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Simultaneous ply-order, ply-number and ply-drop optimization of laminate wind turbine blades using the inverse finite element method

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ABSTRACT

This paper presents a novel methodology to simultaneously determine the optimal ply-order, ply-number and ply-drop configuration of laminate wind turbine blades using simulation-based optimization, considering the shape that the laminates are expected to attain after large elastic deformations. This methodology combines Genetic Algorithms with the Inverse Finite Element Method.

As an actual engineering application, we redesigned the composite stacking layout of a medium-power 40-kW wind turbine blade to reduce its weight, subjected to mechanical and manufacturing constraints such as allowable tip deflection, maximum stress, natural frequencies, and maximum number of successive identical plies. Results demonstrate weight reductions of up to 15% compared to the initial layout, proving that the proposed methodology is a robust redesign tool capable of effectively determining the optimal composite stacking layout of laminate wind turbine blades.

1. Introduction

In the pursuit of better, more competitive and more efficient wind turbines, the structural layout of the blades is one of the design aspects that can lead to significant reductions of weight and costs, while maintaining the reliability of the machine. Improvements on the stacking sequence and the number of plies along the blade provide not only weight and costs savings in the rotor, but also in the tower and foundation. The use of composite materials in the manufacturing process of the blades is a natural choice due to many technical and economic reasons, such as outstanding mechanical properties, excellent strength-to-weight ratio, availability, reliability, and competitive cost. The vast amount of scientific works addressing the search of the optimal stacking sequence and number of plies in the composite laminates of the blades proves that this is one of the most popular design problems in the wind energy community.

The use of laminates with variable stiffness along the blade [1] is of particular interest due to their superior structural performance compared to laminates with longitudinally constant stiffness [2]. Variable stiffness laminates taper material distribution that is achieved by *ply drop*: A material layer can be dropped from the root to the tip of the blade, if it is not essential for its structural stability.

Hence, the optimal design of a blade can be determined by finding the proper laminate distribution that minimizes the weight of the blade, while satisfying all given constraints [3]. This is usually a nonlinear programming problem with integer design variables, like the number of plies and their order, which are continuous design variables, where the mechanical constraints (minimal compliance, maximal stress) are determined using computational mechanics.

Genetic algorithms (GA) [4], based on the natural principle of “survival of the fittest”, are by far the widest methods for the solution of this kind of problem. In a pioneering work on optimization of tapered laminates, Kim et al. [5] developed the “patch-wise layout design method” using GA for minimizing the weight of the structure subject to a strength constraint based on the Tsai-Hill fail criterion, considering as design variables the ply angles and the number of plies in each patch. To ensure fiber continuity between patches, only the stacking sequence in the patch with the maximum number of plies is optimized, and the same sequence is adopted for the remaining patches (although plies can be dropped from patches where the failure constraint is satisfied). Irisarri et al. [6] used a Pareto-based GA to minimize the mass and maximize the buckling margin for a tapered laminate, subject to strength constraint for avoiding instability issues throughout the structure (even if the buckling margin is maximized, it could remain low). They used a Stacking Sequence Table (SST) to describe the sequence of ply-drops ensuring the transition between patches, which allowed them to satisfy design rules without additional constraints. Fan et al. [7] minimized a unique function defined as the sum of the weight

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of the laminate and a term that decreases as the buckling margin increases, penalized by factors considering contiguity and disorientation. They introduced the ply-composition and the ply-ranking chromosomes, whose construction forced the satisfaction of the design rules on continuity, balance and symmetry without using constraints.

Specific to wind turbine applications, Dal Monte et al. [8] presented a multi-objective GA optimization procedure to minimize the mass and maximum displacement of a 7.22-meter blade for the AOC 15/50 Horizontal Axis Wind Turbine (HAWT), by changing the material layup and placement in the shell skin. Integer design variables to optimize categorical variables are used in this case. In a more recent work, Dal Monte et al. [9] present a coupled optimization procedure where both aerodynamic and structural parameters are considered as the design variables, to improve the performance and mechanical integrity of the AOC 15/50 HAWT. In this approach, the blade element momentum (BEM) and the finite element method (FEM) are used for the aerodynamic and structural response, respectively, and the optimization is carried out by GA. Wang et al. [10] applied GA to minimize the weight of a blade of a 30-kW Vertical Axis Wind Turbine (VAWT), subject to constraints on stress, deformation, vibration and buckling, manufacturing and continuity. They consider not only integer design variables (the number of unidirectional plies at each region of the blade) but also continuous ones (the location of spar caps and the thickness of shear webs). Fagan et al. [11] minimized the weight, penalized by the deformation excess, of a 13-meter blade for a medium-power HAWT. In this case, they considered integer design variables defining the amount of plies in the shell skin, the shear webs, and the spar caps of the blade, the end point of the core in the shear webs and the number of shear webs.

In a previous work [12], we widely describe the use of the Inverse Finite Element Method (IFEM) for the design of the blade of a 40 k three-blade HAWT. In this work, we introduce a new method for the determination of the optimal number and order of plies in tapered laminates, capable of accounting for the shape the laminates are expected to attain after large elastic deformations. As usual in the above mentioned literature, we use GA to minimize the weight of the structure subject to manufacturing and mechanical constraints, the latter being evaluated by numerical structural solver. Here, we make a crucial contribution to the optimization of slender structures undergoing large elastic deformations (like most of the turbine blades): the use of IFEM [12,13] for structural analysis. IFEM computes the manufacturing shape of a structure such that it attains a prescribed shape under given loads. By this way, a major requirement is taken into account in the optimal design of the blade: It has to attain a given aerodynamically efficient shape when it is largely deformed by the service loads. This is a novel methodology, and to the best of the authors' knowledge, no other combination of an optimization method and IFEM has been reported in literature so far. Hence, the former blade of [12] is taken as the base case to highlight the current optimization results.

This paper is organized as follows: Section 2 presents the design problem under study, and describes the geometry and material layout of the reference blade, and the mechanical properties of the composite materials adopted. Section 2.3 describes the objective function, the design variables, and the design constraints of the optimization problem. Section 3 describes the GA algorithm used in this work, and its specific setup. Numerical results are given in Section 4, and the concluding remarks in Section 5.

2. Case study

In order to validate the current optimization methodology, let us take as reference the blade of a 40 kW three-blade HAWT designed in our previous work [12]. This turbine has a radius of $R = 6.70$ m and, under operating conditions, it rotates at 72 RPM for a wind velocity of 7 m/s. Three airfoils from the SG604X family [14] were selected for the root (SG6040), the mid-span (SG6042) and the tip of the blade (SG6043), while intermediate airfoils were defined by linear interpolation. The adimmensional chord length and the twist angle distribution vary along the span following classical Schmitz theory. Both of these values are presented in Table 1 along the adimmensional blade span. The resulting shape of the blade is shown in Fig. 1.

Table 1
Chord length and twist angle distribution along the adimmensional blade span.

Blade span [r/R]	Chord [c/R]	Twist [degrees]
0.12	0.170	28.51
0.19	0.140	19.08
0.27	0.118	13.49
0.35	0.090	9.95
0.42	0.080	7.59
0.50	0.070	5.93
0.58	0.060	4.72
0.65	0.055	4.12
0.73	0.050	3.72
0.81	0.045	3.43
0.88	0.041	3.31
0.96	0.039	3.25
1.00	0.038	3.25

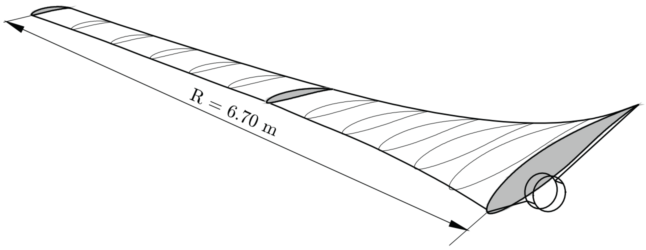

Fig. 1. Geometry of the reference blade, determined in [12].

The aerodynamic pressure over the reference blade was computed using Computational Fluid Dynamics (CFD) for the given operating conditions in [12], and it is depicted in Fig. 2. This problem was numerically solved using the finite volume method as implemented into the open-source software OpenFoam. The steady-state solver for incompressible and turbulent flow *simpleFoam* with the k-ω turbulence model was used along with the multiple reference frame approach

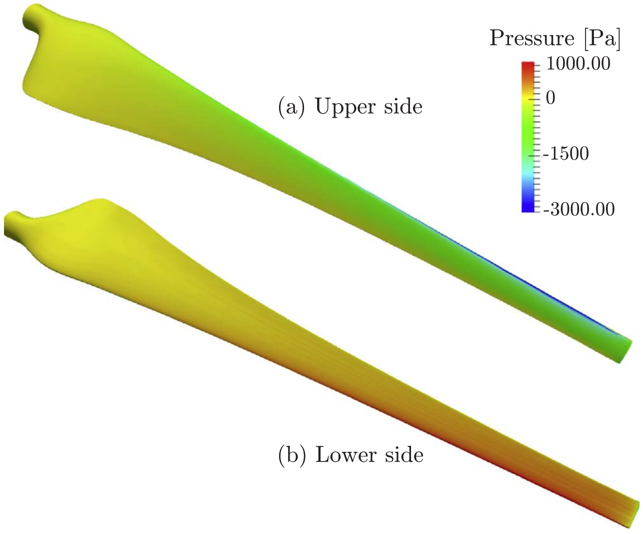

Fig. 2. Resultant aerodynamic pressure over the blade, computed in [12]. View from the upper side (a) and from the lower side (b).