Aerodynamic and structural optimization of wind turbine blade considering natural of frequencies of vibration

Júlia C. S. Kunsch[1], Nícolas L. Oliveira[2], Patrícia H. Hallak[2]

[1]*Graduate Program in Civil Engineering, Federal University of Juiz de Fora*
julia.kunsch@estudante.ufjf.br
[2]*Graduate Program in Computational Modeling, Federal University of Juiz de Fora*
nicolas.lima@ufjf.br, patricia.hallak@ufjf.br
University campus, 36036-900, Juiz de Fora/MG, Brazil

Abstract. In recent years, wind energy has garnered significant global attention due to its immense energy and environmental potential, leading to a substantial increase in both capacity and size of wind turbines. However, this scaling-up has introduced new challenges related to instability caused by the aeroelastic effect, which stems from the interplay between wind loads and the structural deformation of wind turbine blades. Consequently, an effective model necessitates well-defined aerodynamic and structural components. Yet, the complex geometric shapes of turbines demand extensive computational resources for analysis, particularly given their composite materials and intricate configurations. This work proposes an aerodynamic optimization method constrained by the structural model, focusing on the natural vibration frequencies of wind turbine blades. The methodology comprises three phases: defining the aerodynamic model using the CCBlade code in Julia Language, implementing the structural analysis method via FEM for rotating Timoshenko beams and integrating the aerodynamic and structural models on a multi-objective optimization platform. Evolutionary algorithms were employed to enhance wind turbine energetic efficiency and avoid structural instabilities within this study. By leveraging advancements in modeling and optimization techniques, the aim is to contribute to the development of more efficient and reliable wind turbines, further promoting the transition to clean and sustainable energy sources.

Keywords: Wind turbine, Optimization, BEM, FEM

1 Introduction

In recent years, wind energy has received increasing attention worldwide due to its great energy and environmental potential [1]. Notable advancements have been made in the sector, with capacity and size increasing significantly over the last decades; moving from a nominal power of 75kW to 7.5MW and rotor diameter from 17m to over 125m. Although the increase in wind turbine size has helped reduce energy costs, new instability problems have emerged due to the aeroelastic effect [1, 2].

Another important consideration is that wind turbines are highly complex engineering systems. Their analysis is so specific that currently there are few software programs capable of simulating a complete turbine in a detailed manner. The need for a specialized tool means that common optimization solutions are not easily transferred to wind turbine projects. While computational optimization techniques are widely used in the automotive and aerospace industries, much of the knowledge and methods have been adapted to meet the needs of wind blade and rotor designs [3].

An aerodynamically efficient blade is the key necessity to extract maximum power from a wind turbine [4]. Its manufacturing cost accounts for about 15-20% of the production cost of a wind turbine. Investments in research and innovations in blade design have not only enhanced turbine efficiency but also improved its structural properties [4, 5].

This work proposes a method of aerodynamic optimization constrained by the structural model, focusing on the natural vibration frequencies of wind turbine blades. Evolutionary algorithms were used to enhance the energy efficiency of wind turbines by minimizing thrust and maximizing power, while preventing structural instabilities through the constraint of the first natural frequency.

2 Materials and methods

The methodology comprises three phases: definition of the aerodynamic model via Blade Element Momentum (BEM) using the code CCBlade written in Julia, implementation of the structural analysis method via Finite Element Method (FEM) written in Python, and integration of the aerodynamic and structural models in a multi-objective optimization platform, as depicted in Figure 1.

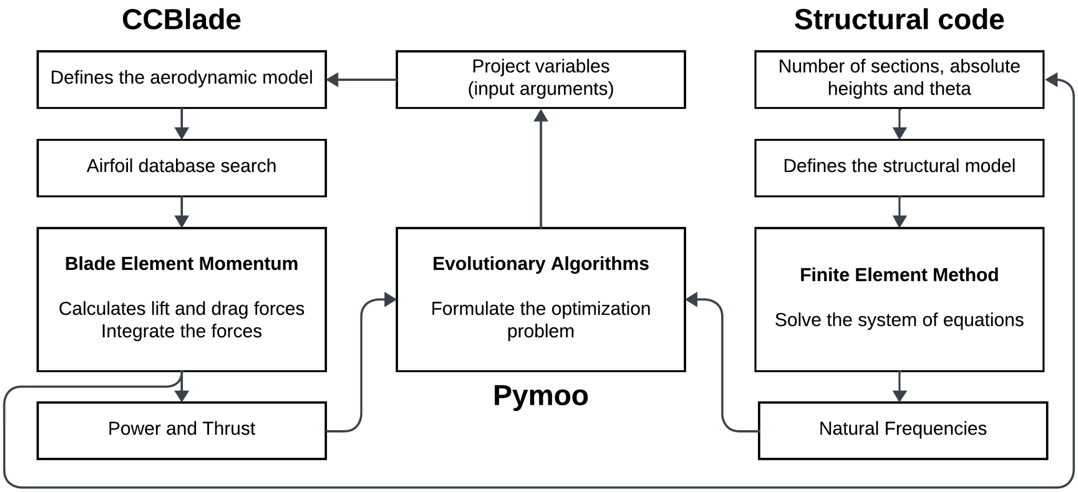

Figure 1. Coupling scheme between the aerodynamic and structural model

During the analysis of the blades by the CCBlade tool, a database consisting of 1,364 airfoils is accessed. It contains information such as the number of Reynolds, lift (C_L) and drag (C_D) coefficients, which are used to calculate the aerodynamic forces acting on the wind turbine blade.

2.1 Blade properties

The reference blades are 61.5 m long and weigh 17,740 kg. These properties are described in documentation publicly available from NREL [6]. However, studies on blade structural design require an understanding of both distributed properties and structural arrangement. Therefore, in Resor's work [7], a concept is presented that meets the most basic design criteria established by IEC (International Electrotechnical Commission) standards.

In the present work, the properties of the materials associated with each element of the blade are assumed to be homogeneous and equal to those of an equivalent material, calculated through a weighted average of the actual characteristics of the blade, as proposed in the work of Otero and Ponta [8]. Thus, through the percentage proportions of the mass of each material present in the blade, as shown in Table 1, it was possible to calculate the modulus of elasticity and the approximate density of an equivalent material, being respectively 36,503 MPa and 1,380 kg/m³.

Table 1. Coefficients in constitutive relations (adapted from [7])

Material	Density (kg/m³)	Blade mass (%)	Young's Modulus (MPa)
E-LT-5500 (UD)	1,920	13.8	41,800
Saertex (DB)	1,780	15.9	13,600
Foam	200	21.8	256
Gelcoat	1,235	0.2	3,440
SNL (Triax)	1,850	31.0	27,700
Carbon (UD)	1,220	17.4	114,500

It was also decided to develop a simplified model of the blade in which only the geometry of the spar associated with its equivalent properties is taken into consideration. Spars are structural elements of the blade that support most of the load, specifically those associated with the wind, generally composed of several layers of materials providing strength and rigidity to the blade. The spars divide the blade section into three main parts: the leading edge, main stringer, and trailing edge, creating a box-shaped structure with shear webs and spar caps that acts as a main beam, boosting flap-wise stiffness [4].

2.2 Aerodynamic model

The analysis of aerodynamic loads in our case is based on the BEM method. This method discretizes the blade into several elements and considers that all sections along the rotor are independent and can be treated separately [9]. The BEM model was originally proposed by Glauert [9], combining two theories, the Blade Element Theory (BET) with the Actuator Disc Theory [10].

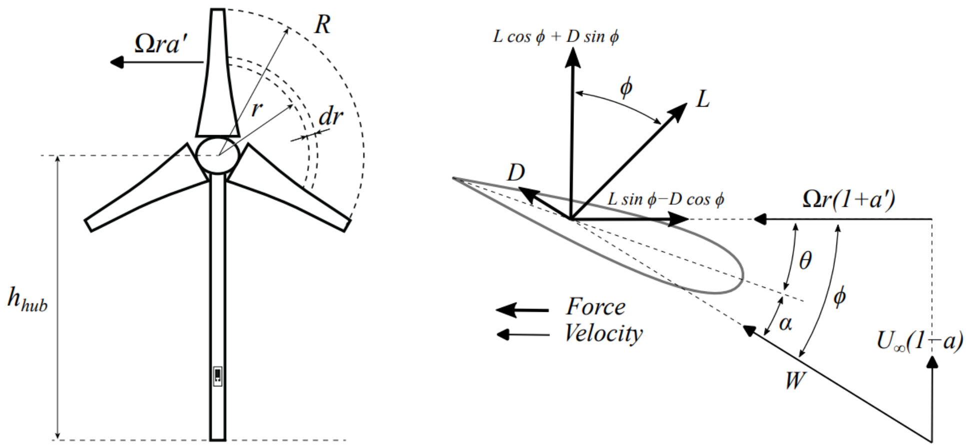

Figure 2. Forces on a blade section [11]

.

Below, the equations used in the BEM method are briefly presented. According to Figure 2, the inclination angle (ϕ) is the angle between the axial wind speed and the tangential wind speed are used to calculate relative speed:

$$W = \sqrt{U_\infty^2(1-a)^2 + (\Omega.r)^2(1+a')^2} \tag{1}$$

Aerodynamic loads respectively, lift, drag, thrust and torque are evaluated as follows:

$$L = \frac{1}{2}.\rho.W^2.c.C_L \quad D = \frac{1}{2}.\rho.W^2.c.C_D \tag{2}$$

$$F_n = L\cos\phi + D\sin\phi \quad F_t = L\sin\phi - D\cos\phi \tag{3}$$

where ρ is the density of the air, c is the chord of the aerodynamic profile, a and a' are the axial and tangential induction factors along the blade span, U_{inf} is the free-stream velocity, ω is the angular velocity, r is the radial position of the blade section

2.3 Structural model

The FEM approach finds approximate solutions through the analysis of sets of elements connected by nodes [2]. In the work of Rao and Gupta [12], the analysis of rotating Timoshenko beams with conical and twisted variations was performed using finite elements. In Oliveira's work [10], an algorithm proposed by Rao was adapted, where instead of inputs being dimensions of rectangles, areas and moments of inertia of each section were used.

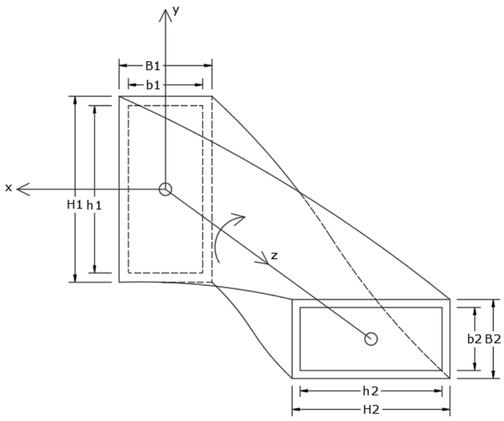

Figure 3. Rotating beam model

As the cross-section of the element changes with z and the element is twisted, the cross-sectional area A and the moments of inertia Ixx, Iyy, and Ixy will become functions of z. In the current context, considering the geometry of the spar cap and shear webs, the cross-section of the beam will no longer be solid but will become hollow. To account for this condition in the simulation, some adjustments had to be made to the calculation of the area and consequently to the coefficients c, a, and d. Now the area will be calculated by:

$$A(z) = B(z)H(z) - b(z)h(z) = c_1(\frac{z}{l})^2 + c_2\frac{z}{l} + c_3 \tag{4}$$

With the external base and height of the hollow section at point 1 being given by B_1, H_1 and internal b_1, h_1, at point 2 given by B_2, H_2 and b_2, h_2. The values of $Ix'x'$ and $Iy'y'$ can now be calculated according to the equations below, where $x'x'$ and $y'y'$ are the axes inclined at an angle θ, as shown in the Figure 3.

$$I_{x'x'}(z) = \frac{B(z)H(z)^3}{12} - \frac{b(z)h(z)^3}{12} = \frac{1}{12l^4}[a_1z^4 + a_2lz^3 + a_3l^2z^2 + a_4l^3z + a_5l^4] \tag{5}$$

$$I_{y'y'}(z) = \frac{H(z)B(z)^3}{12} - \frac{h(z)b(z)^3}{12} = \frac{1}{12l^4}[d_1z^4 + d_2lz^3 + d_3l^2z^2 + d_4l^3z + d_5l^4] \tag{6}$$

2.4 Formulation of optimization problem

When designing a wind turbine, the goal is to achieve the highest possible power output, which depends on the blade shape. Changing its design is one of the methods used to alter stiffness and stability, but it can also affect the aerodynamic efficiency of the wind turbine. The research aims to maximize power and minimize thrust. Maximizing power is a critical factor in optimal designs of wind turbine blades.

$$F_1(X) = min(Thrust) \quad F_2(X) = min(-Power) \tag{7}$$

Maximizing power and minimizing thrust are conflicting objectives in optimizing the rotor of a horizontal-axis wind turbine. The power generated by a wind turbine is proportional to the cube of the wind speed and depends on the rotor diameter and the aerodynamic efficiency of the blades. To maximize power, it is necessary to capture as much wind energy as possible, often requiring increasing the size of the rotor blades and optimizing their aerodynamic profile to enhance energy conversion efficiency. On the other hand, thrust is the horizontal force exerted by the wind on the turbine, which tends to tilt or move it. Reducing thrust is important to minimize structural wear and increase turbine longevity. To minimize thrust, it may be necessary to reduce the size of the blades or adjust the angle of attack to decrease wind resistance, potentially reducing the amount of captured energy.

Additionally, constraining the first natural vibration frequency to be above 1 Hz (eq. 8) is an excellent way to achieve structurally stable design, as it helps the frequency to stay clear of the wind's energy spectrum. This approach mitigates the occurrence of aeroelastic effects that can damage the wind turbine blade structure [5].

$$G(X) : 1st. \, Natural \; Frequency \geq 1Hz \tag{8}$$

Design variables

Certain requirements must be taken into account when determining the lower and upper limits of the variables. For example, the hub height and rotor diameter cannot be increased beyond a certain size due to structural problems, the mass of the blades and the nacelle unit, technical limitations related to installation and material stability restrictions [7].

Taking into account the complexity of the blade structure, in the current optimization problem, 15 design variables were assigned. The column matrix can be represented in the following form:

$$X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}, x_{13}, x_{14}, x_{15}]^T \tag{9}$$

The variables will be the main input arguments of the CCBlade program. Where x_1 is the hub diameter, x_2 to x_6 is the Bézier's coefficients, x_7 is the rotor diameter, x_8, x_9, x_{10}, respectively are the precone, yaw, and azimuth angles, x_{11} to x_{14} is the identification of the airfoils in the assembled database, and x_{15} the number of blades. The variables with their lower and upper limits are shown in Table 2:

Table 2. Design variables

X_n	Variables	Lower	Upper
x_1	hub [-]	0.01	0.02
x_2	y_1 [-]	0.03	0.08
x_3	y_2 [-]	0.06	0.09
x_4	y_3 [-]	0.04	0.08
x_5	y_4 [-]	0.03	0.06
x_6	y_5 [-]	0.01	0.05
x_7	rotor [m]	100	160
x_8	precone [°]	0.0	5.0
x_9	yaw [°]	0.0	5.0
x_{10}	azimuth [°]	0.0	360
x_{11}	airfoil_1 [-]	1	1,364
x_{12}	airfoil_2 [-]	1	1,364
x_{13}	airfoil_3 [-]	1	1,364
x_{14}	airfoil_4 [-]	1	1,364
x_{15}	blade [-]	2	3

3 Results and discussions

In this paper, the wind turbine blade layout selected for optimization was based on the NREL-5MW model [6]. The basic characteristics were considered when defining the properties in the subsection 2.1.

The work utilized the Pymoo platform, a cutting-edge optimization algorithm in Python for single and multiple objectives. It offers various resources for multi-objective optimization, including visualization and decision-making support [13]. Five algorithms were defined to simulate the problem and compare the results obtained: NSGA-II, AGE-MOEA, AGE-MOEA2, UNSGA-III, and RVEA.

- In the NSGA-II algorithm, individuals are first selected based on the front they belong to. Afterward, the algorithm assesses whether all individuals need to be kept alive and whether the front needs to split. If splitting occurs, solutions are chosen based on crowding distance or clustering distance. Finally, to enhance individual selection in the algorithm, a binary tournament mating selection is employed [13].
- The AGE-MOEA has the same structure as NSGA-II, but with a different formula for measuring clustering distance. Non-dominated fronts are classified, and the first front is used to normalize the objective space. Next, the geometry of the Pareto front is estimated. The procedure for enhancing individual selection is similar to NSGA-II [13].
- The AGE-MOEA2 algorithm is considered a successor to AGE-MOEA. It uses the Newton-Raphson method to more accurately estimate the geometry of the non-dominated front. Additionally, it introduces a new method to calculate diversity among generated solutions using geodesic distance, which is a generalization of Euclidean distance [13].
- The UNSGA-III is a unified algorithm that enhances the performance of NSGA-III by introducing tournament selection instead of random selection, where parents for mating are chosen randomly [13].
- In RVEA, an approach called penalized angle distance is utilized to aid in balancing convergence and diversifying solutions in the objective space. Lastly, the distribution of vectors is dynamically adjusted as an adaptation strategy [13].

The simulation of all algorithms required a computational cost of approximately 6 hours on a processor Intel(R) Core(TM) i5-10300H CPU @ 2.50GHz. The simulation parameters are listed in Table 3.

Table 3. Summary of algorithms and parameter settings

	NSGA-II	AGE-MOEA	AGE-MOEA2	UNSGA-III	RVEA
population size	100	100	100	100	100
selection	Tournament	Tournament	Tournament	Tournament	Random
crossover	Simulated Binary	Simulated Binary	Simulated Binary	Simulated Binary	Simulated Binary
crossover fraction	0.9	0.9	0.9	1.0	1.0
mutation	Polynomial	Polynomial	Polynomial	Polynomial	Polynomial
mutation probability	0.06	0.06	0.06	0.06	0.06
eliminate duplicates	True	True	True	True	True

The solutions obtained by each algorithm are shown in Figure 4. As observed, AGE-MOEA, AGE-MOEA2, and UNSGA-III algorithms have produced blade layouts that outperform the NREL baseline values for the study's specified objectives. The Inverted Generational Distance (IGD) measures the proximity of a set of solutions to the Pareto frontier by averaging the distances between each solution. Therefore, the lower the IGD value, the better the set of approximate solutions [13]. Table 4 displays the normalized IGD values of all algorithms mentioned in this paper. As shown in the Figure 4, the Multi-Criteria Decision Making (MCDM) was used, which assists in decision-making through relative weights assigned to each objective function [14]. Three weight cases were assigned for Power and Thrust: 70% and 50%; 50% and 50%; 30% and 70%.

Table 4. Inverted Generational Distance

	NSGA-II	AGE-MOEA	AGE-MOEA2	UNSGA-III	RVEA
IGD	0.94573	0.03827	0.00719	0.22389	1.0

4 Conclusions

It was possible to conclude that optimizing the design variables along the blade achieved a balanced Pareto front between energy generation and aerodynamic thrust. Expanding the search space for features such as the rotor diameter was crucial in the diversity of solutions. The AGE-MOEA2 algorithm outperformed others regarding its IGD and the diversity of solutions presented. However, despite various solutions dominating the NREL blade, this is still a preliminary analysis, the method has some limitations such as simplifying the structural model.

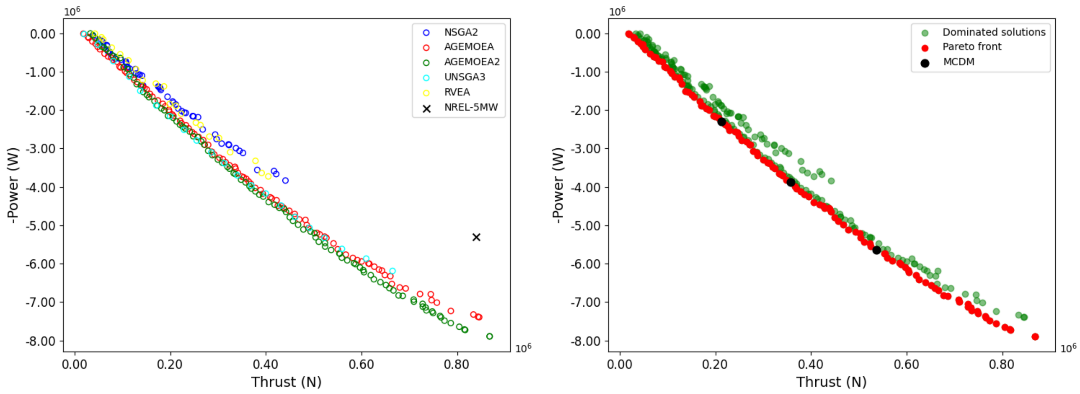

Figure 4. Multi-objective algorithm solutions and pareto front

Acknowledgements. This study was financed in part by the Coordenacão de Aperfeiçoamento de Pessoal de Nível Superior- Brazil (CAPES)- Finance Code 001, CNPq (308105/2021-4, and 303221/2022-4), FAPEMIG (APQ-00869-22 and TEC PPM-00174-18)

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] L. Wang, X. Liu, N. Renevier, M. Stables, and G. M. Hall. Nonlinear aeroelastic modelling for wind turbine blades based on blade element momentum theory and geometrically exact beam theory. *Energy*, vol. 76, pp. 487–501, 2014.

[2] L. Wang, X. Liu, and A. Kolios. State of the art in the aeroelasticity of wind turbine blades: Aeroelastic modelling. *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 195–210, 2016.

[3] M. Muskulus and S. Schafhirt. Design optimization of wind turbine support structures-a review. *Journal of Ocean and Wind Energy*, vol. 1, n. 1, pp. 12–22, 2014.

[4] J. Chen, Q. Wang, W. Z. Shen, X. Pang, S. Li, and X. Guo. Structural optimization study of composite wind turbine blade. *Materials & Design (1980-2015)*, vol. 46, pp. 247–255, 2013.

[5] M. Jureczko, M. Pawlak, and A. Meżyk. Optimisation of wind turbine blades. *Journal of materials processing technology*, vol. 167, n. 2-3, pp. 463–471, 2005.

[6] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5-mw reference wind turbine for offshore system development. Technical report, National Renewable Energy Lab.(NREL), (United States), 2009.

[7] B. R. Resor. Definition of a 5mw/61.5 m wind turbine blade reference model. Technical report, Sandia National Lab.(SNL-NM), Albuquerque, NM (United States), 2013.

[8] A. D. Otero and F. L. Ponta. Structural analysis of wind-turbine blades by a generalized timoshenko beam model. *Advances in Wind Power*, 2010.

[9] M. O. L. Hansen, J. N. Sørensen, S. Voutsinas, N. Sørensen, and H. A. Madsen. State of the art in wind turbine aerodynamics and aeroelasticity. *Progress in aerospace sciences*, vol. 42, n. 4, pp. 285–330, 2006.

[10] N. L. Oliveira, M. A. Rendón, A. C. d. C. Lemonge, and P. H. Hallak. Multi-objective optimum design of propellers using the blade element theory and evolutionary algorithms. *Evolutionary Intelligence*, pp. 1–31, 2023.

[11] F. Mazzeo, D. Micheletto, A. Talamelli, and A. Segalini. An experimental study on a wind turbine rotor affected by pitch imbalance. *Energies*, vol. 15, n. 22, pp. 8665, 2022.

[12] S. Rao and R. Gupta. Finite element vibration analysis of rotating timoshenko beams. *Journal of Sound and vibration*, vol. 242, n. 1, pp. 103–124, 2001.

[13] J. Blank and K. Deb. Pymoo: Multi-objective optimization in python. *Ieee access*, vol. 8, pp. 89497–89509, 2020.

[14] R. Parreiras and J. Vasconcelos. Decision making in multiobjective optimization aided by the multicriteria tournament decision method. *Nonlinear Analysis: Theory, Methods & Applications*, vol. 71, n. 12, 2009.