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Aerodynamic Comparison of Conventional and Bioinspired Turbines for Enhanced Wind Energy Applications in Low Wind Conditions

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Abstract. Wind energy is projected to account for 35% of global production by 2050, with a significant contribution from large wind farms located in high-wind-speed areas. However, in low-wind regions, it is necessary to adapt turbines to maximize efficiency. This has led to the development of blades based on biomimetic principles, which improve performance in such conditions. To validate this approach, a comparative aerodynamic analysis is proposed between a conventional and a bio-inspired turbine. The proposed methodology involves using Computational Fluid Dynamics (CFD) simulations and Blade Element Momentum Theory (BEMT) to predict the behavior of both designs. Variables such as power coefficients (Cp), thrust (Ct), axial force, and torque are evaluated, comparing the performance of the rotors under identical conditions. The goal is to determine the feasibility of bio-inspired turbines and their adaptation to horizontal-axis wind turbines at low wind speeds, starting from 2.5 m/s. The results, validated in CFD and BEMT simulations, show that bio-inspired turbines have up to 33% higher performance compared to conventional rotors, highlighting their potential to improve wind energy efficiency under adverse environmental conditions, especially in regions where wind speeds are low or inconsistent. This demonstrates the viability of bio-inspired designs in enhancing renewable energy technologies.

1 Introduction

The use of Renewable Energy sources (RE's) is an excellent alternative to satisfy future energy demands and the needs of a growing population while minimizing environmental impact [3]. Among these, wind energy stands out for its endless supply and significant economic and ecological advantages over traditional sources [4], diversifying the energy matrices of countries [5]. As high-wind speed sites become scarcer due to the expansion of wind farms, there is growing interest in low- and medium-wind speed areas. The residential sector offers a promising opportunity, given its energy needs and typically low wind

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velocities. Nature-inspired turbine designs have emerged to optimize aerodynamic performance in various wind conditions. In urban settings, microgeneration through wind energy is gaining relevance. Recent studies [11] emphasize the potential of urban wind turbines in contributing to small-scale renewable energy (RE), designed to operate efficiently in variable urban wind conditions. These turbines promise benefits such as reduced dependence on conventional energy sources and seamless integration with urban infrastructure. Bioinspired turbine designs, in particular, take advantage of principles from nature to enhance efficiency and adaptability in low-wind speed environments [16]. For example, [1] investigates the use of tubercle geometry at the leading edge of the blade, improving momentum transfer, lift, and drag reduction. [6] presents a numerical analysis of a bioinspired helical rotor effective at wind speeds as low as 2 m/s, suitable for urban areas. These advances reflect the growing interest in optimizing turbine design by numerical and experimental methods using two key methods: blade element momentum theory (BEMT) and computational fluid dynamics (CFD). BEMT calculates blade efficiency by dividing them into sections and analyzing wind interaction, while CFD simulates airflow to assess design variations [17]. As can be evidenced in [7], a wind turbine is developed that allows adaptively changing its shape under static and low or high-speed conditions, and the performance of the proposed turbine is validated through the CFD numerical simulation method combined with physical experiments. In [2], a bio-inspired blade design based on birds improved efficiency across various tip speed ratios (λ) through CFD validation and optimization, increasing power output robustness by 8.1% compared to conventional BEMT blades, highlighting the potential of biomimetic designs in wind applications.

Interest has grown in exploiting medium and low wind speed zones, creating opportunities for biologically inspired designs like those mimicking the tubercles on humpback whale fins. These tubercles, when fitted to the leading edge of the turbine blades, function as passive flow control devices, enhancing lift and reducing drag, thus improving overall turbine performance in low wind conditions [12]. In this context, our study will explore the adaptation of these bioinspired features, particularly their application to wind turbines, and how they can significantly improve performance and maneuverability in environments characterized by low wind speeds [13, 14]. Furthermore, the potential applications of these cutting-edge tubercles extend beyond wind turbines, offering valuable information for the design of ships, aircraft, fans, and other flow-based systems [15].

2 Approach

The methodological steps to analyze the bioinspired blade using CFD and BEMT are presented (Fig. 1). First, the case study is defined by characterizing the context of the experiment and its causes and determining the differentiating factor of the research.

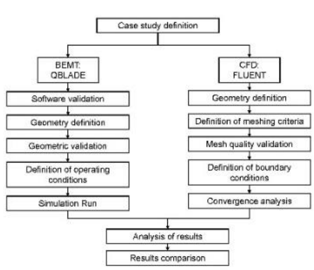

Fig 1. Methodology

Then, the software is analyzed as strategies to predict the behavior and performance of a turbine [8], and finally, the results obtained in each simulation method are analyzed. Each of these steps will be discussed in detail in the following sections.

3 Implementation

3.1 Case of study

A conventional bioinspired turbine design is presented (Fig. 2) by implementing air foils such as 4420 for the Root and 4412 for the remaining blade and undulations at the leading edge, regarding a standard rotor designed entirely of 4412 in an optimized manner (Fig. 2). The bioinspiration principle must be validated by implementing leading-edge protrusions to generate more torque and subsequent generation. This will require rotor reconstruction in Qblade software for the BEMT model and fine meshing in Ansys Fluent for the CFD model. These rotors were extracted from AlbatrosCreate software designed by [10], with 1.2m rotor diameter, cut-in of 2.5m/s, and cut-out of 10 - 15 m / s.

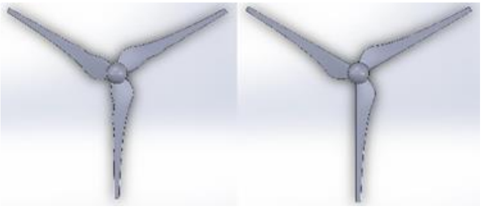

Fig 2. Bio-inspired Wavy Leading Edge Blade and Conventional Blade, respectively.

3.2 BEMT: Qblade.

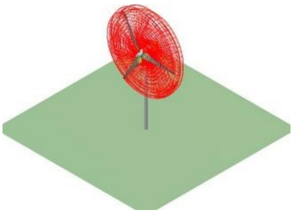

Fig 3. BEMT simulation

Initially, it must be ensured that the software handling is adequate. For this, a software validation will be performed on an experimental case of the literature, comparing torque, Ct, Cp, and power by analyzing the relative error concerning the experimental study and then the global relative error. When validating an error lower than 5%, subsequent studies will use the Qblade software. A 3D reconstruction using Qblade will be used for the bioinspired turbine. Depending on the case study, it is necessary to generate a 3D comparison of the surface offset between the blade reconstruction in BEMT methods and the CAD modeling software, as it tends to smooth the surface more accurately and vary significantly due to the condition between the chord line and thickness. Then, the conditions and operating ranges of the model are defined: angular velocity, linear velocity, density, kinematic viscosity, absolute pressure, and the appropriate number of Reynolds to move from a 2D to a 3D model with motion. Results related to variables such as the thrust coefficient (Ct), the power coefficient (Cp), and the generated power and torque were obtained to compare both rotors.

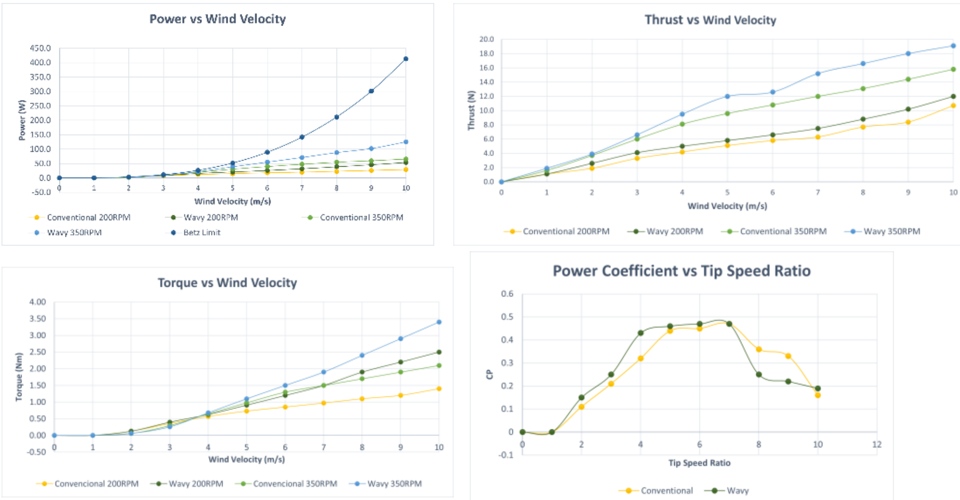

Fig 4. General Results BEMT model Qblade

The results of BEMT simulations show that bioinspired turbines significantly outperform conventional turbines, especially in low wind conditions. The bioinspired turbine generates more power and axial thrust, indicating higher aerodynamic efficiency and better performance in typically unfavorable conditions. At 200 RPM and 3 m/s, the bioinspired turbine achieves 54 W, while the conventional one only 29 W; at 10 m/s, it produces 125 W versus 66 W. The axial thrust is also superior, reaching 12.0 N at 200 RPM and 10 m/s, versus 10.7 N and 19.1 N at 350 RPM compared to 15.8 N. In addition, the maximum power coefficient (Cp) for the bioinspired turbine is 0.47, higher than the 0.45 of the conventional.

3.3 CFD: Ansys Fluent

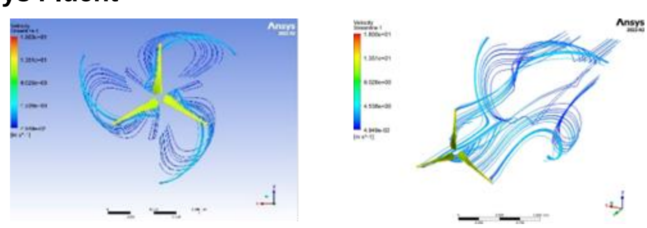

Fig 5. Ansys Fluent Streamlines Visualization

To set up the analysis in Ansys Fluent, it is first necessary to understand the case study conditions. This includes defining the flow domain and the CAD model to create the turbine blade mesh, ensuring it is well-refined. The mesh should have an inflation layer of at least ten layers and an adequate minimum element size on the blade surface to ensure accuracy. The quality of the mesh is verified by measures such as the aspect ratio, element quality, and asymmetry, following the recommendations of [9]. Then, the turbulence model is configured [17]. In this case, the SST k-omega model derived from RANS (Time-Averaged Navier-Stokes Equations) is used since it is effective in predicting flows near the blade surface and in separate areas combining near-surface and free-flow approaches [18]. It is estimated based on the mass conservation principle that the residuals are sufficiently small (close to 1e-6), and a considerable number of initial iterations are used to reach convergence. If the system shows adequate convergence, the results are validated by calculating the static pressure coefficient (SPC) at a point, which, being close to one, shows a stagnation point and, therefore, a reliable simulation. Thus, we proceed to extract variables such as the axial force to generate the calculation of Ct, and, likewise, the torque to calculate Cp. Finally, a general and comparative analysis of the results between both simulations is performed to interpret the feasibility of the case study.

Table 1. Results Comparative Analysis Simulation

Constant Parameters			
Diameter [m]	1.2		
Area [m2]	1.1310		
TSR	7.2		
ω [rad/s]	30		
Wind velocity [m/s]	2.5		
Analysis variables	**Wavy**	**Conv**	**Difference [%]**
Axial force [N]	1.3579	1.0908	24%
M [Nm]	0.040	0.030	33%
Ct	0.7841	0.6299	24%
Cp	0.11087	0.0832	33%
P [W]	1.2	0.9	33%

The analysis shows that the Wavy design outperforms the Conventional in several key parameters. With differences of 0.2671N for axial force, 0.3W difference in theoretical power output, and 0.02767 in power coefficient, it is possible to analyze that the bio-inspired turbine design (Wavy Leading Edge) stands out in comparison to the conventional turbine evaluated by offering better performance in terms of thrust, power and efficiency.

4 Conclusions

The comparative study between conventional and bioinspired turbines highlights that bioinspired designs can significantly improve aerodynamic efficiency and power generation, especially in low-wind conditions. Specifically, the bioinspired turbine demonstrated an 86% increase in power generation at 200 RPM, producing 54 W at 10 m/s versus 29 W for the conventional turbine. At 350 RPM, this improvement was even more pronounced, with the bioinspired turbine producing up to 89% more power at 10 m/s (125 W vs. 66 W). The bioinspired turbine also showed a 12.1% increase in axial thrust at 200 RPM and 10 m/s, reaching 12.0 N versus 10.7 N for the conventional turbine. At 350 RPM, it produced 19.1 N thrust, an improvement of 18.7% improvement over the 15.8 N of the conventional turbine. The power coefficient (Cp) of the bioinspired turbine was 4.4% higher, reaching 0.47 versus the maximum of 0.45 for the conventional turbine. CFD analysis revealed a 33% improvement in Cp and moments for the bioinspired turbine, underlining its superior aerodynamic performance, in addition to a 24% difference between thrust coefficients and axial forces, which positively impacts aerodynamic behavior, benefiting lift and drag efficiency. These results highlight not only the effectiveness of bioinspired turbines but also their potential to change the way we produce wind energy. By adopting these innovative designs, we could make better use of wind resources in less windy areas and drive the transition to more sustainable and efficient energy systems. This evolution in turbine design could open new opportunities for renewable energy and inspire future innovations in this field.

5 Future work

To further validate and refine the results, future research should focus on several key areas. This includes conducting a more comprehensive validation of the 3D models used in BEMT and expanding the range of wind speeds and angular velocities evaluated to cover a broader set of operational conditions. Additionally, refining the mesh used in CFD simulations will improve the accuracy of the results. It is also crucial to evaluate different turbulence models to better capture complex flow dynamics. Introducing dynamic models that account for temporal variations in wind conditions can affect turbine performance. Finally, expanding simulations to include a greater variety of operating parameters and environmental conditions will provide a more complete evaluation.

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