Production of small wind turbine blades by 3D printing: A developed study based on energy efficiency and renewable energy sources

Joana Queiroz[1], Alexandre Costa[2],

Carla Andrade[2] and Francisco Olímpio[3]

1 Universidade Federal do Ceará, Fortaleza (Brazil)

2 Universidade Federal do Ceará, Fortaleza (Brazil)

3 Universidade da Integração Internacional da Lusofonia Afro-Brasileira, Fortaleza (Brazil)

Abstract

This study investigates the use of 3D printing for prototyping small wind turbine blades, with an emphasis on applying the Blade Element Moment (BEM) theory to optimize aerodynamic design. The BEM theory is a widely used approach to predict the performance of wind turbines, combining two fundamental concepts: the analysis of aerodynamic forces in each section of the blade (Atom Element Theory) and the interaction of the rotor with the airflow (Moment Theory). This methodology allows the calculation of the distribution of lift and drag forces along the blade, optimizing the design for greater efficiency. In this work, a Python code was developed to apply BEM and generate the parameters necessary for the manufacture of the blades, such as the twist angle and chord distribution. The blades were prototyped using the FDM (Fused Deposition Modeling) technique, an accessible form of 3D printing that allows the creation of quick and customized models. The study proposes the use of reinforced materials, such as carbon fiber, to improve the structural strength of the blades, minimizing the typical failures of 3D printing. The research demonstrates that 3D printing, combined with BEM, offers a flexible and economical solution for the creation of small-scale wind turbines, with the potential to optimize performance and reduce production costs.

Keywords: 3D printing, Wind turbine, Renewable energy, BEM (Blade Element Momentum), Prototyping.

1. Introduction

The search for efficient and economical solutions for renewable energy generation, as discussed by Goslich (1976), has driven the development of new technologies in wind engineering. In this context, additive manufacturing, particularly 3D printing, emerges as a promising alternative for the prototyping and fabrication of wind turbine blades, especially for small-scale applications. This study explores the feasibility of using 3D printing to produce two-bladed wind turbine blades on a small scale. Two well-established aerodynamic airfoils, GOE 770 and ONERA HOR20, were selected, and a Python based computer code was developed using Blade Element Momentum (BEM) theory as used in the literature by Jauregui-Correa and Franco-Piña (2022) to optimize the blade design. The manufacturing process involved printing each blade individually, as shown in Fig. 1, followed by assembly using a 1 mm diameter carbon fiber cylinder for structural reinforcement. A total of four wind turbines were manufactured - two for each airfoil - due to the need to test two different types of engine. The turbines were subjected to wind tunnel tests, similar to the one used in Ciliberti and Nicolosi (2025), to assess their performance, as shown in Fig. 2. The results indicated that both models performed satisfactorily; however, the GOE 770 airfoil demonstrated superior efficiency for battery charging applications related to green hydrogen production. These findings reinforce the potential of 3D printing as a viable alternative for creating wind turbine prototypes, allowing for performance optimization at lower costs and greater manufacturing flexibility.

2. Methodology

The 3D printing production method has progressed in Industry 4.0 as a method of reducing production costs and optimizing time spent, presenting itself as a solution to problems originating in two extremely important fields for technological development, energy generation and industry, and has been arousing scientific interest for energy applications. The prototyping of wind turbine blades using Python and the BEM (Blade Element Momentum) theory, widely used for the design and aerodynamic analysis of wind turbines and propellers, combines two main concepts: the Blade Element Theory and Momentum Theory to define the positions of the leading and trailing edges, and QBlade software for the aerodynamic design of the blades, where the analysis focused on the relationship between

10.18086/swc.2025.06.28 Available at http://proceedings.ises.org

the stress generated and the rotation of the turbines, aiming to identify the best aerodynamic performance. Therefore, it became necessary to test and print small wind blade models, aiming to increase efficiency for better use of printing material and reduce the time spent in manufacturing each blade unit. The wind turbine blades were printed at the Aerodynamics and Renewable Energy Laboratory (LAERO) of the Federal University of Ceará (UFC) under the guidance of Professor Carla Freitas de Andrade. Given this, the research decided to use the FDM (Fused Deposition Modeling) 3D printing method, one of the most accessible printing techniques due to the low cost of inputs when using thermoplastic filaments, and popular due to the creation of objects by depositing the heated filament layer by layer in different shapes. However, layered deposition has discontinuities that can reduce the strength of the parts, so the blades were developed in such a way as to allow reinforcement with carbon fiber filament. This reinforcement acts as a spar without a tip-to-tip section of the blade, the purpose of which is to increase the strength of the assembly to shear between the layers of the print. The blade connection hub to the rotor has slots that allow the blade to be coupled without the need for a spar section (Figure 3). As shown in Figure 4, the position of the filament in the connection region with the hub and how the slots necessary for the filament to pass through were dimensioned in relation to the screws that secure the hub and the blade visually guide the process of securing the carbon spar after prototyping the airfoils. That is why the blades are printed in parts and adapted to create a rotor space, so that they can be glued together after all the parts have been printed, with the help of the carbon spar. This factor can be seen more clearly in the printing of thinner blades, which require a more "delicate" finish and therefore more delicate printing, an example of which is the ONERA model. It is worth noting that, as it is a simple and easy-to-use raw material, the adhesives generally used to join the parts that make up the blades into a single complete set are super glue (cyanoacrylate), popularly known as SuperBonder, and two-component epoxy, which is usually used on larger objects as it is more resistant and fills gaps in spaces. The Python language was used as a tool to define the positions of the leading and trailing edges for each profile layer. The code developed also defines the size of the chord and angle β (twist) for each section of the blade. Based on the compilation results, the data can be entered into the QBlade software to build the blade model. BEM (Blade Element Momentum) is a widely used theory for the design and aerodynamic analysis of wind turbines and propellers. It combines two main concepts: Blade Element Theory and Momentum Theory. The BEM provides a simplified but effective approach to estimating the performance of wind turbines by calculating aerodynamic forces on sections of a blade and considering the effect of the interaction between the blade and the airflow. Thus, the developed algorithm depends on some data that must be entered by the user, which are: Blade radius value (given in cm); Tip Speed Ratio, TSR, which is a design-dependent factor; Number of blades, n; Optimal lift coefficient, CLopt; Number of sections in the blade; Axial factor, which was set at 1/3; Camber, prot; Optimal angle of attack, αotx. From the data provided, the algorithm defines the values of z_escape and z_attack, which are the values on the z-axis for the trailing and leading edges of each section of the blade. In addition, the values of the chord and angle β (twist) are defined.

3. Results And Discussion

Considering the sequence of practical activities that address the modeling and prototyping of small wind blades on the Ender 3 S1-pro 3D printer, whose efficiency and energy utilization were tested in the Wind Tunnel at the State University of Ceará (UECE). The GOE 770 model was designed and tested at two different pitch angles, +3 and -3, while the ONERA set focused on only one pitch angle, -3. The blade using the ONERA profile was printed in four parts, considering a two-blade turbine model. This is due to its thin design, which makes more accurate printing difficult. However, the blade using the GOE 770 profile, being more robust, was able to be printed in only two parts, considering a two-blade turbine model. For the GOE 770 -3 profile, it was noted that the printing parameters used in the previous blades worked perfectly for our objective and were the most efficient printing code in this test phase. Therefore, the same printing process was used as for GOE 770 +3, in addition to being the same model at different pitch angles. The print settings used by the ONERA model are as follows: 20% infill; layer thickness of 0.3mm; wall thickness of 1.2mm; wall line count of 3; triangular infill pattern; nozzle temperature of 230°C and base temperature of 60°C. The printing speed averaged 75 mm/s, with the entire print taking 6 hours and 42 minutes. As for the GOE 770 airfoil, it was noted that there was no change in the printing parameters, however, there were changes because it is a more robust blade model, so both blades that made up the set were printed in a total time of 5h 2min and 5h5min, respectively. By submitting the blade sets to wind tunnel testing, it is possible to measure the resistance of the blades by applying different wind speeds, and therefore different forces. The time before material rupture, deformation, and various energy outputs are measured. Through this test, it is possible to determine which model is more viable and economically efficient, also modifying the printing parameters used. In this context, the tests indicated that the GOE 770 airfoil demonstrated superior efficiency for battery charging applications related to green hydrogen production than the ONERA model.

4. Tables, figures, equations, and lists

3.1. Tables

The following tables (Tab.1, Tab.2, and Tab.3) show the results obtained in the wind tunnel test.

Table 1: Starting Speed of Models (3 pt)

Models	Starting Speed (m/s)	Speed After Stabilization (m/s)
GOE 770 G1360	5.34	4.9
GOE 770 G915	7.4	6.7
ONERA HOR20 G1360	5.6	5.3
ONERA HOR20 G915	7.3	7.15

Table 2: G1360 Motor Results at 5m/s (3 pt)

Models	Revolutions per minute (RPM)	Voltage (V)
GOE 770 G1360	973	16.5
ONERA HOR20 G1360	867	14.8

Table 3: G1360 Motor Results at 6m/s (3 pt)

Models	Revolutions per minute (RPM)	Voltage (V)
GOE 770 G1360	1240	21.1
ONERA HOR20 G1360	1050	17.7

3.2. Figures

Fig. 1: 3D Printing of The GOE 770 Model

Fig. 1 shows the blade made from the GOE 770 profile immediately after 3D printing, made in PLA in 5 hours of printing

Fig. 2: 3D Printing in Wind Tunnel Test

Fig. 2 shows a prototype being tested in a wind tunnel while charging a battery used to produce green hydrogen.

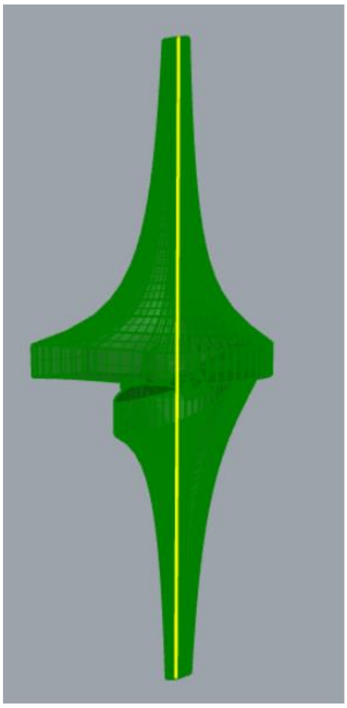

Fig. 3: Visualization of the internal position of the carbon spar in the airfoils

Fig. 3 shows that, using computational fluid dynamics, the carbon spar is attached to the assembled blade assembly.

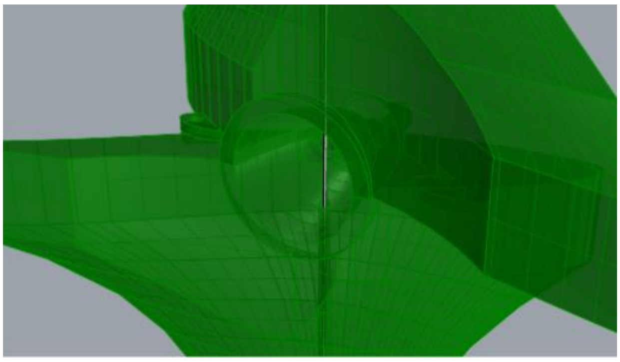

Fig. 4: Position of the reinforcement filament in the coupling region of the blade with the hub

Fig. 4 also uses computational fluid dynamics to show the assembly of the cube with the spar.

3.3 Equations

Using BEM, based on the data provided, the algorithm defines the values of z_ trailing edge and z_ leading edge, which are the values on the z-axis for the trailing and leading edges of each section of the blade. In addition, the values of the chord and angle β (twist) are defined. This data can then be entered into the QBlade software to construct the blade design.

The formula for calculating theradial interference factor is given by:

$$-a' = \frac{\text{fator axial}\cdot(1-\text{fator axial})}{(\text{TSR}\cdot\mu)^2}\} \quad (1)$$

Where μ is given by the fraction in relation to the total radius size, that is:

$$\mu = \frac{r}{\text{raio}} \quad (2)$$

And TSR is the ratio between the tangential speed of the turbine blade tip and the wind speed (this relationship is described in Equation 3). It describes how fast the blade tip is moving relative to the wind. This parameter is crucial in the design and operation of wind turbines, as it directly influences the efficiency of energy conversion and the operational stability of the turbine.

$$\lambda = \frac{\omega \cdot \text{raio}}{U} \quad (3)$$

The formula for calculating the angle φ (paddle angle) in radians is:

$$\phi = \arctan\left(\frac{1 - \text{fator axial}}{\text{TSR} \cdot \mu \cdot (1 + a')}\right) \quad (4)$$

The conversion of angle φ to degrees is:

$$\phi = \deg r\,ees\left(\arctan\left(\frac{1 - \text{fator axial}}{\text{TSR} \cdot \mu \cdot (1 + a')}\right)\right) \quad (5)$$

The formula for calculating angle β (twist) is:

$$\beta = \phi - \alpha_{\text{ot}} \quad (6)$$

Given that the chord, c, is given by:

$$c = \frac{8\pi \cdot \text{raio} \cdot (\text{TSR} \cdot \mu)^2 \cdot a'}{\text{TSR} \cdot n \cdot C_{L\text{opt}} \cdot \sqrt{(1 - \text{fator axial})^2 + (\text{TSR} \cdot \mu \cdot (1 + a'))^2}} \text{\^{}2\}\}} \quad (7)$$

Each rope value is divided by 100 so that it is in meters (the unit in which the data must be entered into QBlade).

The attack and escape coordinates are calculated as follows:

$$x_{\text{ataque}} = \cos(360° - \beta) \cdot \text{prot} \cdot c \quad (8)$$

$$y_{\text{ataque}} = \sin(360° - \beta) \cdot \text{prot} \cdot c \quad (9)$$

$$z_{\text{ataque}} = \frac{\mu \cdot \text{raio}}{100} \quad (10)$$

$$x_{\text{fuga}} = \cos(180° - \beta) \cdot c \cdot (1 - \text{prot}) \quad (11)$$

$$y_{\text{fuga}} = \sin(180° - \beta) \cdot c \cdot (1 - \text{prot}) \quad (12)$$

$$z_{\text{fuga}} = \frac{\mu \cdot \text{raio}}{100} \quad (13)$$

The z_attack and z_escape are divided by 100 to convert them to meters, the unit accepted by QBlade. The code has a graphical interface based on the customtkinter library. This means that anyone, even those who do not know how to program, can use the algorithm for prototyping projects.

3.4 Lists

List 1 shows the 3D printing parameters used in the manufacture of the GOE 770 and ONERA airfoils.

- Layer thickness: 0.3mm
- Infill density: 15
- Printing temperature: 225°C
- Nozzle temperature: 70°C
- Printing speed: 65mm/s

- No bed
- Infill pattern: triangles
- Printing time for GOE 770 blades: 5 hours 2 minutes and 5 hours 5 minutes, respectively.
- Printing time for ONERA blades: 6 hours and 42 minutes.

5. Conclusion

The study confirmed the viability of 3D printing as an efficient and affordable alternative for developing small-scale wind turbine blades. Applying Blade Element Momentum (BEM) theory in conjunction with QBlade software made it possible to optimize blade design and analyze the aerodynamic behavior of different profiles. Wind tunnel tests showed that the GOE 770 profile performed better and was more efficient for power generation applications focused on battery charging and green hydrogen production when compared to the ONERA HOR20 profile. The fused deposition modeling (FDM) manufacturing process proved to be suitable, especially with carbon fiber reinforcement, which increased structural strength and reduced flaws in the printed layers. This combination ensured a good balance between cost, manufacturing time, and mechanical performance, while also allowing for greater flexibility in the prototyping process. It is concluded that the integration of computational modeling, aerodynamic optimization, and additive manufacturing represents a promising solution for the advancement of small wind turbines, favoring the development of sustainable, low-cost technologies applicable to different energy contexts.

6. Acknowledgments

FUNCAP - Ceará Foundation for Scientific and Technological Development (Research and Innovation Network on Renewable Energy, Rede VERDES, grant 07548003/2023), CNPq – National Research Council, Universal - Proc. No. 408431/2023-7 and Research Productivity Grant Proc. No. 307096/2021-1.

7. References

Goslich, -D.H. (1976). Energy from the wind: an economic method to make use of wind power.

Jauregui-Correa, J.C., Franco-Pinã, J.A., Design Process for Scaled Model Wind Turbines Using Field Measurements. Journal of Fluids Engineering, 147 (3), 031107. https://doi.org/10.1115/1.4067387

Ciliberti, D., Nicolosi, F., 2025. Lateral-directional wind tunnel tests of the PROSIB 19-pax aircraft model. Advances in Aerodynamics, 7(3). https://link.springer.com/article/10.1186/s42774-024-00189-x