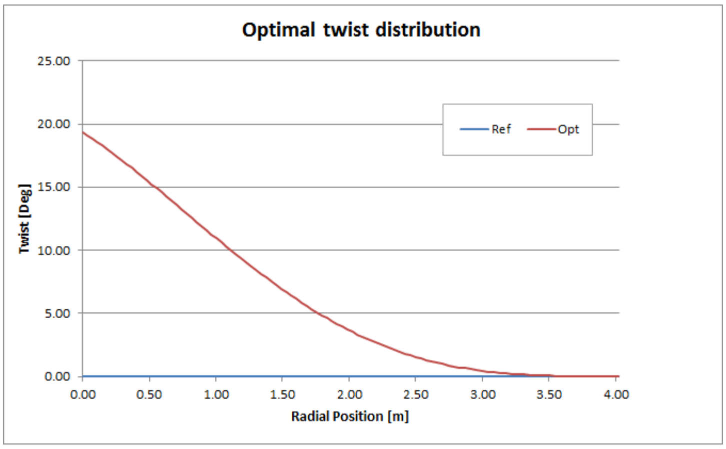

Figure 8 Optimal twist distribution.

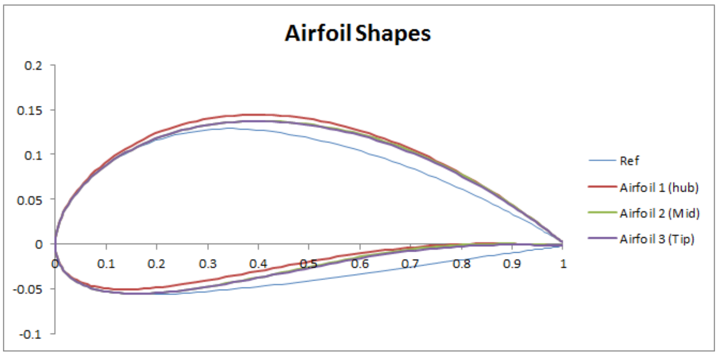

Figure 9 Optimal airfoil shapes.

Looking at the computational time, this increased in the second example, due to the increase of degrees of freedom and the amount of airfoil calculations for each iteration.

CONCLUSIONS

An investigation focused on the integration of airfoil design into blade design has been performed. In this first attempt, open source solvers have been used, coupled with an advanced optimization algorithm.

The first results proved that design the blades in combination with airfoil design, lead to better overall performance, including a fair distribution of airfoils along the blade.

In order to obtain more realistic results however, the description of the airfoils should be generalized by using for instance, Bezier curves also for the airfoil shapes.

Also, more accurate solvers, like RFOIL and Aeromodule, should be implemented. In the present work, the selection of the tools has been driven by the objective to focus the investigation on the basic aspects of such integration, more than on obtaining optimal solutions.

From this point of view, it cannot be neglected the importance of the structural model to work in multidisciplinary way with a complete design scheme. In the examples, the thickness has been prescribed; by adding a structural model, the thickness distribution along the blade could let be free to change and the optimal value would be a result of competing structural and aerodynamic tendencies. This will be the subject of future work.

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