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Wind Turbine Performance Enhancement by Geometrically Bio-Inspired Blade Design Based on Flying Seeds

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Abstract

Given the escalating demand for energy resources, it is imperative to diversify renewable energy options while concurrently enhancing their efficiency to bolster competitiveness against conventional fossil fuel-based sources. Furthermore, decentralized energy generation, situated closer to consumers, assumes significance. In this context, the deployment of small wind turbines in urban settings emerges as a focal point of this study. To devise a small wind turbine capable of functioning effectively amidst variable urban air currents, a bio-inspired design approach was adopted. Brazilian forest flying seeds were selected as a basis for optimizing the geometry of vertical wind turbine blades. The urban public transport corridors, characterized by air currents reaching speeds of up to 6 m/min, were chosen as the designated environment for the turbine's design. Consequently, the development, production, and testing of a small vertical turbine yielded promising

results, demonstrating an energy generation capability up to 100% higher than conventional geometries.

Keywords: Bioinspired Design, Flying Seeds, Renewable Sources, Wind Generator

1. Introduction

The increasing global population necessitates proactive measures to ensure the sustainability of energy resources across diverse sectors of society. Consequently, there is a mounting demand for innovative energy sources, particularly renewables, to mitigate reliance on fossil fuels and curb carbon dioxide emissions [1].

Carbon dioxide emissions stand as a significant contributor to greenhouse gases and subsequent global warming trends. In response to the escalating global energy crisis and escalating environmental degradation, the promotion of clean energy, notably renewables, emerges as a pivotal strategy to diminish fossil fuel consumption while enhancing energy efficiency and curbing carbon emissions [2].

In recent years, governmental bodies and research institutions have prioritized the development of energy generation systems rooted in clean and renewable sources, such as hydrogen, wind, and solar energy [3].

Wind energy stands out as a clean energy production owing to its relatively low effective cost. The rapid proliferation of wind turbines underscores their capacity to generate carbon-free energy at a competitive price.

Historically, wind energy utilization dates back millennia, with ancient civilizations harnessing wind power for various applications, such as sailboats, water-pumping mills, and grain-crushing windmills [4]. Nonetheless, the inherently unstable nature of wind, characterized by turbulence and rapid fluctuations in speed and direction, has spurred the development of diverse turbine designs aimed at optimizing performance [5].

A advantageous way to clean energy production is windy energy because of its lower effective cost. For this reason, the use of wind turbines has been growing quickly, due to the ability of this type of equipment, to produce energy in a clean (carbon-free) way and at a competitive cost.

There are reports that, in 3,500 BC, the Egyptians used boats propelled by the wind (sailboats). Around 2,000 BC, the Chinese were already using wind energy to drive a mill to pump water. In turn, between 500 to 900 AD, the Persians designed windmills to be

used to crush grain . Since then, the use of energy sourced from air currents has increased remarkably, and nowadays the study of this type of equipment has intensified [6].

On the other hand, the unstable characteristic of wind, associated with its levels of turbulence, usually resulting in air flows characterised by rapid changes in the speed and direction, has led to the development of various constructive types of turbines to improve their performance [7].

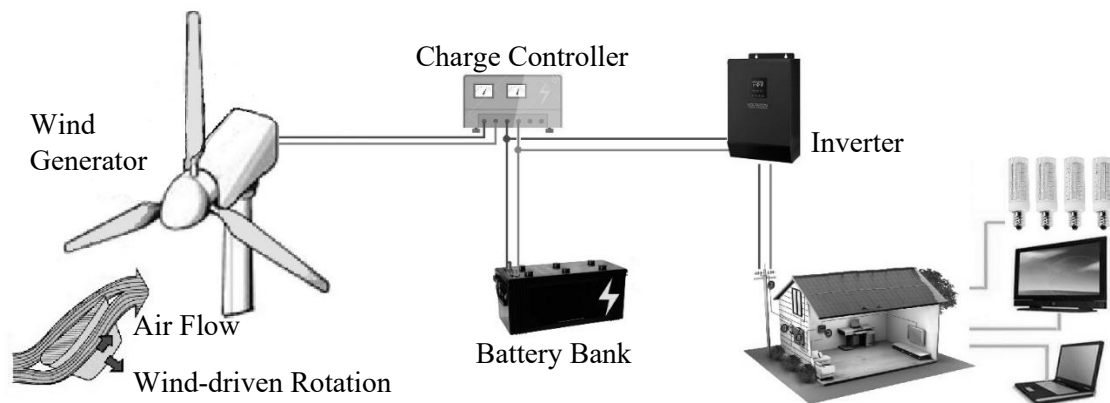


Figure 1. Typical design of horizontal shaft rotor wind turbines and principle of converting air flow into rotor motion.

1.1 Types of wind turbines

Modern wind turbines can be classified into two major groups depending on the orientation of the axis of rotation: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [8].

HAWTs have dominated the wind energy industry for several decades. However, HAWTs have some inherent problems, such as size limits due to blade-induced stresses and deficiencies under turbulent flows [9]. In turn, when comparing the latter to the vertical shaft type, some advantages can be enumerated, such as, not needing to include a yaw mechanism to adjust the rotor to changing wind direction, easy maintenance due to the location of the gearbox and generator system at the base of the turbine, as well as potentially better performance under unstable and tilted wind conditions. Figure 1 shows examples of the main kind of use for wind energy.

Thus, it can be stated that vertical-axis wind turbines (VAWTs) may be more suitable for urban applications due to several distinct advantages they have over conventional horizontal-axis wind turbines.

According to Rubio et al. [5], VAWTs can be classified into two basic categories based on the forces driving the rotor blades, namely, drag-driven Savonius VAWTs and lift-driven Darrieus VAWTs. The author affirmed that the Savonius VAWTs have lower efficiency in the transformation of wind energy resources than the Darrieus VAWT. It could be attributed to the lower torque generated at low wind speeds. However, the Savonius-type is constructively simpler and has lower manufacturing cost.

The Savonius rotor was developed by the Finnish engineer Sigurd J. Savonius in 1922 and patented in 1929, it is characterised by the conversion of wind energy into mechanical energy driven by the aerodynamic drag [10]. As it can be seen in Figure 2 (a), the Savonius rotor is one of the simplest wind turbines, which has a similar shape to the letter S. In addition, it is possible to see the principle of operation of Savonius VAWT and Darrieus VAWTs.

Darrieus VAWTs produce energy by passing airflow through a blade with airfoil shape geometry, where the yaw motion arises due to the presence of pressure difference. Figure 3 shows three basic types of VAWTs: (b) Egg-beater, (c) H-rotor and (c) Helical VAWTs.

Although VAWTs have a simple structural configuration, their aerodynamic analysis shows complexities, mainly because the attack angle of VAWTs experiences constant changes within each revolution, unlike HAWTs. This characteristic induces the emergence of vortices from the leading and trailing edges of the blades, which causes load fluctuations on the blades, which can mean operation oscillations, noise, and even blade fatigue [8].

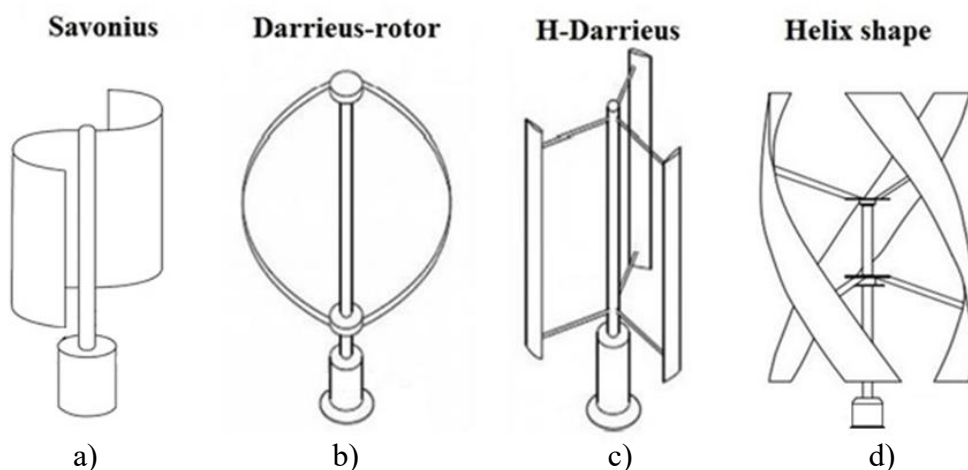


Figure 3. Schematic of a (a) Savonius VAWT, (b) Egg-beater VAWTs, (c) H-rotor VAWT, and (d) Helical VAWTs.

On the other hand, there is considerable airflow in urban areas with a great potential for power generation, such as those that happen in road dividers, the side of railway tracks, and the top and around high-rise buildings. Thus, the development of an efficient wind energy system closer to the point of use (customer) meeting the demand for local power, reducing the use of the electricity generated in non-sustainable ways, reducing the possibility of overloading the system at the existing grid infrastructure, adding a sustainable bias into the cities, supports the local economy and taking the environmental care into account [11].

Thus, due to the positive characteristics of this type of turbine, several authors have been studying the factors and parameters that influence its performance for power generation.

Torresi et al. [10] describe the experimental evaluation of a Savonius rotor connected to an AC brushless servo motor when it is submitted to an unsteady flow field. The authors directly obtained the torque measurements from the Servo Amplifier torque monitor. Results show that since the rotor has a geometrical symmetry of 180° , it is characterised by a lack of periodicity every half revolution due to the complex interaction of the vortex shedding during the rotating buckets (See Figure 2 a).

The second style of vertical-axis wind turbine (VAWT) design is characterised by the vertical arrangement of the blade axis concerning the wind flow (stream). Figure 2(c) shows the Darrieus-type turbine, idealised by the French engineer Georges Darrieus who patented the design in 1931 [12].

Danao et al. [7] used a wind tunnel to evaluate the performance of a vertical-axis wind turbine when unsteady wind conditions are applied. The authors tested wind velocities of 6, 7, and 8 m/s. The results showed that the unsteady power coefficient fluctuates following the changes in wind speed. So, small amplitudes have no effect on the cycle power coefficient.

Eriksson et al. [13] compared the performance of three different wind turbines; one horizontal axis wind turbine and two different concepts of vertical axis wind turbines; the Darrieus turbine and the H-rotor. Aspects such as structural dynamics, control systems, maintenance, manufacturing, and electrical equipment were evaluated. The authors affirmed that the vertical axis wind turbine appears more advantageous when compared

with the horizontal axis wind turbine in several aspects. It shows the best power coefficient (aerodynamic efficiency) to the higher range of the tip speed ratio (λ),

Peng et al. [3] studied several aspects of vertical wind turbine operations, the analysis by computational fluid dynamics (CFD) simulations, and their field tests comparison. The analysed results showed that if the tip vortices are alleviated and redirected towards midspans, both the power efficiency and the wake recovery (free stream conditions) of turbines can be noticeably improved.

According to Kumar et al. [11], the limited acceptance of VAWTs is due to incomplete performance and the absence of precise resource assessment tools. Also, they affirmed that new research is crucial in making VAWTs a viable, dependable, and affordable power solution, for example, for people without access to a minimum level of electricity. Thus, the authors show tests with Savonius-type turbines with different blade configurations for rotational performances. The straight blade design was found to have the least rotational performance (RPM) while the best performance was recorded for the curved blade type.

On the other hand, Griffith et al. [14] address the subject of offshore wind use, in this case, the floating VAWTs appear as a potential technology solution to reduce costs and increase performance. The authors explored the performance and cost associated with the design space for floating VAWTs by the study of the rotor configurations and platform fixing. Once the RPM is a key design variable impacting all aspects of the design, aerodynamic loads, drivetrain sizing, platform dynamic loads, and structural dynamic resonance, the VAWT option comes as the best option because it is compact and has a modular design.

Normally, this equipment can have its performance improved by remodelling and/or re-designed or even new designs. It can be made by varying the design, the materials composition, the manufacturing process, eliminating bond lines, changing the disassembly design to reduce transport cost, increasing configuration options, and there are some new technologies and developments in conversion systems, among others.

For this purpose, several works have been published, but there is not much research focused on the application of new design methodologies, especially those aimed at innovation.

To increase the efficiency of the gear-driven generator, Puri et al. [15], have applied the design optimization methodologies based on the use of nature-inspired algorithms to solve optimization problems, namely, gravitational search algorithm (GSA), and particle

swarm optimization (PSO). Aspects such as temperature rise, efficiency, regulation, and maximum flux density in stator teeth were taken as targets for optimization of the design.

Joustra et al. [16] used a methodology called Design Inclusive Research and also applied concepts of Circular Product Design in the development process to the large wind turbine blades. According to the authors, the current designs do not take structural reuse into account, even though the potential of this recovery strategy can be an important goal in the future, and mainly the methodology addressed, which regards the act of design as essential for the circular economy, in particular when the design assignment can be carried out by the researcher himself.

On the other hand, some authors have suggested solutions for optimising the wind generator design by applying biological concepts found in nature's evolutionary solutions. As mentioned by Johnson [6], biomimicry can be used as an alternative to improve the design of wind generators in specific situations.



Figure 3. Features of the owl's wing to guarantee noiseless flight (right), Graphical example of the flow that occurs in the humpback whale dorsal fin (left).

In turn, Meder et al. [17] studied the effects of wind-induced mechanical interactions in the leaf of a plant (*Rhododendron*) on energy production and also if the performance can be replicated by artificial leaves. The results showed that bioinspired wind generators based on plant leaves can be used as small autonomous energy sources.

Thus, this work mainly involves the development and evaluation of a vertical axis wind micro-turbine (VAWT) which aims to use the air currents in urban bus routes. To improve the performance of this VAWT, the application of concepts from Biomimetics are used to reduce the vibration caused by the vortices that arise during blade rotation.

2. Biomimetic and Bioinspired Developments

Scientists and engineers have been increasingly turning toward nature in search of design inspiration to solve problems and create innovative products. Essentially, biomimetics is about the application of methods and systems found in nature to engineering and technology. It has produced many innovations with superior features to other solutions created by conventional methods [18].

This can be attributed to the fact that nature has been evolving for billions of years. Thus, it has produced effective solutions to innumerable complicated real-world problems. The rigorous competition of natural selection means that waste and inefficiency are not tolerated in natural systems, unlike many of the technologies developed by humans.

Since owls are night-time predators, they should have a silent approach flight to capture their prey. Thus, the owls have devolved mechanisms that reduce noise during flight. According to Wei et al. [19], the secret lies within their feather structures, which have sharp edges along their fronts (serrations), which are in contact with the air during flight. These serrations break up the air turbulence that normally causes wind noise, reducing the noise generated during flight, as showed in Figure 3 (a). Based on this feature, one of the most widespread examples of biomimicry is the use of this capability to reduce noise on the Japanese Shinkansen high-speed train.

Over the past years, several authors have been approaching the subject of energy generation systems performance improvement, both those which use the flow of water and wind power, by associating the design of seawater or flying animals to better performance in energy conversion.

Huera & Gharib [20] carried out a study by observing the role of the trailing edge region near the back of a flipper in fish propulsion. The authors have used a simplified robotic system to demonstrate that the continuous variation of the trailing edge angle at the back of the fin modifies the propulsive performance substantially.

Inspired by bird wings that enable robust aerodynamic force production and stable flight, Ikeda et al. [21], propose the use of a flexed blade design for small wind turbines. The authors affirmed that the solution achieved a ranged power coefficient widest, overcoming the performance of conventional straight blades in the robustness index.

Bio-inspired wind farms can be an example of innovation and sustainability when the movement of fish can be used as an inspiration to improve the performance and usability of the turbine generators. In this way, several researchers have been working to develop new turbine blades and strategic allocation of wind generators.

In this way, when fishes move in groups they form spirals which eases fishes behind as they save a lot of energy. So some projects that work with a larger number of generators, can use this technique in the placement of vertical-axis wind turbines to make them close to each other. So it made ten times more wind power in a lot less land use.

Some researchers have studied the improvement of wind turbine generators' efficiency by optimising the aerodynamic shape of the blades. For example, in their work, Marimuthu et al. [22], observed the improvement of airfoil dynamic performance by using micro-grooves on the shape mimicking shark skin. On the other hand, authors have approached the fact that whales show high efficiency, speed, and manoeuvrability, despite their large size and weight. In this sense, it can be observed that the shape of the fins of Humpback whales, have irregular protrusions known as tubercles, which add extra efficiency to the fast manoeuvres to capture prey, it can be stated that these tubercles passively modify the flow over the long fins gives them greater lift and less drag. An graphical example of the flow that occurs in the humpback is showed in Figure 3 (b) whale dorsal fin According to Kulkarni et al. [23], several researchers have modified the shape of horizontal axis wind turbine blades based on these natural characteristics.

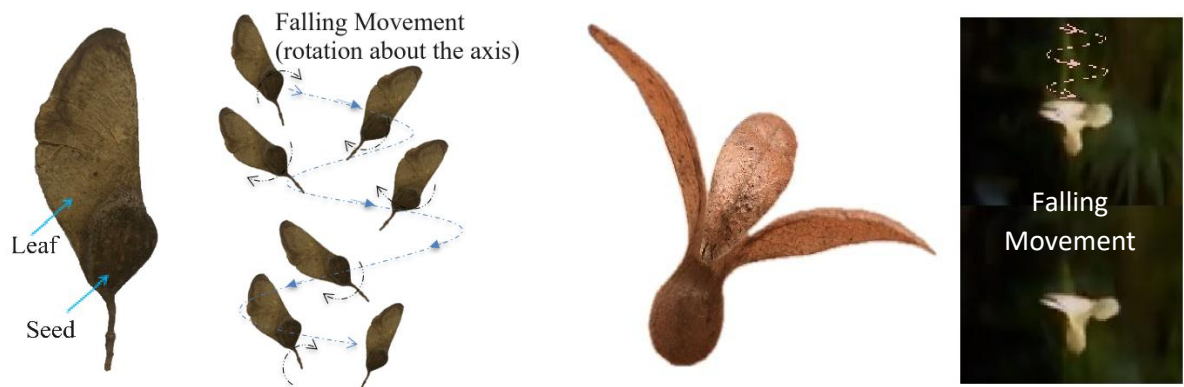


Figure 4. a) Single leaf winged seeds from a tipuana tree, *Machaerium tipu* Benth, (right), b) Pajeú tree seed (*Triplaris Gardneriana*): image of the seed and the movement of the seed during the fall flight.

On the other hand, Molteno [24] introduces a theoretical work on numerical analysis of the aerodynamic performance of flying seeds. The author concludes that this type of biological architecture shows possible applications in energy conversion systems, since operating in low-Reynolds number conditions to achieve better power efficiency.

Regarding this, one of the main objectives to be achieved in this study is to improve the performance of small wind turbines through the application of concepts from Biomimetics, using aerodynamic characteristics of the flying seed as inspiration to develop a small vertical axis wind turbine.

2.1 Case study of geometrically bio-inspired wind turbine blade design: Problems and Requirements

This section aims to align the key challenges and requisites encountered throughout the design, fabrication, and operation phases of the equipment under development.

For the creation of a modular wind microturbine intended for urban environments, several requirements emerge: reduction of production costs; utilization of advanced manufacturing processes to expedite product development while ensuring superior quality; development of optimized designs to enhance power generation performance; mechanical robustness to ensure durability, lightweight construction, and facile maintenance.

Given the unpredictable and volatile nature of urban wind patterns, as discussed in the literature review, vertical wind turbine configurations exhibit superior performance, particularly under lower wind speeds and fluctuating wind directions.

This research endeavors to advance small-scale vertical axis wind turbines (VAWTs) through the application of bioinspired design principles, aiming for high-efficiency energy conversion alongside attributes such as cost-effectiveness, easy installation, and modular architecture. These turbines can serve as clean energy sources for recharging electronic devices, contributing to sustainable energy solutions in urban settings.

As illustrated earlier, biomimicry offers an innovative pathway, drawing inspiration from nature's solutions, which have evolved over time to deliver optimized performance. Nature presents us with various seed dispersal strategies, including airborne dispersal. Flying seeds possess aerodynamic structures enabling flight, glide, or dispersal over significant distances from the parent plant.

These seeds typically feature hard, flattened wings of fibrous, paper tissue, facilitating wind dispersal and rapid germination. Their aerodynamic design ensures stability during flight, maximizing dispersal distance which can reach distances of kilometres [25],

Various types of winged seeds exist in nature, including those with a single leaf structure, as depicted in Figure 4 (a). These structures are meticulously balanced to rotate

around their center of gravity, allowing for prolonged airborne travel facilitated by wind currents [26].

Various tree species produce seeds with multiple wings, enhancing their stability during flight and enabling greater dispersal distances, even in the presence of mild air currents.

Among these, seeds known as "helicopter seeds" stand out, featuring three rigid fibrous wings at their extremities. This design ensures stable flight, making them particularly suitable for study and application in this context. In Brazil, the *Triplaris Gardneriana* tree of the *Polygonaceae* family, locally referred to as Pajeú, produces seeds with slightly inclined wings that facilitate rotational motion during descent, resembling the autorotation of a falling helicopter. Figure 5 illustrates this seed type during flight.

Drawing inspiration from the efficient airflow utilization of the Pajeú seed for extended flight, a bioinspired design was adopted for a small vertical turbine intended for urban environments characterized by variable airflow dynamics.

The helical inclination of the Pajeú seed serves as the basis for the design of a Savonius wind turbine, as depicted in Figure 4 (b). The manufacturing process for the prototype rotor, essential for capturing the conceptual and functional aspects of the final product, utilizes additive manufacturing, specifically Fused Deposition Material (FDM) technology. This process enables the fabrication of parts with intricate geometries using various polymeric materials available, and the final weight/strength ratio achieved [27], aligning with the design and functional requirements of the Savonius rotor model. chosen for its versatility, the polymer materials available,

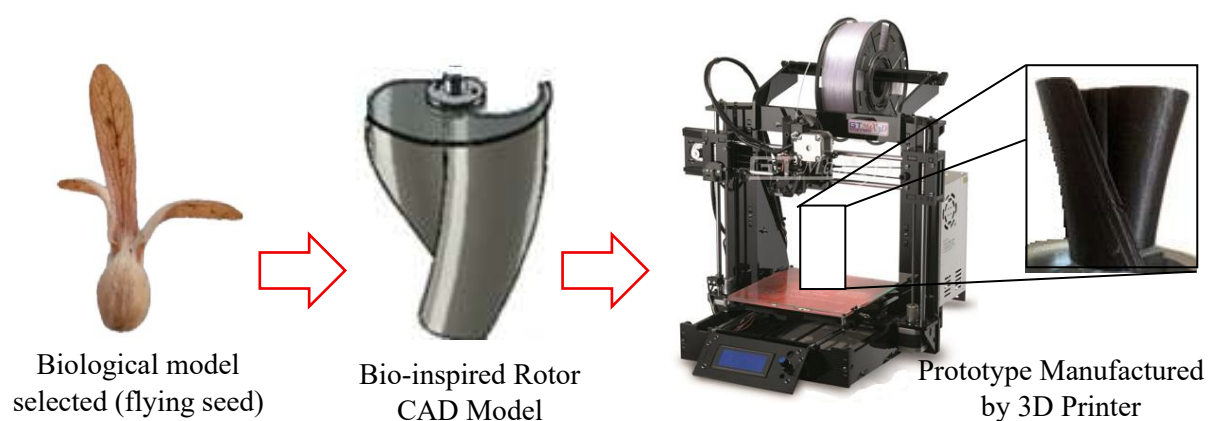


Figure 5. Method to obtain an optimised turbine rotor prototype produced using additive manufacturing process.

Figure 5 shows the methodology used to design, develop, and manufacture the prototype of the Optimised Vertical Axis Wind Turbine (OVAWT) rotor produced using Fused Deposition Material (FDM) technology as an additive manufacturing process and an image of the obtained part.

3. Microturbine performance measurements

By the application of the technological approach biomimetic, was idealised and constructed a special type of rotor for wind turbines by the bio-inspiration abstracted from the flying seeds.

The 3D drawing used attempts to mimic the helix curvature present in the seed, which was reproduced by layer-by-layer deposition of material in an additive manufacturing process. Since the microturbines manufactured must have a reduced size and compact design, a motor generator directly coupled to the rotor (Figure 6) was chosen. The Direct-Drive solution was used to join the turbine through a shaft, connected directly to the rotor of the generator. In this sense, by using a direct drive, the gearbox is excluded from the system. This can be an advantage since the gearbox is often associated with breakdowns and need of maintenance [8].

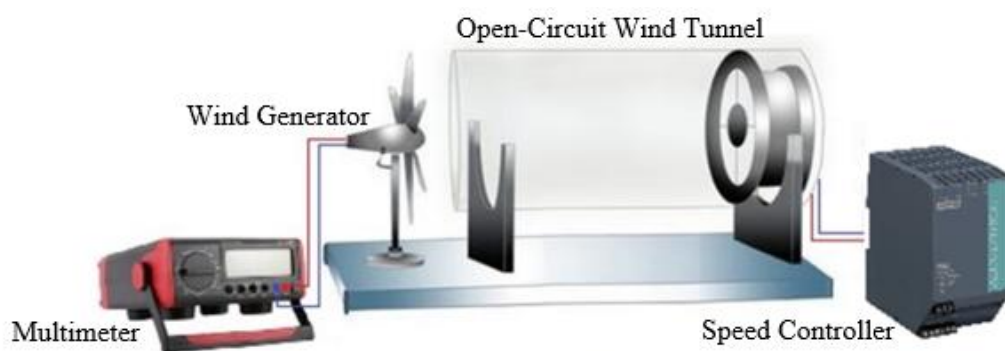


Figure 6. Experimental setup using a small-size educational open-circuit wind tunnel.

Tests were made to evaluate comparatively the performance of the idealised model evaluation against two other rotor types tested at Rubio et al. [5]. For this purpose, a small-size educational open-circuit wind tunnel was set up. Figure 7 shows the experimental setup with the different components necessary to assess the performance of both the new rotor geometry idealised, and also rotors proposed in the literature.

To evaluate the performance of the designed turbine, a commercially available horizontal-axis wind turbine (HAWT) was also tested, and its results were compared with the Savonius-type vertical-axis wind turbine (VAWT) obtained by applying the DT methodology al Rubio et al. [5], as well as with the optimized vertical-axis wind turbine (OVAWT) manufactured in laboratory.

In the next item, the results obtained in the tests are presented and analysed to better understand the influence of the variables involved in the tests.

4. Results and Discussion

The performance evaluation of the three micro wind vertical turbines was conducted at the Group for Innovation and Materials Technology (GiTeM) within the Mechanical Engineering Department of the Federal University of Minas Gerais. An open-circuit educational wind tunnel specifically developed for this purpose served as the wind source. Due to the dimensions of the test bench (170mm diameter x 800mm length), the microturbine prototypes were constrained to a maximum height of 60mm.

Airflow variation within the wind tunnel was achieved by adjusting the fan speed using a frequency converter attached to the motor. Wind speed was meticulously measured using a digital anemometer with an accuracy of 0.1 m/s, ensuring precise readings at multiple points within the air exit zone.

Initial wind speeds for all turbine models commenced at 4 m/s. As the turbines initiated rotation, they began generating power in the form of DC voltage. Consistently, an escalation in wind speed led to a corresponding increase in generated voltage, peaking at 7 m/s. Notably, among the three wind rotor designs, the Biomimetic model exhibited exceptional performance, achieving a power coefficient of 0.305 at 7 m/s.

To facilitate a comparative analysis of the microturbines' performance, factors such as average size and mass were maintained with minimal variance. Table 1 presents the DC voltage values obtained for various wind speed settings across all tested turbines.

Wind Speed (m/s)	Output DC voltage (mV)								
	Horizontal Axis Wind Turbine (HAWT) 5.34 gr			Vertical Axis Wind Turbine (VAWT) 12.45 gr			Optimized Vertical Axis Wind Turbine (OVAWT) 16,10 gr		
1.5	159	203	180	406	408	420	-	-	-
2.0	258	300	288	605	790	670	-	-	-
2.5	428	427	447	834	840	795	-	-	-
3.0	758	668	775	910	990	958	981	952	890
4.0	1060	949	1077	1210	1165	1192	1175	1205	1250
5.0	1402	1404	1399	1334	1287	1306	2560	2430	2477

Table 1 - DC voltage values obtained for wind speed variation for the tested turbines

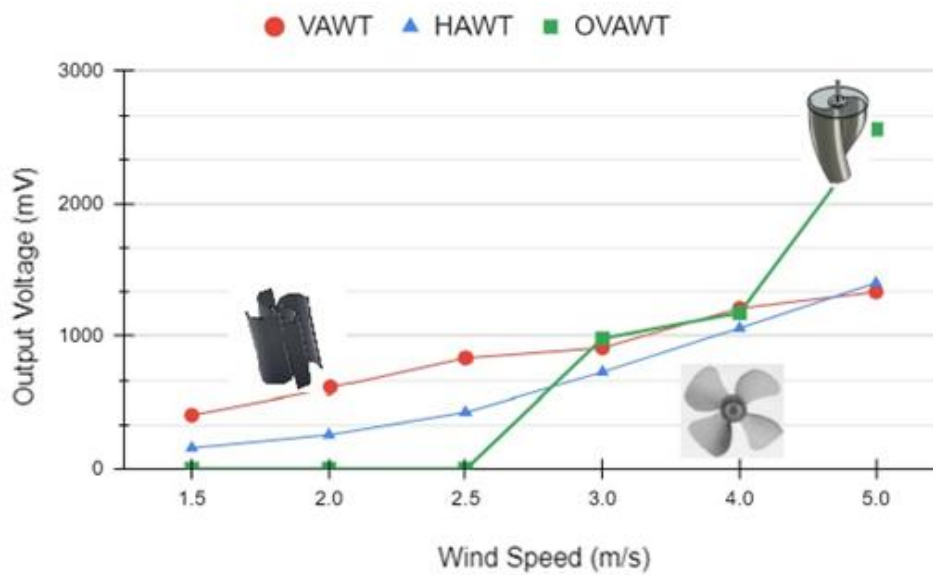


Figure 7. Performance curves of the wind turbines tested.

Figure 7 shows the voltage curves generated by the three-rotor designs studied, where the superiority of the Biomimetic rotor over the other designs can be noted, particularly at a speed of 5 m/s.

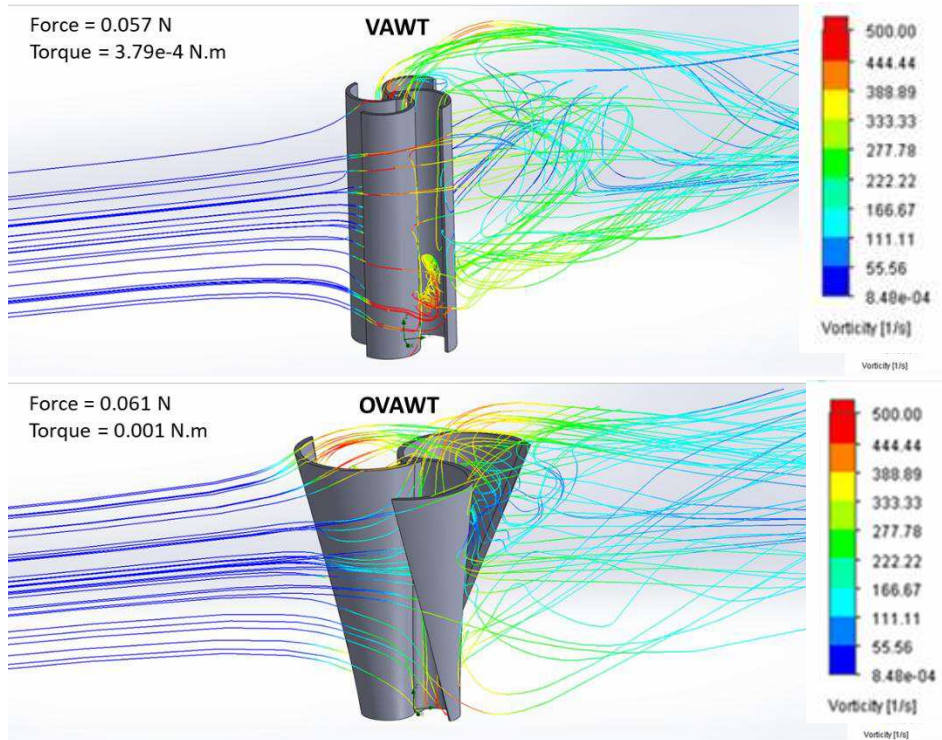


Figure 8. CFD simulation results.

These results are supported by the numerical simulation of air flow conducted using Computational Fluid Dynamics (CFD) software (Figure 8). It can be inferred that the OVAWT configuration exhibited greater vorticity compared to the VAWT configuration. This increased vorticity results in a greater force to rotate the turbine, which can lead to benefits such as higher torque, advantageous for energy generation [28]. However, it may also result in increased structural wear and fatigue due to the additional stresses introduced by the vortices.

5. Finals Remarks

The primary aim of this research was to assess the efficiency of three distinct designs of horizontal and vertical axis wind microturbines. An experimental setup was established to evaluate these microturbines, utilizing a small-scale open-circuit educational wind tunnel. Various wind speed values were tested to gauge performance.

Considering site-specific requirements, spatial constraints, and the potential application of the developed system as a power source for electronic devices, such as charging mobile equipment at bus stops (bus lanes), an analysis of user needs, unique products, services, and suitable technologies was conducted.

The utilization of a shape inspired by flying seeds and additive manufacturing (3D printing) facilitated the development of an innovative vertical microturbine, offering enhanced performance in situations involving limited space and variable wind conditions.

To assess performance, the newly designed bio-inspired microturbine (OVAWT) was compared against a commercially available horizontal axis wind turbine (HAWT) and another conventional vertical axis wind turbine (VAWT). An experimental setup was employed to determine turbine performance using the power curve under wind speeds of 1 and 5 m/s. To mitigate friction variations across tests, the same motor-generator base was utilized for all three models.

The OVAWT Savonius model demonstrated superior performance, achieving a maximum power coefficient of 32.5%, followed by the VAWT model with 21.4% and the HAWT with 13%.

These results affirm that the bioinspired design optimally harnesses airflow, resulting in higher energy generation levels. It is noteworthy that the optimized shape's limited rotation at low wind speeds is attributed to its increased mass (blade thickness), necessary for the proper manufacturing of the helical blade shape.

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Data availability: The authors confirm that the data supporting the findings of this study are available within the article.

Code availability: Not applicable.

Declarations

Ethics approval and consent to participate: All authors have previously approved this paper and judged that there is no ethical infringement.

Consent to participate and publication: All authors would like to declare that they have approved their participation and consent about the publication in this journal.

Competing interests: The authors declare no competing interests.

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