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DESIGN SIMULATION AND EXPERIMENTAL VERIFICATION OF OPTIMIZED SAVONIOUS WIND TURBINE PROFILE

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ABSTRACT

Nepal holds significant hydropower potential but has yet to fully exploit it, resulting in limited power production capacity. To address this energy gap, Nepal can tap into wind energy, capable of generating up to 3000 MW, with 448 MW currently exploitable. Nepal traditionally favors horizontal axis wind turbines (HAWTs) but has only recently begun exploring vertical axis wind turbines (VAWTs). VAWTs, such as the Savonius design, are preferred for their simplicity and efficiency in low wind speeds and turbulent environments.The report outlines its design using SOLIDWORKS 17, detailing material selection, dimensions, and assembly. Experimental testing showed it achieved 266 rpm, 0.305 Nm torque, and 27.841 ω angular velocity at 6.3 m/s wind speed. Theoretical values at the same speed were 214.9 rpm, 0.377 Nm, and 22.5 ω, with mean absolute errors between experimental and theoretical results at 18.85% for torque and 15% for rotational speed. Suggestions to enhance efficiency include advanced materials such as carbon fiber.

Keywords*:* HAWT, Savonius, Wind Power

1. Introduction

Wind energy has advanced significantly as a renewable energy source, with wind turbines now playing a crucial role in electricity generation worldwide. Originally conceptualized by Georges Darrieus, vertical-axis wind turbines like the Savonius leverage back wind pressure on their blades to efficiently capture energy from wind blowing in any direction. This unique design, although versatile, typically exhibits lower efficiency compared to traditional horizontal-axis turbines, making it more suitable for smaller-scale applications such as powering electronic devices or charging batteries. Ongoing research continues to focus on enhancing the efficiency and reliability of wind turbine technology, reflecting global efforts to accelerate the adoption of clean energy solutions and reduce dependence on fossil fuels.

The main objective is to design, simulate, and analyze the performance of a Savonius wind turbine. Specific objectives include fabricating an optimized turbine profile, conducting experiments to measure shaft rotational speed under varying wind conditions, and validating theoretical, experimental, and simulation results.

2. Methodology

The goal of this research is to study the generated energy from back wind pressure of moving vehicle using Savonius wind turbine under relatively lower wind speed. Different steps involved in methodology of the research are listed below;

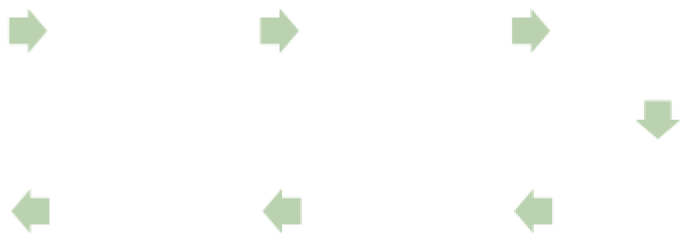

Figure 1: Research framework for this study

2.1 CFD Analysis

The CFD analysis of the Savonius turbine consists the following detailed step-by-step procedure of the simulation:

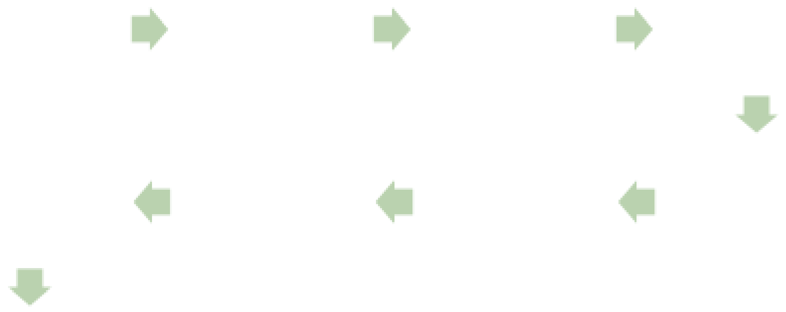

Figure 2: Step-by-step procedure of the CFD analysis

2.2. Litreture Review

Danao, L.A. et.al [3] suggested in their article named "A Numerical Study of Blade Thickness and Camber Effects on Vertical Axis Wind Turbines" that, the findings of a two-dimensional computational investigation of the impact of rotor blade thickness and camber on the performance of a 5kW vertical axis wind turbine. The turbine's performance is plotted for a variety of tip speed ratios, and thorough research are presented to understand how and, more significantly, why the turbine's performance varies with thickness and camber.

N.H. Mahmoud [4], et al performed an experimental investigation utilizing a wind tunnel experimental setup; the results suggest that two-bladed Savonius rotors are more efficient than three- and four-bladed Savonius rotors. The rotor with end plates has a higher efficiency than one without end plates. Blades with overlap ratios perform better than blades without overlap ratios. As the Aspect Ratio increases, so will the Coefficient of Performance (Cp).

Mohammed Hadi Ali Lecturer University of Mustansiriya presented research paper on savonius wind turbine of double and triple Blades at lower wind velocity [5]. The experiment technique was carried out and tested in the wind tunnel, and the necessary measurements were gathered to investigate the performance of the two blades and three blades savonius wind turbines and compare them to determine which one performed better. The performance [torque coefficient (Ct) and power coefficient (Cp)] was examined as a function of the dimensionless parameter tip speed ratio (λ) at low wind speeds in terms of starting acceleration and maximum no-load speed.

The study was carried out by Md Aminul Hassan and Dr. C B Vijaya Vitala [6]. The study was conducted to investigate the possibility for energy extraction from wind on roadways. The study found that at a height of 120 cm, the maximum potential for impact wind energy was accessible. The aspect ratio is an important component to consider when designing VAWT.

K.K. Sharma, et al [7] has investigated the performance of a two-stage two-bladed variant of the Savonius rotor. Experiments were carried out in a subsonic wind tunnel. The factors investigated include overlap, tip speed ratio, power coefficient (Cp), and torque coefficient (Ct). To get the best possible rotor performance, an optimized overlap ratio was applied. The investigation found that a maximum Cp of 0.517 was achieved at a 9.37% overlap condition. Similarly, the power and torque coefficients drop when overlap increases from 9.37% to 19.87%.

Ahmed Y., et al [8] has devised a model with three frames and cavity vanes, which was constructed and tested in a low-speed wind tunnel. This model has a high drag coefficient because the vanes shut the frame on one side while moving in the direction of the wind, capturing the wind efficiently. On the other side, the frame rotates in the opposite direction of the wind, allowing the wind to pass through with no resistance. The model is tested in a wind tunnel at varying wind speeds. This new model provides a maximum power coefficient of 0.32 at a wind speed of 8.2 m/s and a tip speed ratio of 0.31.

The experimental investigation presented in the of work of Fred W., et al [9] intends to evaluate the effect of blade number on the performance of a Savonius type wind turbine model. The studies compared two, three, and four blade wind turbines to demonstrate how tip speed ratio, torque, and power coefficient are related to wind speed. A simulation of wind turbine pressure distribution will be performed using the ANSYS 13.0 software. The study found that the number of blades influences the performance of a wind turbine. The Savonius type with three blades provides the highest performance at high tip speed ratios. The maximum tip speed ratio is 0.555 at a wind speed of 7m/s.

Prof. Vaibhav Bankar and Ashwin Dhote [10] presented research paper on “Design, Analysis and Fabrication of Savonius Vertical Axis Wind Turbine”.

The research findings suggest that installing these turbines at a height of 8 to 10 meters above ground level can provide approximately 10% of power consumption. They recommend considering non-corrosive materials like reinforced glass fiber for turbine blades due to their elasticity, despite being more costly than aluminum alloy.

A study done by Vinit. V. Bidi and team [11] The potential for highway power generation was assessed using VAWT. The primary goal of the research was to manufacture the turbine at the lowest possible cost utilizing readily available materials. The turbine was tested at median of [12] Highways accounting into power generation of 102.4 watts. The turbine rotated at 342rpm at minimum speed of 12.77 m/s.

The study carried by [13] We investigated the relationship between aspect ratio and turbine performance. The study discovered that turbines with smaller aspect ratios have a greater power coefficient. A thicker blade resulted in increased in-service stability.

2.3 Design Considerations

Zhang, Baoshou et al [14] obtained a shape-complicated blade described by a bent quadratic polynomial curve. Optimal profile of Savonius blade looked like a “hook”, with design parameters a_2 = 0.017902 and a_1 = 0.039233. The design parameters were taken into consideration with reduction scale of 0.5 for simulation analysis and experimental verification.

$$\text{Optimal Savonius: } y = 0.017902x^2 - 0.039233x + 0.2059$$

Where, x = angle in radian, y = distance from center to edge of profile

2.3.1 Material and Dimensions

The wind turbine blades can be made from a variety of materials, including ABS plastic, glass fiber reinforced polyester resin, glass fiber reinforced epoxy with mineral fillers, carbon fiber reinforced epoxy, wood and polycarbonate sheet. Factors such as the complex geometry of the blade, the lack of nearby fabrication machinery, and the availability of suitable materials will be considered, and polycarbonate sheets will be chosen for the Savonius blades

The materials and dimensions which are used in the project are as follows:

Table 1: Material and Dimensions

S.N.	Parts Name	Materials
1	Shaft	Mild Steel
2	Nuts and bolts	Mild steel
3	Savonius blades	Aluminum Sheet
4	Bearings	Steel
5	Stand	Mild Steel

2.3.2 Blade Design

Table 2: Blade Dimension

Blade Diameter(d)	250 mm
Eccentricity(e)	40 mm
Height(H)	460 mm
No. of Stages	Single Stage
Thickness	2 mm
Aspect Ratio (AR)	1 H/D

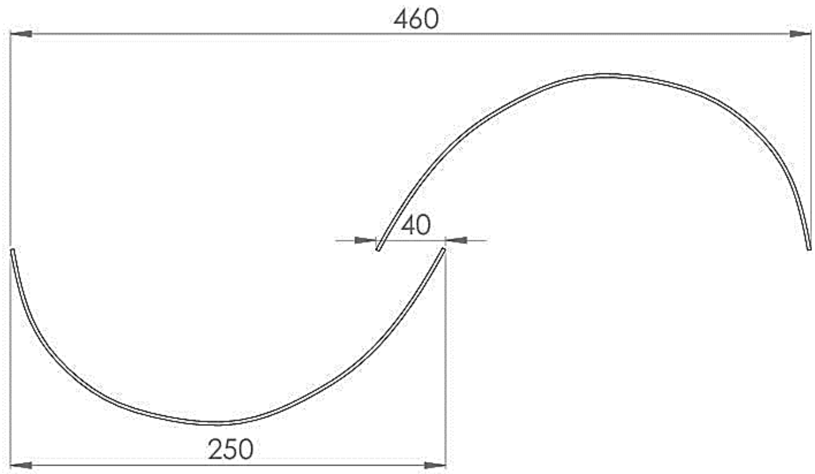

Figure 3: Design of Blade Profile

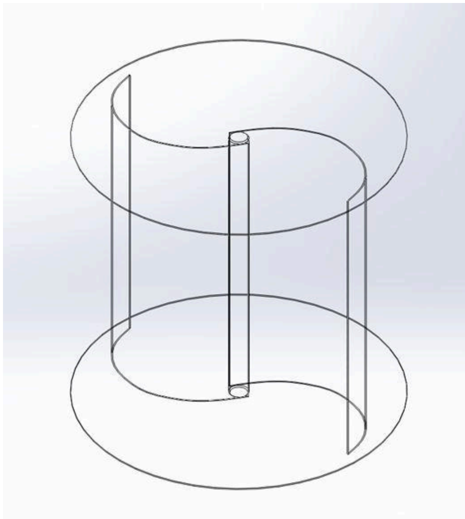

Figure 4: Wireframe View of Turbine

Assumed Parameters:

Table 3: Assumption of Parameters

S.N	Parameter	Values
1	Power coefficient of Savonius Rotor (C_{ps})	0.262
2	Density of Air (ρ)	1.225 kg/ m^3
3	Tip Speed Ratio (λ)	1

2.3.3 Power Calculation

Since the maximum efficiency for Savonius turbine is at aspect ratio (AR) = 1,

So, assuming

Aspect ratio (AR) = H/D

Height of Blade (H) = 460 mm

Eccentricity (e) = 40 mm

Diameter of blade profile (d) = 250 mm

So, Diameter of blade (D) = 2d-e = 460 mm

Now, the power of the wind is given by the formula

Power of the wind (P_w) = (ρ*A*v^3)/2

For savonius turbine, The torque generated by the turbine can be calculated using the following formula:

Torque, T = P/ω = (R*C_{ps} *ρ*A*v^2)/2

Angular speed, ω = (λ*v)/R

N = (ω *60)/2π

Turbine power, P = T* ω

η =P/ P_w

Where, ρ = Density of air, kg/ m3, v =Wind velocity, m/sec, λ = Tip speed ratio

R = Radius of turbine, N = Rotational speed, rpm, η = Efficiency

A = Swept Area(m^2) = H*D = 0.46*0.46 = 0.2116m^2

2.4 Experimental Setup

The experimental setup for the Savonius turbine included measuring instruments such as a digital tachometer and digital anemometer to record RPM and wind speed. Data collection involved measuring wind speed and rotational speed in a step-by-step process during the experiment.

3. Results

The process of fabrication of turbine blade for experimental setup is ongoing so, final result is on the process. The Savonius wind turbine, which was originally designed using SOLIDWORKS 17, is undergoing fabrication and assembly according to the design specifications. After completion, the final model will be prepared for experimental verification.

3.1 Results via Theoretical Analysis

During theoretical rotational speed, torque, wind power, turbine power and efficiency were calculated using formula and equations mention on Chapter Two. Power coefficient of Savonius Rotor (C_{ps}) was considered as 0.262 [14].

Table 4: Theoretical Data

S.N.	Wind Velocity, v (m/s)	Wind Power, P_w (W)	Turbine Power, P (W)	Theoretical Rotational Speed, N (RPM)	Theoretical Torque, T (Nm)	Theoretical Angular speed (ω)
1	2.3	1.577	0.413	78.480	0.050	8.214
2	3.1	3.861	1.012	105.778	0.091	11.071
3	4.1	8.933	2.340	139.900	0.160	14.643
4	4.6	12.615	3.305	156.961	0.201	16.429
5	5.8	25.287	6.625	197.907	0.320	20.714
6	6.3	32.407	8.491	214.968	0.377	22.500

The following chart in Figure 5 illustrates that wind power increases significantly with wind velocity, showing a sharp exponential growth. In contrast, turbine power also increases with wind velocity but at a slower, more linear rate. This highlights the potential for generating higher wind power at higher wind speeds, though the actual power harnessed by the turbine is comparatively lower due to efficiency and mechanical limitations

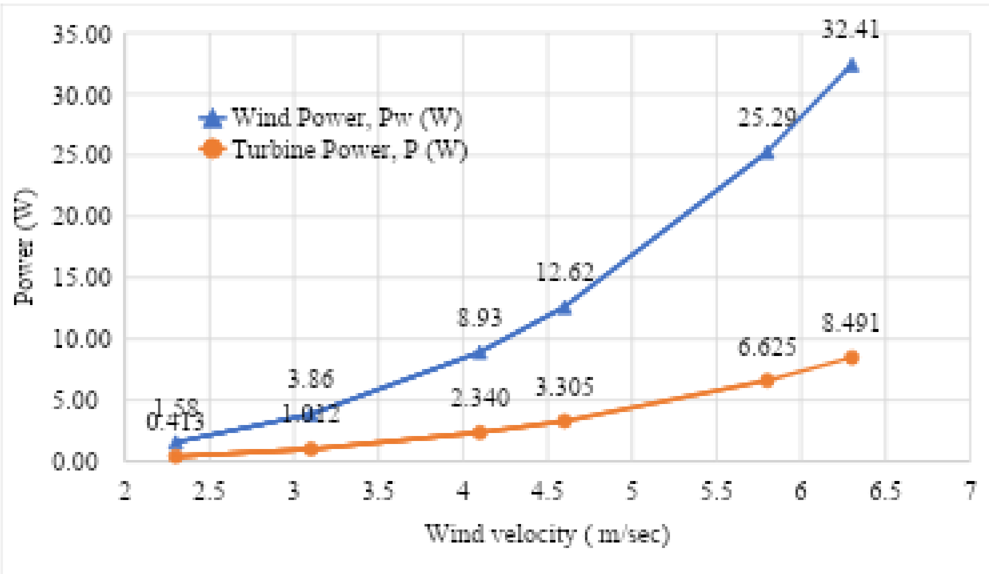

Figure 5: Wind Power vs Turbine Power

3.2 Result via CFD Analysis

The aim of the analysis was to study the velocity and pressure distributions of the Savonius turbine blades at different wind velocities. The wind velocities considered for the analysis were in range of 2 m/s to 7 m/s. The analysis was conducted using the SOLIDWORKS 17 Flow Simulation module, which utilizes the finite element method (FEM) to solve fluid flow equations.

Table 5: CFD Analysis Result Table

S.N.	Wind Velocity, v (m/s)	Simulated Torque, T (Nm)	Maximum Velocity at Profile, (m/s)	Maximum Total Pressure, (Pa)
1	2.3	0.058	4.18	101337.05
2	3.1	0.077	5.38	101349.64
3	4.1	0.136	7.14	101368.09
4	4.6	0.174	8.02	101379.25
5	5.8	0.274	10.12	101411.46
6	6.3	0.323	11.00	101427.02

The chart in Figure 6 shows a linear relationship between wind velocity from a wind tunnel and the maximum velocity at a specific profile. As the wind tunnel velocity increases from 2.3 to 6.8 m/s, the maximum velocity at the profile rises from 4.18 to 11 m/s. The data points and the connecting line illustrate that the maximum velocity at the profile increases proportionally with the wind tunnel velocity

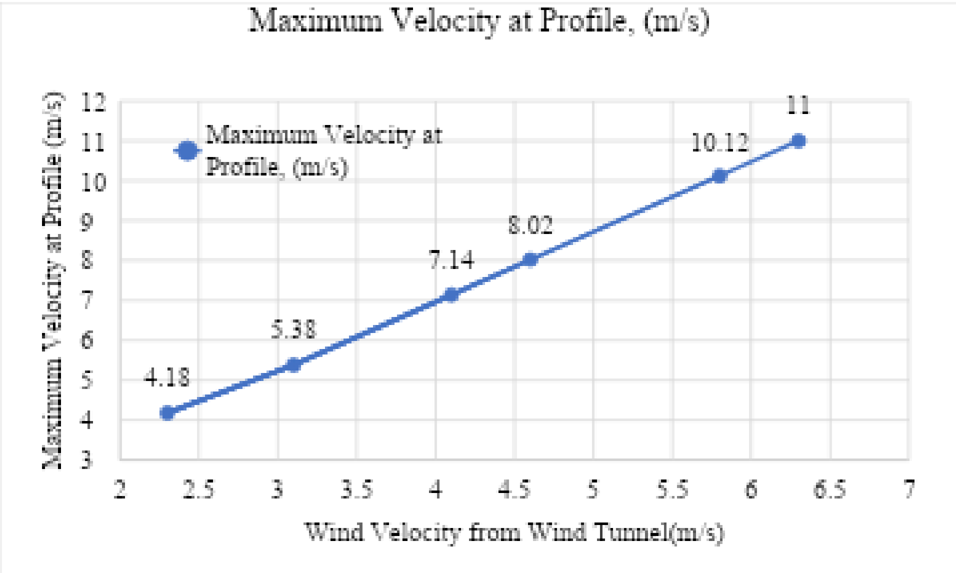

Figure 6: Maximum Velocity at Profile vs Wind Tunnel Velocity

The chart in following figure exhibits a nearly linear relationship between wind velocity from a wind tunnel and the maximum total pressure at a specific profile.

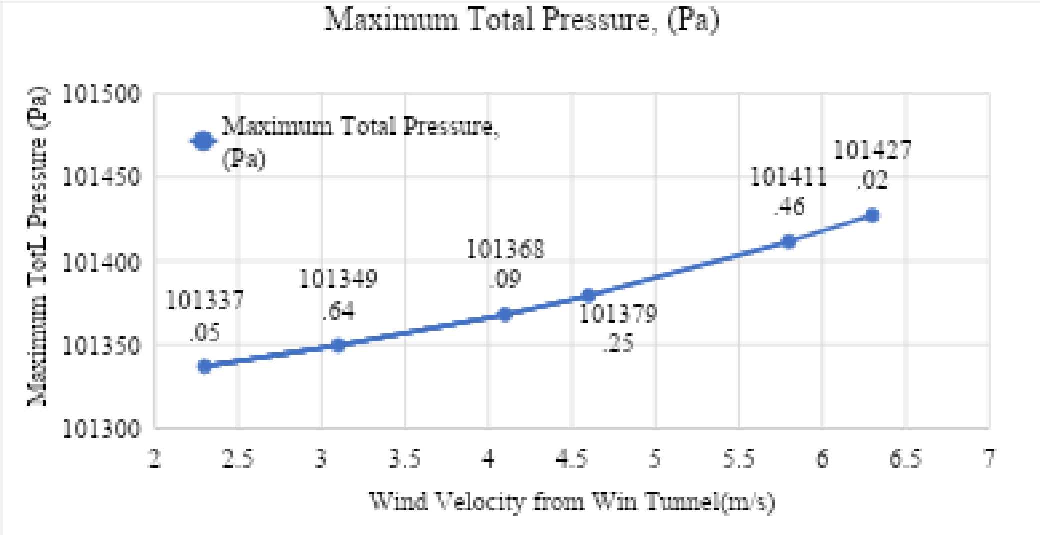

Figure 7: Maximum Total Pressure vs Wind Tunnel Velocity

3.3 Result via Experimental Analysis

Experiment and testing were performed on wind tunnel at Aerospace laboratory of Pulchowk Campus, Kathmandu, Nepal.

Table 6: Experimental Data

S.N.	Wind Velocity, v (m/s)	Wind Power, P_w (W)	Turbine Power, P (W)	Experimental Rotational Speed, N (RPM)	Experimental Torque, T (Nm)	Experimental Angular speed (ω)
1	2.3	1.577	0.413	77	0.051	8.059
2	3.1	3.861	1.012	135	0.072	14.130
3	4.1	8.933	2.340	162	0.138	16.956
4	4.6	12.615	3.305	184	0.172	19.259
5	5.8	25.287	6.625	251	0.252	26.271
6	6.3	32.407	8.491	266	0.305	27.841

3.3.1 Wind Velocity Vs Angular Speed of Turbine Shaft

The chart shows the relationship between wind velocity (in m/s) and angular speed (in ω) for both theoretical and experimental values. As the wind velocity increases from 2.3 to 6.3 m/s, both the theoretical and experimental angular speeds increase. The experimental angular speed consistently exceeds the theoretical angular speed across all wind velocities. Notably, at 6.3 m/s wind velocity, the experimental angular speed reaches 27.8 ω, while the theoretical angular speed is 22.5 ω.

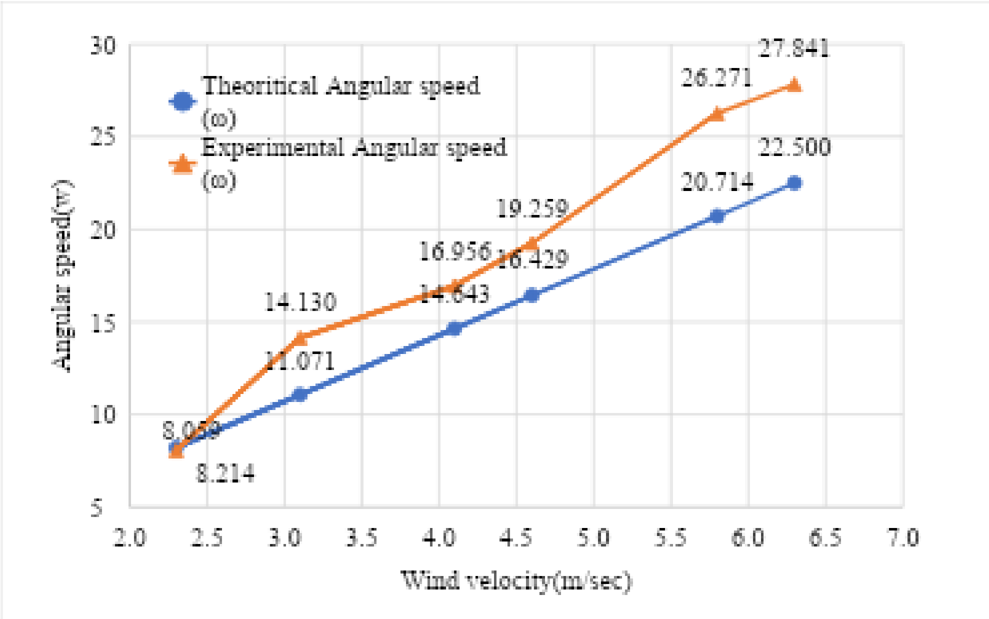

Figure 8: Theoretical Angular Speed vs Theoretical Angular Speed

3.3.2 Wind Velocity Vs Rotational Speed of Turbine Shaft

The chart illustrates the relationship between wind velocity (in m/s) and rotational speed (in RPM) for both theoretical and experimental values. As wind velocity increases from 2.3 to 6.3 m/s, both theoretical and experimental rotational speeds rise. The experimental rotational speed is consistently higher than the theoretical rotational speed at each wind velocity. At 6.3 m/s, the experimental rotational speed reaches 266 RPM, while the theoretical speed is 214.9 RPM.

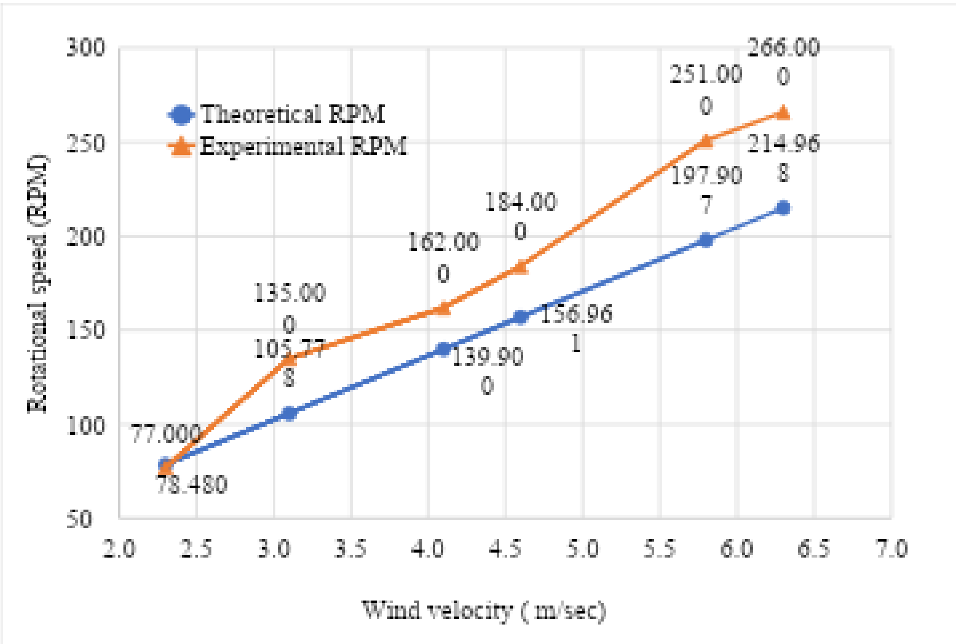

Figure 9: Theoretical Rotational Speed vs Experimental Rotational Speed

3.3.3 Wind Velocity Vs Torque of Turbine Shaft

The chart displays the relationship between wind velocity (in m/s) and torque (in Nm) for theoretical, experimental, and simulated values. As wind velocity increases from 2.0 to 6.0 m/s, the torque also increases for all three measurements. The theoretical torque is consistently higher than both the experimental and simulated torques, while the experimental torque is generally higher than the simulated torque. At 6.0 m/s wind velocity, the theoretical torque reaches 0.377 Nm, the experimental torque is 0.323 Nm, and the simulated torque is 0.305 Nm.

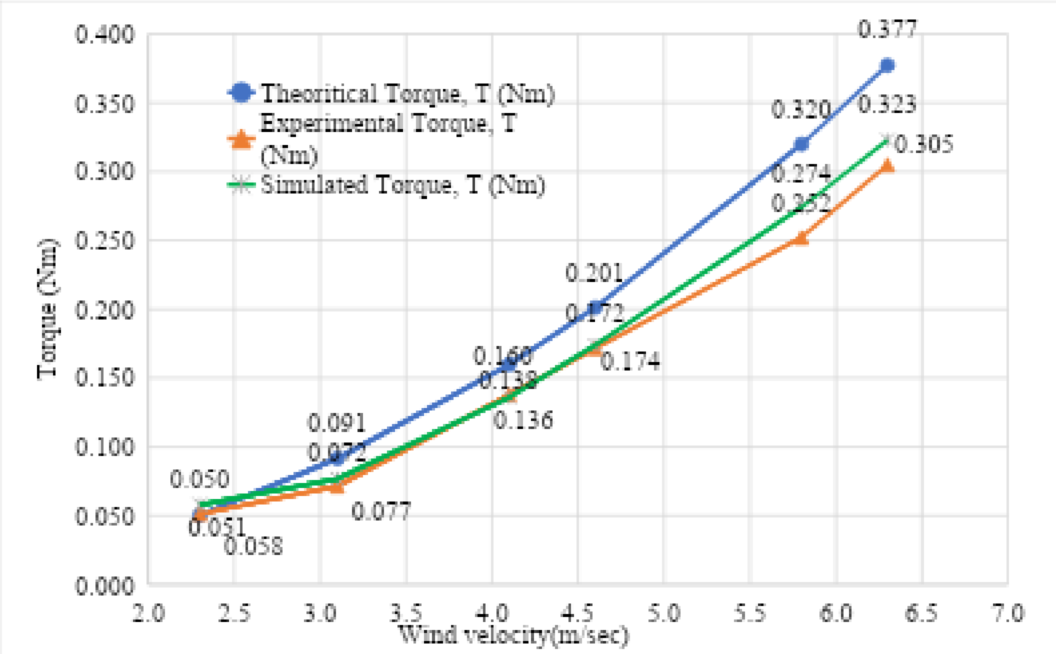

Figure 10: Theoretical Torque vs Simulated Torque vs Experimental Torque

4. Conclusion

The Savonius wind turbine, designed and tested in a wind tunnel from 2.3 to 6.3 m/s, showed maximum experimental rotational speeds of 266 rpm and minimum of 77 rpm, with corresponding theoretical values of 214.9 rpm and 78.4 rpm. Experimental torque ranged from 0.051 to 0.305, with theoretical and simulated values close in range. Mean absolute errors for torque and rotational speed were 18.85% and 15%, respectively. This study underscores the potential of Savonius turbines in renewable energy, pending further refinement to enhance efficiency and integration into clean energy systems.

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