Multi-Objective Structural Design Optimization of a Wind Turbine Blade

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Abstract. This paper studies the structural design of a 60m long 5MW wind turbine blade to achieve optimum results using different optimization techniques. Due to the high aspect ratio of this component, its design involves many challenges, including large deflections, stability, and aeroelastic phenomena. Therefore, it's proposed an optimization problem with conflicting objectives and design constraints based on international standard IEC-61400-1 and Certification Guidelines. The two objective functions are the minimization of the structural weight of the blade and the maximization of the first natural frequency of vibration. Using a parametrized Finite Element Model, the composite layup of the blade, including the material of each ply, number of plies, and fiber orientation, are the design variables. The results were compared to the reference blade developed by the National Renewable Energy Laboratory (NREL) to validate the optimization strategy.

Keywords: Multi-objective optimization; Wind turbines; Structural optimization.

1 Introduction

The increase in interest and market share of renewable energy fonts has led to significant advances in the design of wind turbines both on and offshore. They seek to increase turbine efficiency by building longer blades, which imposes several structural challenges and limitations. As the length and aspect ratio of these blades increases, so does their aerodynamic performance. However, it also becomes more challenging to avoid aeroelastic and stability phenomena due to low rigidity. Satisfying the constraints on the design of such components can consume a considerable amount of time and resources. Because of that, the implementation of optimization techniques has been widely studied both in the renewable energy and aeronautic field. In this study, a model was developed and optimized using a multi-objective evolutionary algorithm. The industry-standard failure criteria are adopted to specify the structural characteristics of a wind turbine blade built-in composite laminated materials to achieve an optimum solution between structural efficiency and rigidity. This paper is organized as follows: Section 2 describes the formulation of the multi-objective optimization problem discussed in this paper. Section 3 presents the load cases to be considered on the blade. The results of the numerical experiment are provided in Section 4, and finally, the conclusions and future works are presented in Section 5.

2 Structural Optimization Problem

2.1 Multi-objective Optimization

Unlike a single-objective optimization, in multi-objective cases is not trivial to define the optimum solution. In most cases, the minimum point of one objective function does not allow the minimization of another objective. Therefore, usually, the Pareto optimal concept is used. A solution $\mathbf{x}^*$ belonging to the feasible sample space is called the Pareto optimal point if no other point $\mathbf{x}$ reduces at least one objective function without increasing another one.

2.2 Non-Dominated Sorting Genetic Algorithm II (NSGA-II)

The Non-Dominated Sorting Genetic Algorithm was proposed by Deb [1] as a solution to two main problems. The first one is the numerical complexity of multi-objective non-dominated sorting evolutionary algorithms, and the second is the non-elitism approach of those. The solution for the first problem is achieved with a new approach to defining the non-dominated fronts. Instead of, for each solution, iterating through all other solutions to determine if this specific solution is dominated or not and repeating this process for every non-dominated front, the NSGA-II implements two variables defined for every individual of a population. The domination count n_P tells how many solutions dominate the solution P and the dominated set S_P that has the solution that the solution P dominates. The first front is defined by every solution that has $n_P = 0$. After that, every solution q on the set of dominated solutions has its n_P decreased by one, and the solutions that now have $n_P = 0$ are the second front and so on. The first approach takes $O(MN^3)$ comparisons (where M is the number of objectives and N is the number of individuals on each population), and the NSGA-II approach takes only $O(MN^2)$ comparisons.

The solution for the second problem is achieved by continuously comparing the new population, created by standard genetic algorithm, with the previous population, as shown in Figure 1, where P_t is the previous solution and Q_t the new solution. The comparison between those solutions generates the new non-dominated fronts, and these fronts are selected until the original number of individuals in the population is reached. To define which solution on the same front is taken over another, the crowding distance parameter is calculated to favor a solution on a less crowded area.

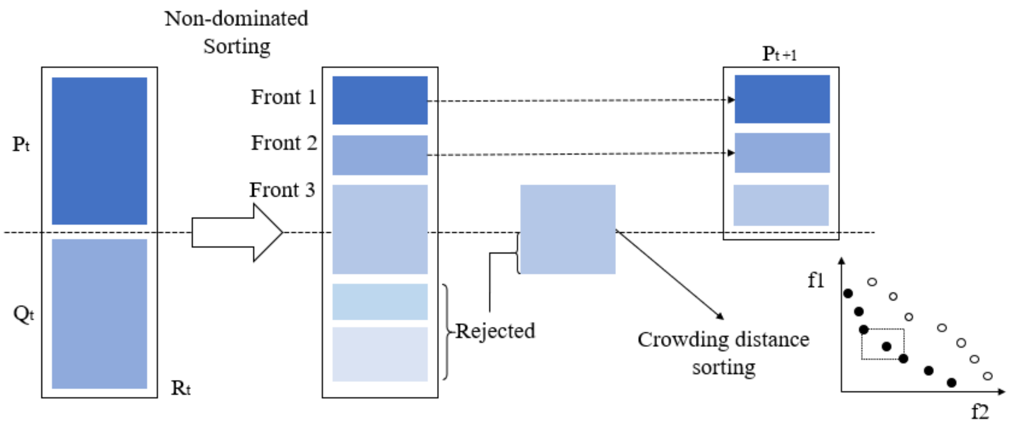

Figure 1. NSGA-II sorting procedure.

2.3 Problem Definition

The blade structure is defined as an outer shell that gives the blade its aerodynamic airfoil shape. The internal structure consists of two spars positioned at 15 and 50% of the airfoil chord, usually done on wind turbines blade design according to Griffin [2].

The design variables are the layups on different regions of the blade. The blade was divided into 15 regions (Figure 4), the outer shell is divided into 3 parts, and each of the two spars completes the 5 different layups in each airfoil section (Figure 2), and span-wise, the blade was divided into 3 sections (Figure 3). It was considered the possibility of plies at 0°,45°,-45° and 90° for carbon fiber and fiberglass plies.

Table 1. Material's mechanical properties

Material	E_{xx} (GPa)	E_{yy} (GPa)	G_{xy} (GPa)	υ_{xy}	ρ (kg/m³)	Ply thickness (mm)
0° Carbon Fiber [3]	139,0	9,0	5,50	0,32	1560	2,0
0° Fiberglass [3]	41,0	9,0	4,10	0,30	1890	1,0
Divinycell [4]	0,25	0,25	0,073	0,35	200	5,0

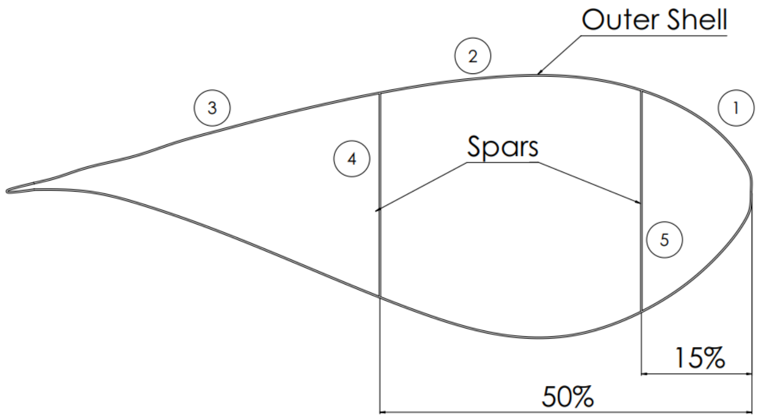

Figure 2. Layup regions across the blade chord.

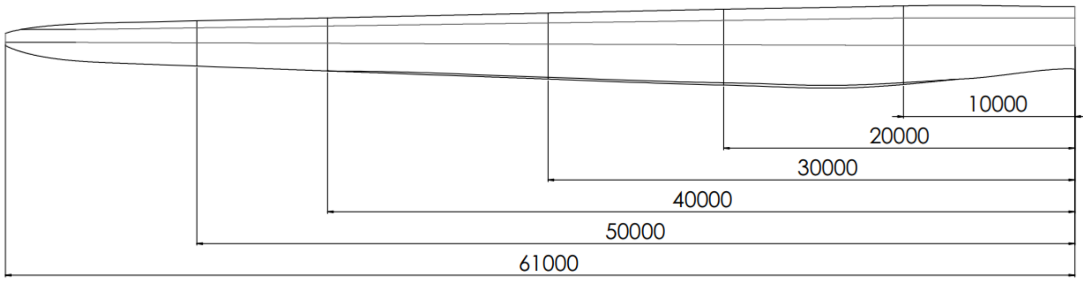

Figure 3. Layup regions across the blade span.

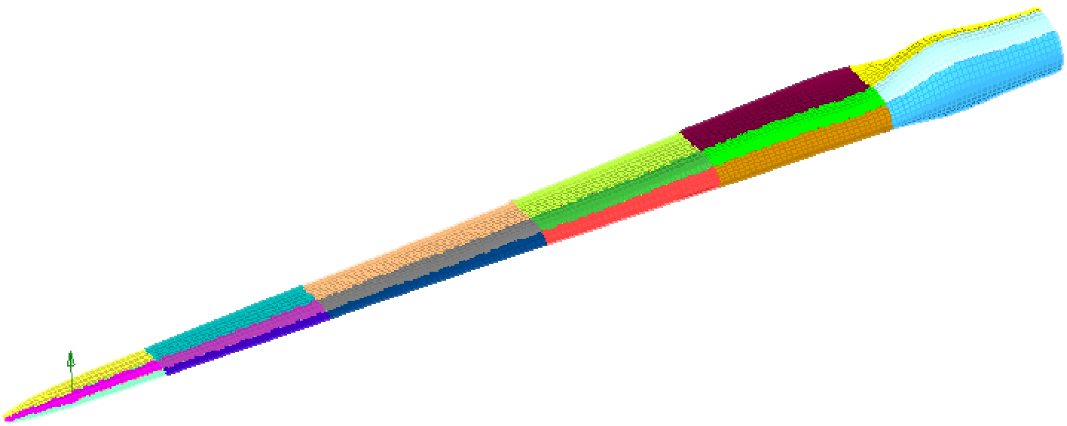

Figure 4. Finite element model of the blade.

The optimization objectives were to minimize the blade's total mass and maximize the component's first natural frequency of vibration. The optimization algorithm used was the NSGA-II, implemented in python, using the library pymoo developed by Blank and Deb [5]. The optimization algorithm was coupled to a finite element model made on Femap® through Application Programming Interface (API) scripts that update the layups, run the analysis and collect the output data. As design constraints, strain and deflection criteria were used, but those are explained later.

The multi-objective optimization problem is written as:

$$\min \quad (f_1(\mathbf{x}), f_2(\mathbf{x})) = (M(\mathbf{x}), -\omega_1(\mathbf{x})) \tag{1}$$

$$\text{s.t.} \quad g_1(\mathbf{x}) = \frac{\delta_{max}(\mathbf{X})}{\bar{\delta}} - 1 \leq 0 \tag{2}$$

$$g_2(\mathbf{x}) = \frac{\varepsilon_{max}(\mathbf{X})}{\bar{\varepsilon}} - 1 \leq 0 \tag{3}$$

where $(\mathbf{x})$ is the vector of design variables, $M(\mathbf{x})$ is the mass of the blade, $\omega_1(\mathbf{x})$ is the first natural frequency of vibration, $\delta_{max}(\mathbf{x})$ is the blade deflection at its tip, $\varepsilon_{max}(\mathbf{x})$ is the maximum specific strain, $\overline{\delta}$ and $\overline{\varepsilon}$ are the allowable maximum wing tip deflection and specif strain, respectively.

The allowable strains were defined based on the material data in [3] and [4], and on the material partial safety factors described in [6]. The maximum deflection is based on the minimum clearance of 30% between the blade tip and tower, defined in [6] and on the geometry data available on [7], resulting in a maximum deflection of 10 m.

3 Load Cases

The loads and partial safety factors applied to the loads that were used on the analysis were calculated according to the regulatory standard IEC 61400-1 [6] and using the aeroelastic software FASTv8, developed by NREL [8]. The software only provides output for nine stations along the span of the blade. In the analysis at each of those stations, the 3 components of internal forces and the torsional moment (M_Z) calculated were applied at each airfoil's aerodynamic center, which was assumed to be at 25% of the chord.

From all load conditions defined at [6] the most critical (using the tip deflection as a criterion) was at energy production situation on extreme turbulence model (ETM) and with a wind velocity of 24 m/s and 8^{o} of wind incidence on the horizontal direction. Therefore that was the one used in the optimization process. Figure 5 shows the pontual loads calculated using FASTv8 on the critical condition.

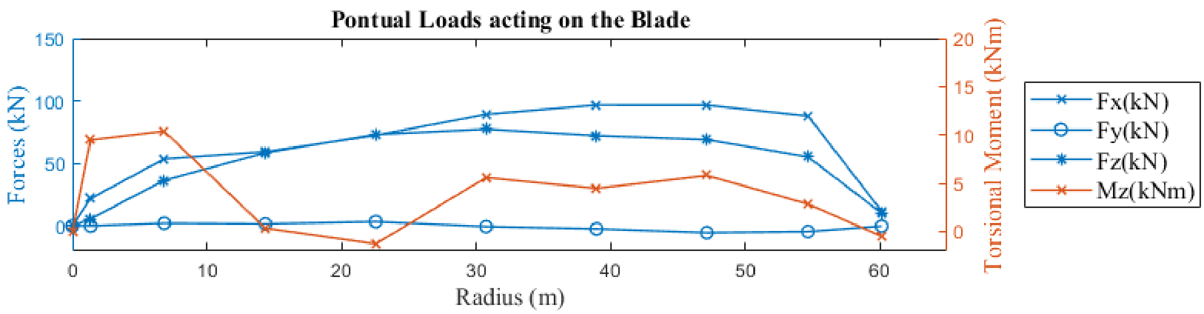

Figure 5. Pontual loads calculated using FASTv8 on the critical condition.

4 Results

The optimization process resulted in the Pareto front depicted in (Figure 6). Several decision-making algorithms have been developed in the literature to extract preferable solutions. However, for this study, a visual inspection of the Pareto front is used to extract the desired non-dominated solution. As can be seen in Table 2, the solution with minimum mass ($\omega_1(\mathbf{x})$) presents a higher first natural frequency and a smaller wing tip deflection ($\delta(\mathbf{x})$).

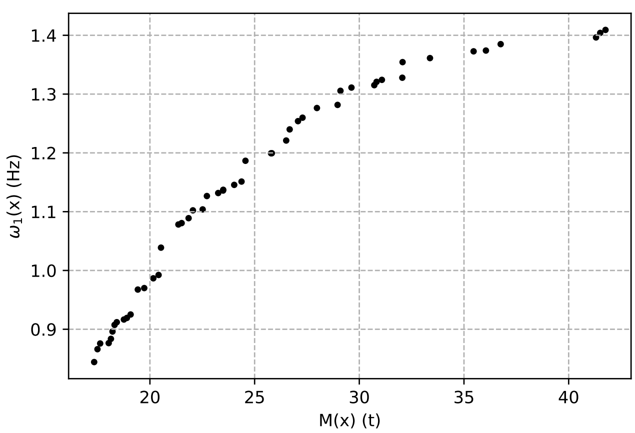

Figure 6. Pareto front obtained for $M(\mathbf{x})$ and $\omega_1(\mathbf{x})$.

Table 2. Comparison between original and optimized blade parameters.

Objective functions/constrains	Reference Blade (NREL)	Optimized Blade
$M(\mathbf{x})$ (t)	17,740 [7]	17,336
$\omega_1(\mathbf{x})$ (Hz)	0,664 [7]	0,844
$\delta(\mathbf{x})$ (m)	10,90 [9]	7,08

The strain values were not compared because those were not available on any of the bibliography of the NREL 5MW blade used as reference.

5 Conclusions

This paper discussed the structural design problem of long wind turbine blades using a multi-objective optimization methodology. The optimization algorithm used is the NSGA II, largely used in literature. A total of 130 design variables were used to parameterize the blade composite layup properties. The results found by the optimization process have shown that the methodology implemented can provide excellent results and can be used as a design strategy. It is important to note that a non-dominated solution (extracted from the Pareto front) was found, presenting a lower mass with a higher natural frequency of vibration and a lower deflection of the blade tip. Future studies should consider other aspects in the formulation of the multi-objective optimization problem, such as the addition of buckling constraints and aeroelastic analysis. In addition, different algorithms should be used in comparative studies to assess their performance.

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