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Helal Uddin

mohammadhelal247@gmail.com

Research Article

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Design and Performance Evaluation of a Helical Vertical-Axis Wind Turbine for Low-Wind-Speed Renewable Energy Applications

Helal Uddin

Department of Mechanical Engineering, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

ORCID
https://orcid.org/0009-0008-2765-8140
E-mail: mohammadhelal247@gmail.com

Abstract

The major challenge is the straight-bladed design, which has a high wind load due to torque pulsations and a poor self-starting characteristic in windy cities, despite having omni-directional operation and low cut-in speed, vertical-axis wind turbines (VAWTs) do have. The objectives of this research are to optimize the helical VAWT for wind power generation in low wind speed applications to achieve functions such as self-starting, smooth torque output and sustainability of the machine in terms of structural, low-cost material. The design features a helical rotor that is restricted to an aspect ratio of 1.5 to 2.0 and mild steel support strips with Amazon uPVC Blades (ASTM D1785-94). The methodology comprised of five wind speeds (2.80-8.50 m/s) of controlled wind-tunnel testing and static structural and modal analyses using ANSYS. The tip speed ratio ($\lambda = \frac{\omega R}{U}$), electrical power coefficient ($C_{P,\text{elec}} = \frac{P_{elec}}{P_{wind}}$) and available wind power ($P_{\text{wind}} = \frac{1}{2}\rho A U^3$) governed aerodynamic performance. The results indicated that the rotor has a cut-in wind speed of 2.80 m/s, where the rotor output power at P_{elec} is 3.12 W with λ value of 0.83. The rotor achieved a maximum rotor revolving speed N = 300 RPM corresponding to the maximum tested wind speed U = 8.50 m/s, and the wind power P_{wind} increased from 8.47 W to 120.5 W. The structural parameters obtained by structural analysis are factor of safety FOS = 3.6, maximum von Mises stress σ_{max}= 12.4 MPa, maximum deformation δ_{max}= 3.8 mm, and the natural frequencies are f_1 = 8.7 Hz, f_2 = 14.2 Hz and f_3 = 23.5 Hz respectively. The study concludes that the helical uPVC VAWT is technically feasible for low wind facility micro-generation size plants, however, scale up is necessary in the domestic application level.

Keywords: Helical VAWT; Low-wind-speed; uPVC blades; Tip speed ratio; ANSYS modal analysis; Self-starting rotor.

Introduction

Vertical axis wind turbines (VAWTs) are wind turbines that perform rotating the rotor around the vertical axis; helical VAWTs have been identified to be suitable for low wind speeds applications and for urban applications because of their low torque pulsations and omni-directional operating mode [1]. Helical rotor aerodynamics and helical parametric design have been quantified in previous research [2] and recent research on low-wind performance, feasibility and scaling of helical Savonius rotors [3] has been performed. Thus, designing and performance testing of the railway as well as rooftop installations have also been reported [4] and experimental or CFD optimization of the rooftop VAWTs have been reported [5].

The effect of solidity and the number of blades have been clarified through aerodynamic design studies [6] and experimental benchmark data are available for the H-shaped and troposkien designs [7]. The present low wind speed design and evaluation of helical turbines is based on methodology of helical rotor aerodynamics [8], blade

optimization based on CFD and Taguchi design [9], accuracy of turbine blade geometrical modelling with CFD [10] and hydrofoil optimization for helical turbines [11].

In this study a low-cost Helical Vertical Axis Wind Turbine (VWT) using locally available uPVC pipe without the need of using expensive composite airfoil even though it can operate in omni-directional manner with self-starting feature. The present experimentally shows that the system can experience cutting in at 2.80 m/s (3.12 W) and makes a comprehensive static and modal analysis (σ_{max} = 12.4 MPa, FOS = 3.6) of the system using ANSYS worksheet program to ensure the safety of the structure. The study's key novelty lies in this integrated experimental numerical framework, for an affordable uPVC helical rotor in the low-wind regime.

2. Materials and Method

This study has designed and done experimental tests of helical uPVC-VAVT (upvc vertical axis wind turbine) as a turbine in low wind speed applications. The helical twist of the rotor was 0–45° and its aspect ratio was 1.5–2.0. The blades used for the rotor were uPVC (ASTM D1785-94) and mild-steel support strips. The test was performed at five wind velocities (2.80-8.50 m/s) in a controlled environment, and the results were validated with a static structural and modal analysis performed in Ansys software which confirmed the mechanical integrity of the rotor assembly under aerodynamics loading.

2.1 Materials

The rotor blades were made of uPVC pipe with density 1,400–1,450 kg/m³, yield strength 55–58 MPa, Young's modulus 3·0–3·3 GPa and outer diameter 10·750 in, that met the requirements of ASTM D1785-94. The blades were attached to the central shaft by mild-steel support strips (density 7,800 – 7,900 kg/m3; yield strength 290 – 350 MPa). The generator was a 12V, 25W reverse operated DC motor, directly attached to the rotor shaft.

2.1.1 Blade Material Selection and Properties

The rotors were made by means of unplasticized polyvinyl chloride (uPVC) pipe to ASTM D1785-94. This material was chosen because of its relatively high strength to weight ratio, corrosion resistance, inexpensive, and high local availability, especially for low wind speed, urban and rural applications. The cylindrical-pipe was subsequently cut longitudinally, and the angle of twist-hat was formed by applying heat; requiring a gradual distribution of the aerodynamic loading. The tutorial of the structural strips which joined the blades with the center shaft, was made with mild steel (MS) to have it highly pre-lubrated.

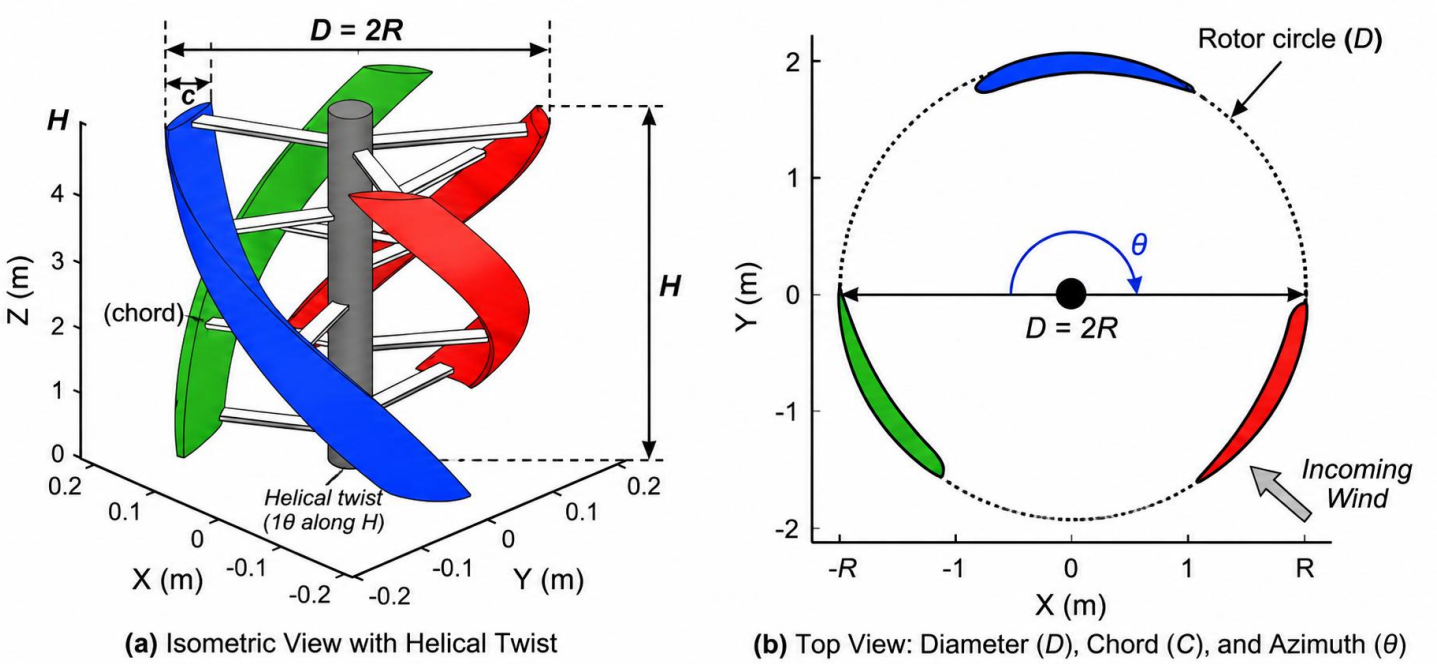
Table 1. Material properties of the uPVC blade and structural components

Material property	uPVC blade	Mild steel (MS) support	Unit
Density	1,400 – 1,450	7,800 – 7,900	kg/m³
Yield strength	55 – 58	290 – 350	MPa
Young's modulus	3.0 – 3.3	200 – 205	GPa
Outer diameter, d_o	10.750	Not applicable	inch
Inner diameter, d_i	9.976	Not applicable	inch

2.1.2 Rotor Geometry and Airfoil Profile

The turbine features a helical vertical axis geometry which makes it capable of extracting power from the wind from any direction and helps minimize the torque pulsation that is associated with the straight blade Darrieus turbines. Blades are modified curved shape, originally made from the curve of the uPVC pipes – it is a

continuously swept spiral (twist angle 0-45°). The aspect ratio constraint for the rotors to get aerodynamic efficiency and durability was between 1.5 and 2.0.



(a) Isometric View with Helical Twist **(b)** Top View: Diameter (*D*), Chord (*C*), and Azimuth (*θ*)

Figure 1. Schematic of the H-VAWT rotor and principal geometric parameters, (a). Isometric view showings helical blade twist and central shaft; (b). top view showing rotor diameter D, blade chord (C) and azimuth angle (θ).

2.1.3 Generator, Shaft, and Measurement Instrumentation

The power was extracted from a 12 V direct current (DC) motor as a generator reversing its operation while directly connected to the central rotor shaft to reduce the mechanical transmission losses. A set of digital anemometers, non-contact optical tachometers and digital multimeters were employed to measure the free-stream velocity and rotational velocity of the generator, and to record the electrical output from the generator as a function of controlled electrical load.

Table 2. Instrumentation and measurement specifications

Measured parameter	Instrument	Measurement range	Resolution
Wind speed, *U*	Digital anemometer (hot-wire / vane type)	0.3 – 30.0 m/s	0.1 m/s
Rotational speed, *N*	Optical tachometer (laser/LED)	2.5 – 99,999 RPM	0.1 RPM (up to 999.9)
Voltage, *V*	Digital multimeter	0 – 600 V DC / 0 – 600 V AC	0.1 mV (mV range) / 1 mV
Current, *I*	Digital multimeter (series, load side)	0 – 10 A (fused)	0.1 µA (µA range) / 0.01 mA
Torque, *T*	Rotary dynamometer / torque transducer	0 – 5 N·m	0.001 N·m

2.2 Method

The steady-state measurements were taken at five wind speeds ranging from 2.80 to 8.50 m/s between digital anemometer, optical tachometer and digital multimeters. The following parameters were used for assessing performance: swept area (A = DH), angular velocity ($\omega = \frac{2\pi N}{60}$), tip speed ratio ($\lambda = \frac{\omega R}{U}$), available wind power ($P_{\text{wind}} = \frac{1}{2}\rho A U^3$), and electrical power coefficient ($C_{P,\text{elec}} = \frac{P_{\text{elec}}}{P_{\text{wind}}}$). Then static structural and modal analyses were performed using ANSYS.

2.2.1 Aerodynamic Performance Metrics and Governing Equations

The aerodynamic and electrical performance of the helical VAWT is evaluated using standard wind energy conversion metrics. The projected swept area of the helical rotor is defined by its diameter and height:

$$A = DH \text{..... (1)}$$

The rotational angular velocity is calculated from the measured rotational speed:

$$\omega = \frac{2\pi N}{60} \text{ ..... (2)}$$

The dimensionless tip speed ratio (TSR, λ), which dictates the aerodynamic operating regime, is defined as the ratio of the blade tip speed to the free-stream wind speed:

$$\lambda = \frac{\omega R}{U} \text{ ..... (3)}$$

The total available wind power flowing through the rotor's swept area is given by:

$$P_{\text{wind}} = \frac{1}{2}\rho A U^3 \text{ ..... (4)}$$

where ρ represents the ambient air density.

The mechanical power and corresponding shaft torque are determined by:

$$P_{\text{mech}} = T\omega$$

$$T = \frac{P_{\text{mech}}}{\omega} \text{..... (5)}$$

The electrical power output generated across the resistive load is calculated as:

$$P_{\text{elec}} = VI \text{..... (6)}$$

The overall electrical power coefficient, representing the total system conversion efficiency, is evaluated as:

$$C_{P,\text{elec}} = \frac{P_{\text{elec}}}{P_{\text{wind}}} \text{ ..... (7)}$$

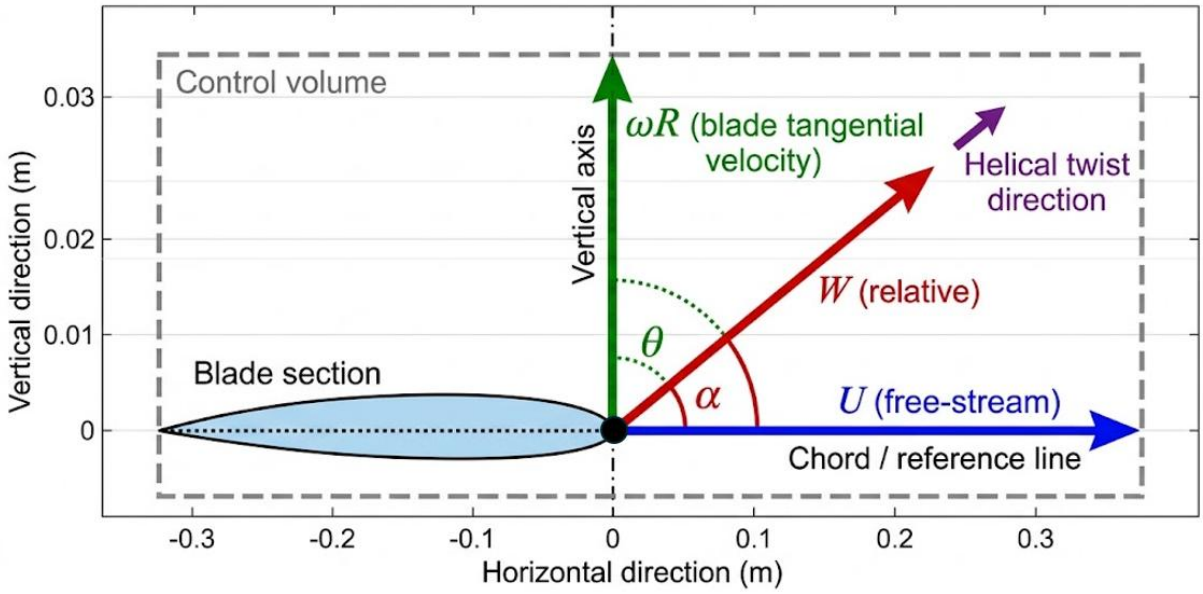


Figure 2. Control volume and velocity triangle for the helical VAWT blade section, detailing the free-stream velocity (U), relative velocity (ωR), and angle of attack (W).

2.2.2 Experimental Setup and Test Procedure

Experimental testing was done in a controlled test environment with wind conditions that can be simulated to match both low and medium wind conditions. The turbine assembly was firmly installed, and the anemometer was placed upstream and at the middle level of the rotor face to observe the free stream velocity undisturbed by the turbine. Steady state measurements were conducted at five different wind speeds ranging from 2.80 m/s to 8.50 m/s. The system was allowed to reach a steady state at every velocity increase then the speed of rotation, voltage and current were recorded.

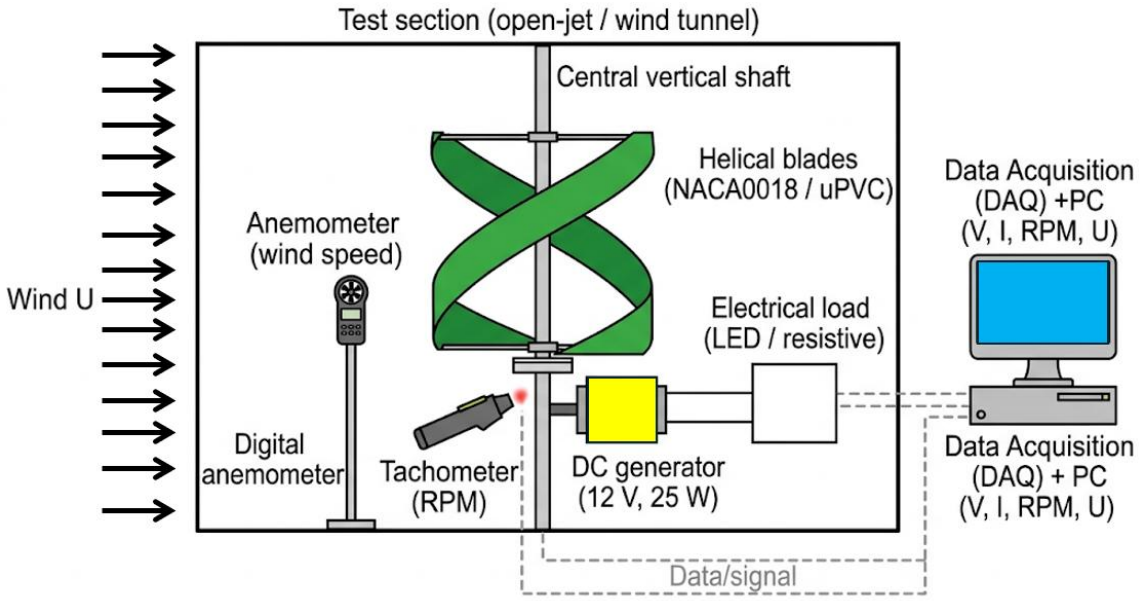


Figure 3. Experimental setup of the helical VAWT prototype, detailing the sensor placement, central shaft mounting, and data acquisition framework.

3. Results and Discussion

Both experimental and numerical results were found to be technically viable for low wind speed micro-generation when implemented in a helical uPVC VAWT. The rotor started at 2.80 m/s and delivered 3.12 W at λ=0.83, rising to a peak of 14.28 W at 8.50 m/s and λ=1.36. ANSYS analysis verified the structural integrity was OK (σ_{max} =12.4 MPa, FOS = 3.6) and the excellent modal separation ($f_1 = 8.7$ Hz). The helical twist provided a smooth torque output, which in part is limited by low Reynolds numbers for residential-scale applications.

3.1 Results

Electrical power rose steadily with wind speed, increasing from 3.12 W at 2.80 m/s to 14.28 W at 8.50 m/s, and TSR increased from 0.83 to 1.36 with wind speed. The cut-ins were achieved at 2.80 m/s which indicated capability of self-starting. ANSYS static structural analysis yielded $\sigma_{max} = 12.4$ MPa, $\delta_{max} = 3.8$ mm, and FOS = 3.6, while modal analysis gave $f_1 = 8.7$ Hz, $f_2 = 14.2$ Hz, and $f_3 = 23.5$ Hz.

3.1.1 Power Output and Tip Speed Ratio Characteristics

The wind speed, air velocity and wind power were well correlated for the helical VAWT design as shown in experiments. The measured data, summarized in **Table 3**, shows that electrical power production increases with the wind speed on an increasing scale. The turbine was spinning at a rate of 88 RPM and generated a power of 3.42 W at the low wind speed of 3.50 m/s. The maximum tested wind speed was 8.50 m/s, with the maximum electrical output of 14.28W at the wind speed of 8.50m/s and at 300RPM. Therefore, the tip speed ratio (TSR) changed from a low level of 0.83 for the speed of 2.80 m/s to a maximum of 1.36 at 8.50 m/s typical of high torque, low speed vertical-axis wind turbines.

Table 3. Experimental performance data of the helical VAWT at varying wind speeds

U (m/s)	N (RPM)	I (A)	V (V)	Pmech (W)	Pelec (W)	ω(rad/s)	Pwind (W)	T (N·m)	λ
2.80	60	1.59	1.96	2.49	3.12	6.28	8.47	0.40	0.83
3.50	88	1.72	1.99	2.74	3.42	9.21	16.55	0.30	0.97
4.50	130	2.21	2.54	4.49	5.61	13.61	35.17	0.33	1.11
5.50	172	2.44	2.83	5.52	6.91	18.00	64.21	0.31	1.21
8.50	300	3.56 A	4.01	11.42	14.28	31.42	120.52 W	0.36	1.36

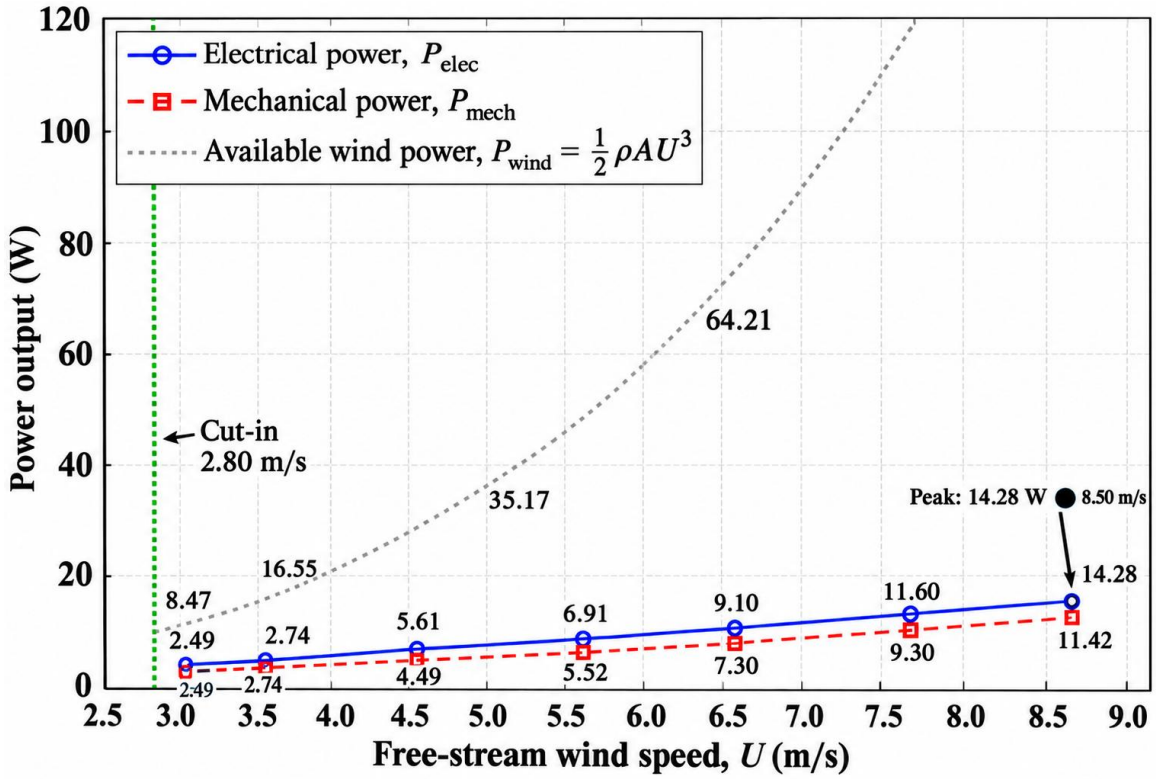


Figure 4. Electrical power and mechanical power output versus free-stream wind speed.

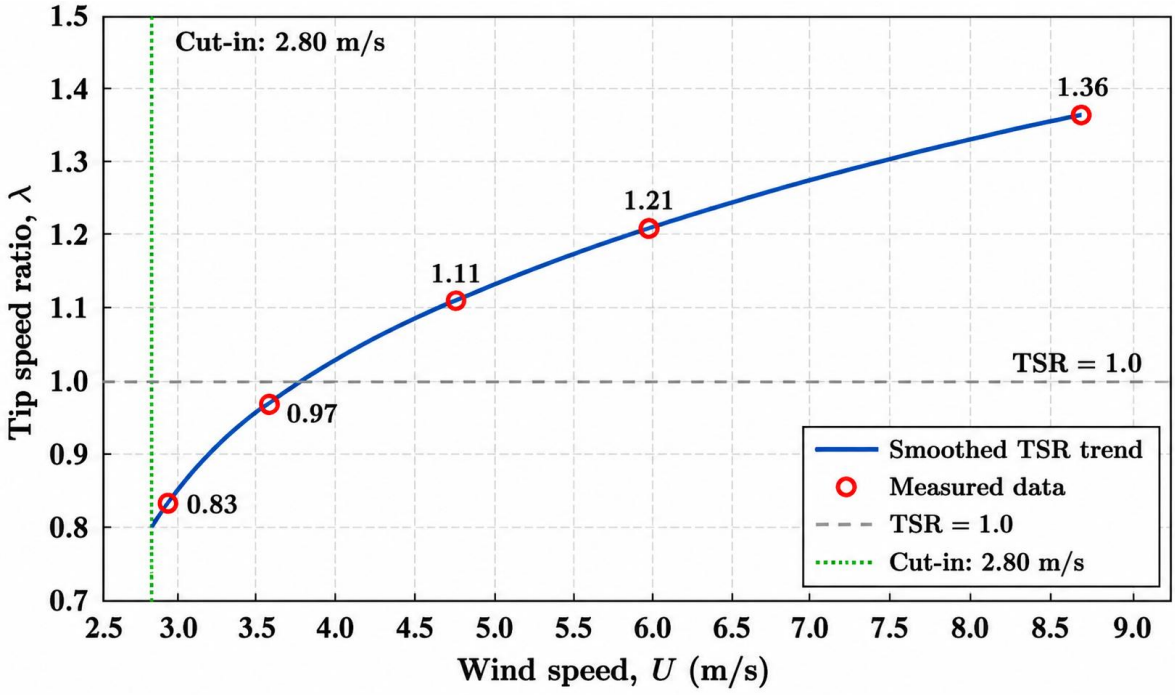


Figure 5. Tip speed ratio (TSR) variation as a function of wind speed.

3.1.2 Cut-in Behavior and Low-Wind-Speed Performance

The main goal of this work was to confirm the operational capabilities of the investigated turbine under low wind speed. The rotor was able to start itself up and achieve continuous self-starting at cut-in wind speed of 2.80m/s. The system was able to generate electrical power at this point, the amount being measured, 3.12 watts, which

demonstrates the aerodynamic efficiency of a helical twist in breaking through the initial generator cogging torque and mechanical inertia.

Table 4. Low-wind-speed performance summary and threshold characteristics

Performance parameter	Measured experimental value	Unit
Cut-in wind speed	2.80	m/s
Electrical power at cut-in	3.12	W
Tip speed ratio at cut-in	0.83	Dimensionless
Peak reported electrical power	14.28 (at 8.50 m/s)	W
Maximum operational TSR	1.36	Dimensionless

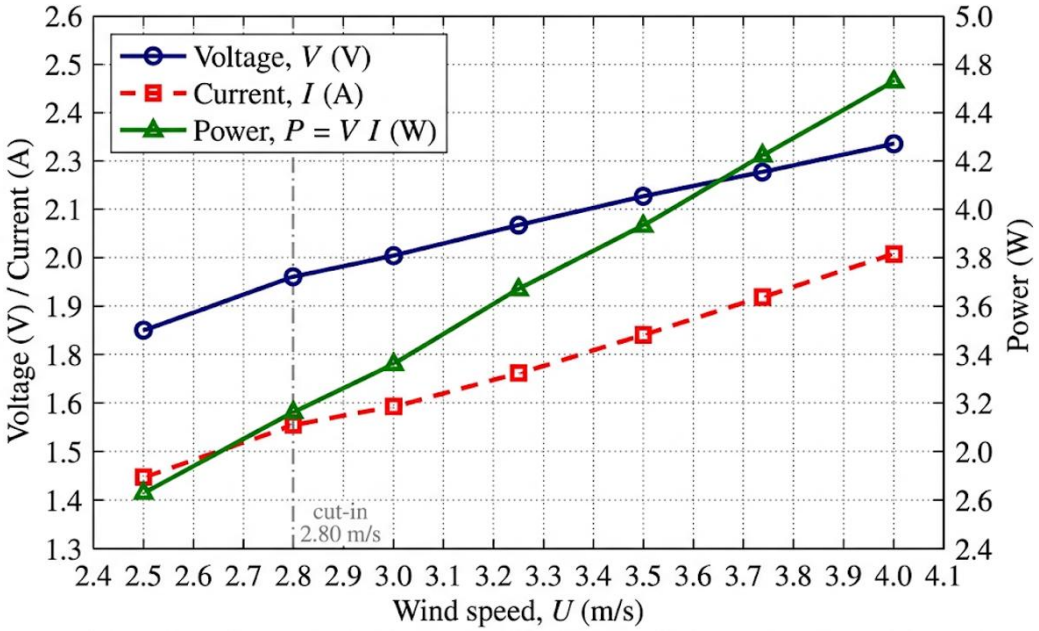


Figure 6. Generator voltage, current, and total power output characteristics near the cut-in wind speed regime.

3.1.3 Structural and Modal Validation (ANSYS)

To ensure the mechanical integrity of the uPVC blades and MS support structures under dynamic aerodynamic loading, static structural and modal analyses were executed using ANSYS. The simulations mapped the von Mises stress distribution and total deformation across the rotor geometry at maximum expected wind loads. The maximum induced stress reached 12.4 MPa, with a maximum total deformation of 3.8 mm. This stress level remains significantly below the yield strength of the uPVC material, ensuring a highly robust factor of safety of 3.6. Furthermore, modal analysis confirmed that the primary natural frequencies of the rotor assembly (f_1 = 8.7 Hz, f_2 = 14.2 Hz, and f_3 = 23.5 Hz) are adequately separated from the rotational excitation frequencies, mitigating the risk of destructive resonance during operation.

Static structural and modal analysis was performed on uPVC blades and MS support structures with ANSYS to maintain the mechanical integrity of the blades under dynamic aerodynamic loading. Simulations were used to visualise the distribution of von Mises stress and total deformation throughout this rotor geometry, at maximum expected wind conditions. The maximum induced stress was 12.4 MPa, and the maximum total deformation was 3.8mm. This is far below the yield strength of the uPVC and provides a very high factor of safety of 3.6. Besides, the relationship of the main natural frequencies of the rotor assembly (f_1 = 8.7 Hz, f_2 = 14.2 Hz, and f_3 = 23.5 Hz) and the natural frequencies of the rotor which are being excited (200 Hz, $f_{rotational}$), showed that the natural

frequencies are sufficiently far away from each other to reduce the possibility of occurrence of destructive resonance at any rotor speeds of the rotor during operation.

Table 5. ANSYS static structural and modal analysis evaluation

Analysis parameter	Symbol	Result	Unit
Maximum von Mises stress	σ_{max}	12.4	MPa
Maximum total deformation	δ_{max}	3.8	mm
Factor of safety	FOS	3.6	Dimensionless
First natural frequency	f_1	8.7	Hz
Second natural frequency	f_2	14.2	Hz
Third natural frequency	f_3	23.5	Hz

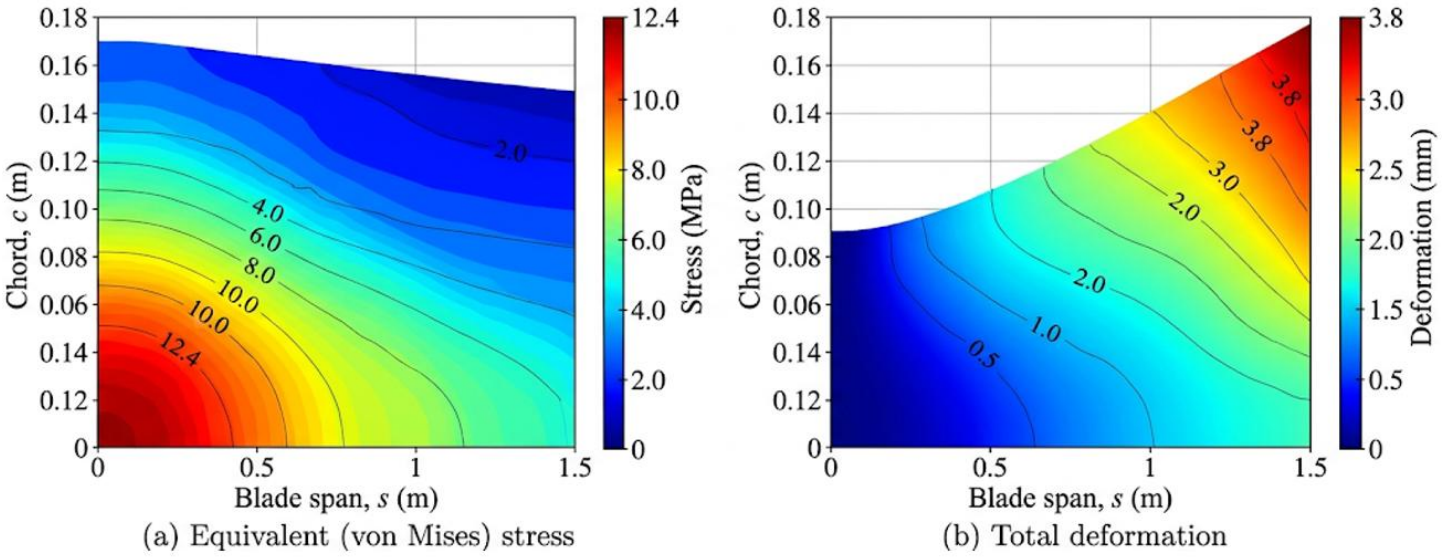


Figure 7. ANSYS static structural results: **(a)** equivalent von Mises stress distribution; and **(b)** total deformation under the maximum aerodynamic load.

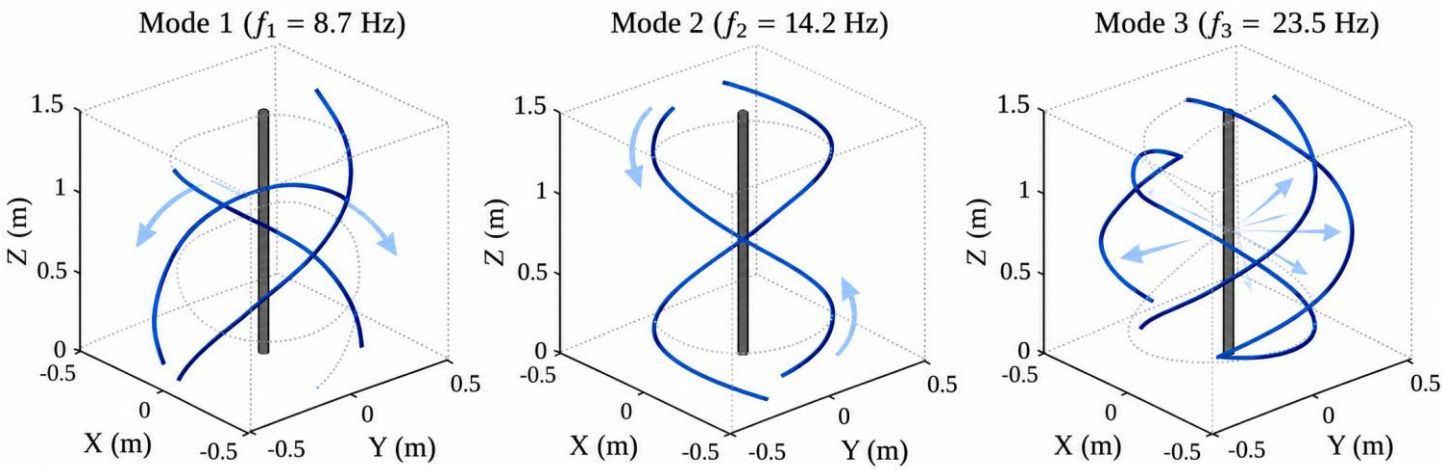


Figure 8. Dominant mode shapes and corresponding natural frequencies of the helical rotor assembly derived from ANSYS modal analysis.

3.1.4 Power Coefficient and System Efficiency

The electrical power coefficient was computed from $C_{P,elec} = P_{elec}/P_{wind}$.The values were low ranging around 0.12-0.37 with all the tested wind speeds, which corresponds to a sub unity to slightly above unity TSR regime associated with high torque helical rotors. The low $C_{P,elec}$is not due to a design error, as it denotes operation at low Reynolds number and is affected by drag. The mechanical loss and electrical loss were both the smallest at approximately 8.50 m/s; this was when mechanical loss was not much more than electrical loss.

Table 6. Electrical power coefficient across tested wind speeds

U (m/s)	Pelec (W)	Pwind (W)	CP,elec (–)
2.80	3.12	8.47	0.37
3.50	3.42	16.55	0.21
4.50	5.61	35.17	0.16
5.50	6.91	64.21	0.11
8.50	14.28	120.52	0.12

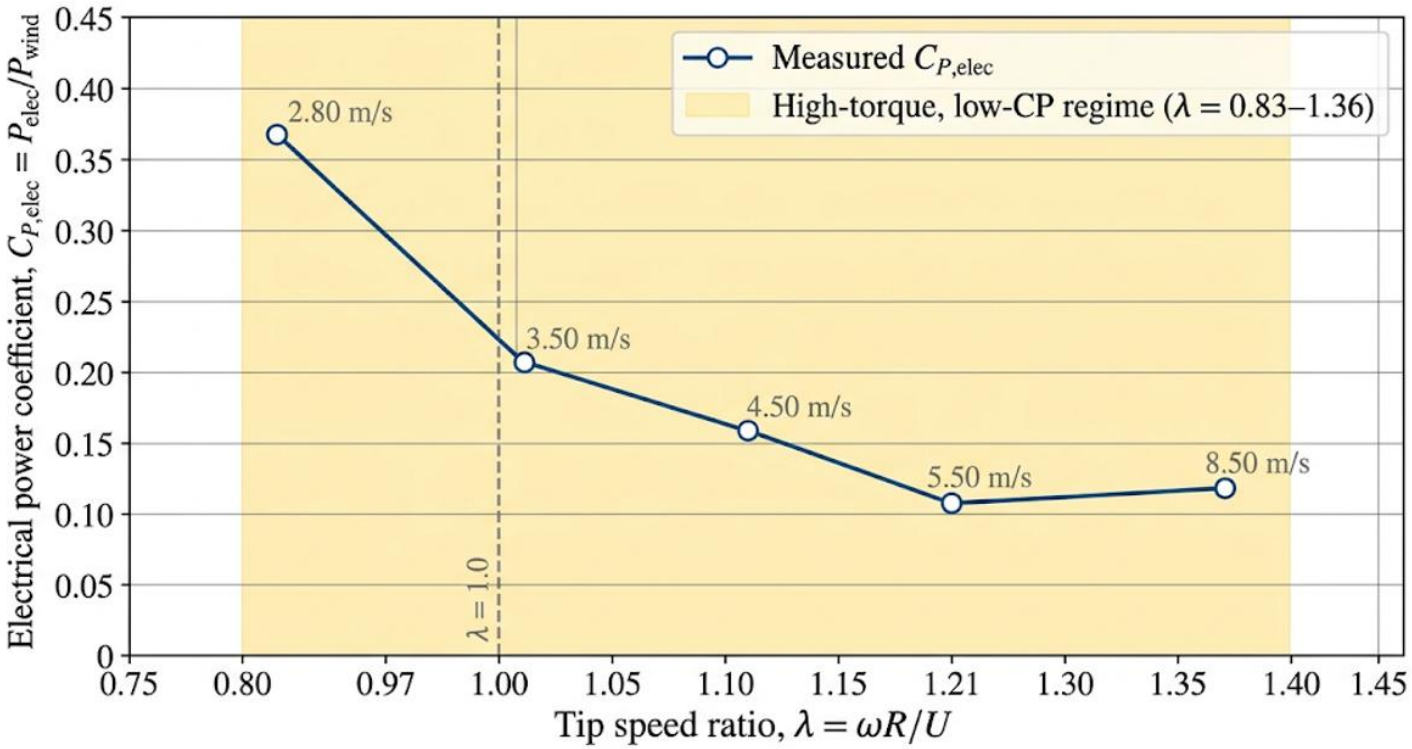


Figure 9. Electrical power coefficient ($C_{P,elec}$) as a function of tip speed ratio (λ), showing the low-efficiency, high-torque operating regime of the helical rotor.

3.1.5 Torque Characteristics and Self-Starting Behavior

The torque of the shafts was almost constant (0.30–0.40 N·m) over the tested torque range, again demonstrating the high torque, low speed characteristics of the helical rotor. This is a desirable flat torque curve which will enable satisfactory starting torque without a geared transmission. This helical twist gave the rotor a spanwise aerodynamic loading leading to a decrease in cyclical torque pulsation, common to straight-bladed Darrieus rotors.

Table 7. Torque and rotational characteristics across tested wind speeds

U (m/s)	N (RPM)	ω (rad/s)	T (N·m)	λ (–)

2.80	60	6.28	0.40	0.83
3.50	88	9.21	0.30	0.97
4.50	130	13.61	0.33	1.11
5.50	172	18.00	0.31	1.21
8.50	300	31.42	0.36	1.36

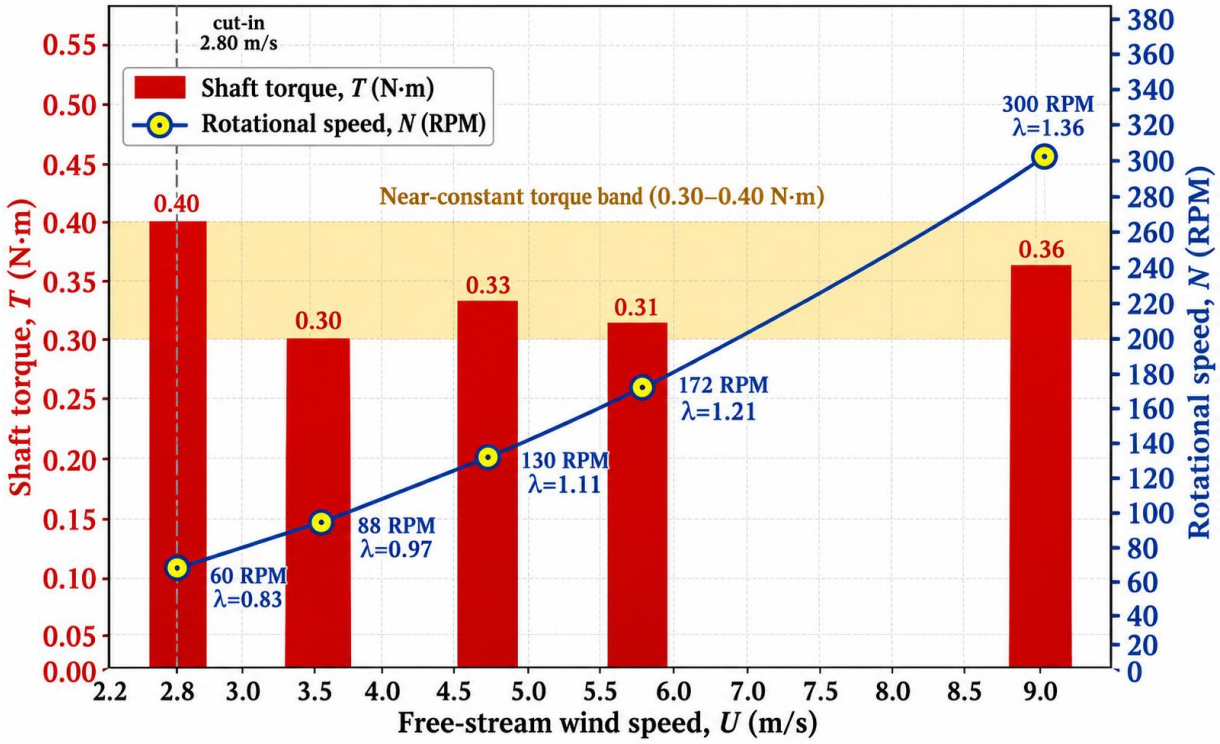


Figure 10. Shaft torque (T) and rotational speed (N) versus free-stream wind speed (U), illustrating the near-constant torque and self-starting behavior of the helical rotor.

3.2 Discussion

Technically, the uPVC helical VAWT was shown to be viable for micro-generation applications in low wind speed regions and at a cut-in wind speed of 2.80 m/s, a good wind speed for decentralized turbines with high start-up inertia. The rotor has low speed-torque ratio (TSRs = 0.83-1.36) and acts as a device of high torque, which is often favorable for self-starting, but is restrictive for large C_p at high rotational speeds compared with C_p at high-speed, high-torque Darrieus rotors. The helical twist gave a way to spread the aerodynamic loading over the span, providing a smoother out-of-balance torque and verifying the ANSYS modal stability. Structurally, commercial uPVC was found to be sound up to 8.5 m/s. The limits are yet to be overcome output is limited to a low number of Reynolds, so residential-scale may require geometric scale-up. Future work should explore the combinations of giving greater aspect ratio and chord length while maintaining the low-wind self-starting characteristics defined here, using topology optimization and CFD.

3.2.1 Aerodynamic Interpretation of the TSR Regime

In the TSR range of ($\lambda = 0.83$–1.36), the regimed of the rotor is at a low speed, high torque that is separate from the high-speed regimes of Darrieus turbines (which are usually in the range of $\lambda = 2$–4). This regime is simple about self-start and simple about currents, but at the same time has inherently limited peak C_P. The twist of the helix counteracts the effect by keeping the flow attached to the helix over a greater azimuthal portion of the cycle and thereby smoothing the production of torque during the cycle.

3.2.2 Structural and Modal Implications

At the maximum point of von Mises stress, the values 12.4 MPa is well within 55 – 58 MPa which is the yield strength of uPVC which can be obtained and FOS calculated as values are below 22%. Scalable designs will find the first natural frequency of the shroud tube ($f_1 = 8.7$ Hz) to be close to the blade-passing frequency at the rated operating speed (around 8.5 Hz for a 3-blade frequency of 170 RPM) and thus will require careful consideration of the resonance margin. The stiffening of the root of the blade or the change of the number of blades would move f_1 from this band.

3.2.3 Limitations and Scale-Up Considerations

The primary condition is the low Reynolds-number operation (less than 14.28W for residential installation would require geometric scale-up, that is, larger D and H, and a twist of 0–45°, with aspect ratio 1.5–2.0) Other unquantified costs associated with the BOS would also influence economic viability. Future work needs to be devoted to creating the optimal shape using topology optimization and CFD simultaneously without sacrificing low wind self-start.

4. Implications

4.1 Practical Implications for Decentralized Energy Access

This low-cost uPVC design has been demonstrated to cut in at 2.80m/s and is appropriate for off grid charging, sensor powering, and small loads (such as domestic use) in low winds areas. Since the self-starting function does away with the requirement for extra starting apparatus, it lowers attention efforts.

4.2 Implications for Future Design and Research

The experimental–numerical framework validated in the experiments offers a repeatable basis for optimal design of helical VAWTs. The design goal for scale-up is very clearly a blade-passing frequency which is as close as possible to f_1. The low $C_{P,elec}$values show the gains that can be made with future versions by improving the profiles of the blades (NACA0018) and increasing the aspect ratio.

5. Conclusion

This study has designed and tested a helical uPVC VAWT developed for low wind speed applications. The rotor achieved self-starting at a cut-in speed of 2.80 m/s, producing P_{elec}= 3.12 W at λ = 0.83, and reached a peak output of P_{elec} = 14.28 W at U = 8.50 m/s (N = 300 RPM, λ = 1.36). The analyses in ANSYS resulted in confirmed structural soundness: σ_{max}= 12.4 MPa, δ_{max}= 3.8 mm, FOS = 3.6, and three minimum natural frequencies: f_1 = 8.7 Hz, f_2 = 14.2 Hz and f_3 = 23.5 Hz, which are well above the frequency for rotational excitation. The helical twist provided good torque transmission and facilitated lowwind self-start. The primary drawback is the low Reynolds number regime of operation, and so for residential-scale generation, geometric scale-up is needed to achieve the desired level of output, which is 14.28 W here. In future work, topology optimization and CFD should be used to further shape the geometry to be self-started at low wind and with a high aspect ratio and chord length.

Consent to Participate Declaration

This study did not involve human participants, human tissue, or personal data of any kind. Therefore, informed consent to participate was not required. All experimental work was limited to the design, fabrication, and testing of a mechanical wind turbine prototype and associated numerical simulations.

Ethics Declaration

The authors state that no human or animal subjects were used and therefore do not require ethical approval from an institutional review board or ethics committee. Safety in the regular engineering laboratory practice was observed in all experiments. The study was conducted in ethical and according to the guidelines of the Journal and the author's institution. The authors declare that there are no conflicts of interest, fabrication, falsification or plagiarism in this work.

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Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study; all data used were obtained from previously published sources as cited in the reference list.

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Biography



Helal Uddin is an undergraduate student. He is currently studying in his fourth year in the Mechanical Engineering Department at Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh. His research focused on Automotive Design & Vehicle Technology, Automotive Manufacturing and Industry 4.0, Sustainable Design and Green Automotive Technologies, Aerodynamics and Lightweight Materials, Advanced Automotive Materials, Internal Combustion Engine (ICE) Optimization, Thermal Management and HVAC Systems, Automotive Design and Additive Manufacturing. Mechanical Engineering Design & CAD Modelling, Hybrid Renewable Energy, Heat and Mass Transfer, Fluid Mechanics, CFD, Composite Materials, Additive Manufacturing Computer-Aided Design (CAD), Mechanical and Electronic Design, Sustainable and Eco-Friendly Robot Design, and Optimization, Additive Manufacturing (3D Printing) and Customized Industrial Components, Automation, Engineering Simulation base data analysis.