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A Numerical Approach for Evaluating the Aerodynamic Effectiveness of Vertical Axis Wind Turbine by Different Types of Airfoils.

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Abstract

This study conducted numerical research on Vertical Axis Wind Turbines (VAWTs), examining various airfoil thicknesses and cambers to evaluate their effects on power output at different tip speed ratios. Both symmetric and non-symmetric airfoils were analyzed, with findings indicating that symmetric airfoils exhibited an initial increase followed by a decrease in power output as the tip speed ratio rose. A significant rise in power generation was also noted as the azimuthal position shifted from 0° to 90°. Among H-darrieus, Savonius, and helix-type VAWTs, H-darrieus turbines showed superior power coefficient (Cp) with increasing wind velocity, while Savonius turbines initially performed better but declined at higher wind speeds due to increased stress. Helix-type VAWTs consistently demonstrated lower Cp values compared to the other two designs.

Keywords: Vertical Axis Wind Turbines, airfoils, tip speed ratio, power coefficient, wind velocity

1. Introduction

Concerns about pollution, global warming, and the depletion of fossil fuels have intensified the focus on renewable energy sources, including biomass, solar, geothermal, hydroelectric, and wind energy. Wind energy, in particular, has seen dramatic growth and has become a major research focus. Wind turbines, classified into horizontal-axis wind turbines (HAWTs) and vertical-axis wind turbines (VAWTs), are key to harnessing this energy.[1] HAWTs, while efficient, require larger land areas, are expensive to install, and demand high maintenance. They operate by positioning their blades along a horizontal axis parallel to wind flow, making them suitable for regions with steady wind patterns. However, their limitations have led to increased interest in VAWTs.

VAWTs, with their rotor shaft oriented perpendicular to the wind, are gaining popularity due to their compact size, ease of installation, and ability to capture wind from any direction. They are particularly effective in urban settings with turbulent winds and can be installed close to the ground, simplifying maintenance. VAWTs come in two main types: Darrieus and Savonius.[2] The Darrieus turbine operates using lift forces from rotating aerofoils and is more efficient than the Savonius, which uses drag forces but produces less power. Recently, hybrid designs that combine both types have emerged, enhancing performance in various conditions.

Advancements in wind turbine design are supported by computational tools like computer-aided design (CAD) and computational fluid dynamics (CFD). These methods allow for precise predictions of turbine performance, offering cost-effective alternatives to physical testing.[3] CFD, in particular, simulates complex aerodynamics and helps optimize designs under varying wind conditions. Ongoing research focuses on improving VAWT performance by experimenting with different airfoils, adjusting blade pitch angles, and testing models at various wind speeds to find optimal configurations for both efficiency and cost-effectiveness.

2. Research Methodology

The study aims to identify the most effective Vertical Axis Wind Turbine (VAWT) by analyzing the aerodynamic properties of the Savonius rotor. A numerical analysis is conducted using air as the fluid, measuring torque and angular speed at varying wind speeds to evaluate performance without temperature effects.

2.1 Mathematical Relations

The straight, long blades of a VAWT allow us to ignore flow effects.[4] I will simulate a three-bladed Darrieus rotor in 2D using ANSYS Fluent for CFD simulations.

$$\text{TSR} = \lambda = \frac{Vrotor}{V} = \frac{\omega \times r}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where,
ω = rotational speed (rad/s)
r = radius of the rotor (m)
V = wind velocity (m/s).
The produced-to-available torque ratio is known to as the torque coefficient (C_T).

$$C_T = \frac{T}{T_w} = \frac{T}{\frac{1}{2} \times \rho \times A \times r \times V^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where,
T =torque (N-m)
ρ = air-density (1.225 kg/m^3)
A = swept blade area

$$C_P = \frac{P_T}{P_A} = \frac{P_T}{\frac{1}{2} \times \rho \times A \times V^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The maximum power of the turbine is calculated as

$$P_T = T \times \omega \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The turbine's power output is influenced by the angular momentum of the wind stream at the test section.[5] The rotor's power output is derived from torque and angular speed, while the measured angular speed is used to calculate the tip speed ratio.

3. Data Collection and Analysis

Data analysis involves processing and interpreting information to derive insights, while data collection focuses on gathering information from various sources. In this study, all simulations were performed using ANSYS Fluent, and data was obtained from its output results.

3.1 Grid Independence Test and Validation

I conducted a grid-independent test for the NACA 4424 version with mild camber and a TSR value of 3.[6] The mesh refinement revealed minimal variation in the power coefficient (Cp) beyond an element size of 0.1 m. For optimal performance, I selected a rotational mesh size of 0.015 m.

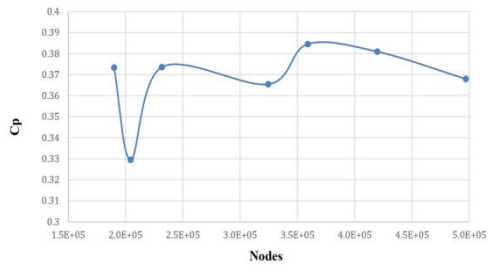


Fig. 1. Grid Independence Test Result

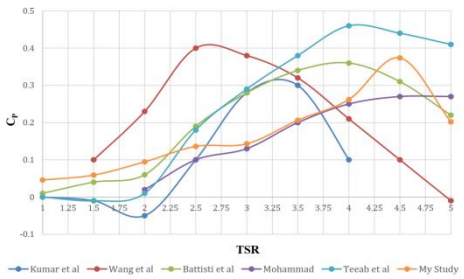


Fig. 2. Validation of My Study

3.2 Boundary Conditions

The free stream wind velocity at the inlet ranges from 5 m/s to 15 m/s, with turbulent viscosity set at 10 and turbulence intensity at 5%.[4] The outlet allows reverse flow, maintaining a gauge pressure of 0 Pa. The blade wall is stationary while the flow domain rotates at 100 rad/s, applying a periodic boundary condition.

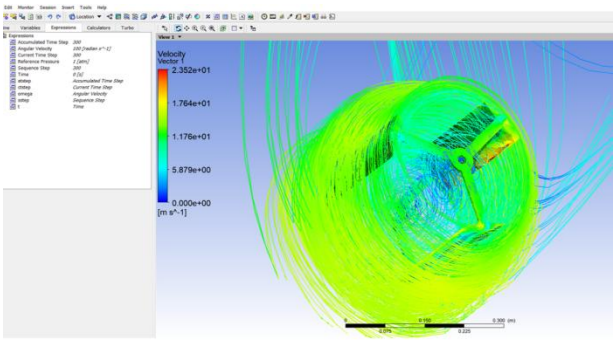


Fig. 3. Velocity Vector

3.3 Wind Speed Effect on Drag and Lift Force

Vertical Axis Wind Turbines (VAWTs) have a key advantage in their ability to operate without requiring a specific wind orientation, making them ideal for areas with fluctuating or rotating winds.[7] However, the cyclic aerodynamic forces on VAWTs can lead to fatigue and lower power coefficients (Cp) compared to Horizontal Axis Wind Turbines (HAWTs).

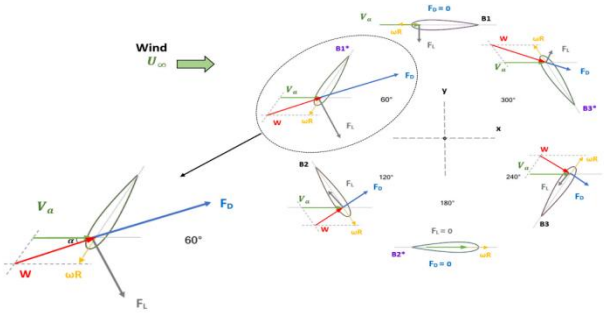


Fig. 4.Wind Speed Effect on Drag and Lift Force

In H-Darrieus wind turbines, the aerodynamic forces acting on the blades are significantly influenced by the azimuthal angle (θ) and the angle of attack (α) of the wind.[8] These forces are categorized into lift forces (F_L), acting perpendicular to the flow, and drag forces (F_d), aligned with the wind's relative velocity. Analysis shows that as the tip speed ratio (λ) increases, drag forces rise, and the distribution of lift forces shifts, impacting performance.

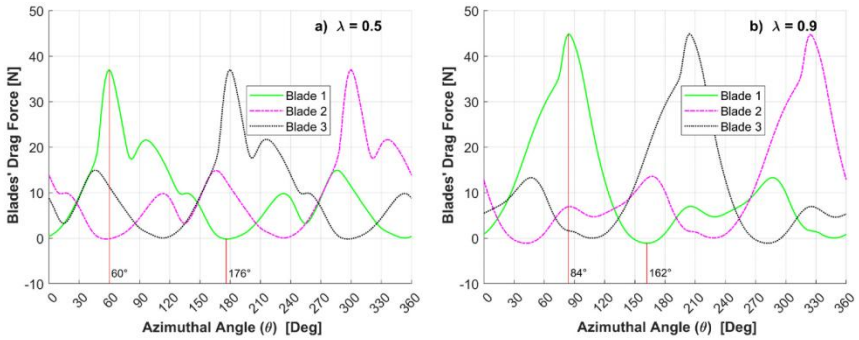


Fig. 5. Drag Force for Blades at Various Azimuthal Angles for Velocity of 8 m/s

The staggered peaks and troughs of both drag and lift forces during the blades' 360-degree rotation indicate that while one blade experiences maximum force, others are at different phases.[9] Understanding these variations is crucial for optimizing wind turbine design, allowing for improved efficiency and reduced structural stress through effective harnessing of available wind energy. Computational simulations and experimental testing are essential in analyzing these complex aerodynamic interactions.

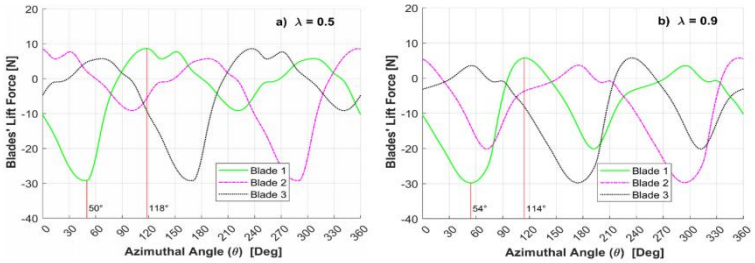


Fig.6. Lift Force for Blades at Various Azimuthal Angles for Velocity of 12 m/s

4. Results and Discussions

This chapter analyzes the findings from the previous chapter, indicating that the modified NACA 4424 aerofoil blade with mild camber enhances the Darrieus turbine's efficiency and self-starting capability. A pitch angle of -4° proves optimal, yielding a higher power coefficient across varying tip speed ratios compared to other angles.[10]

4.1 Comparison of Studies

The study by H. Beri et al. examined the effect of the cambered NACA 2415 aerofoil on the self-starting capability of Vertical Axis Wind Turbines (VAWTs), finding that while cambered aerofoils could enhance self-starting, they also reduced the turbine's coefficient of power, resulting in decreased efficiency. In contrast, my research revealed that the modified moderately cambered NACA 4424 aerofoil blade significantly increased self-starting torque and improved the power coefficient. Similarly, Wang and colleagues found that power coefficients tended to decline with increased camber, with symmetrical airfoils outperforming unsymmetrical ones. [11]

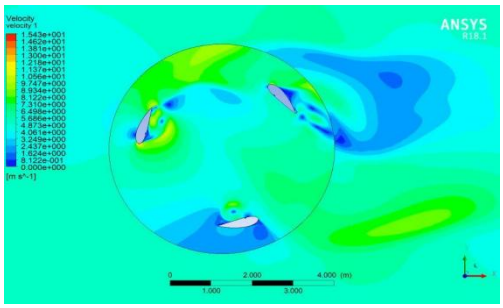


Fig. 7. Velocity Contour of The Blade Models

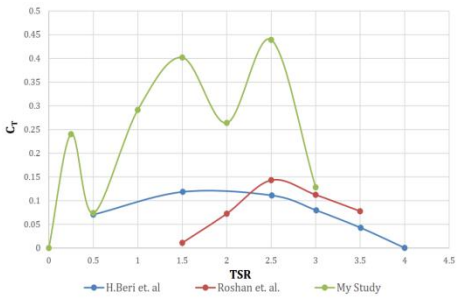


Fig. 8. Comparison of The Result

4.2 Summary of Drag Forces

In Vertical Axis Wind Turbines (VAWTs), dynamic stall occurs as blades rotate, leading to rapidly changing angles of attack (α) and fluctuating lift and drag forces. Unlike "static stall," where flow separation increases drag forces beyond lift at high angles of attack, dynamic stall involves oscillating pitching motions. Vortex generation at the leading edge occurs, shedding later and causing the lift and drag forces to vary with blade rotation. According to Laneville & Vittecoq, the tip speed ratio (λ) and azimuthal position (θ) influence the angle of attack, directly affecting the aerodynamic forces experienced by the blades during their rotation.

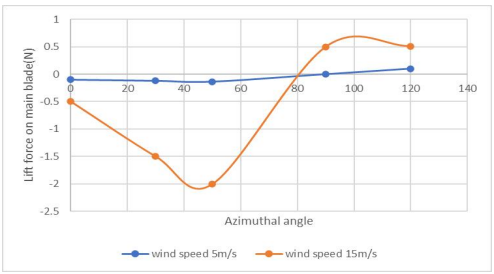


Fig.9. Lift Force on Blade for Different Position

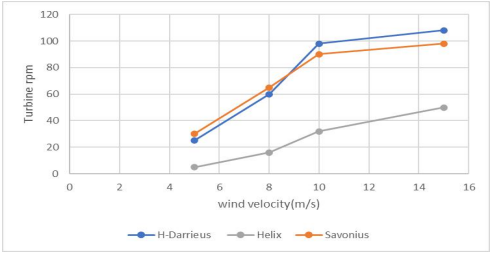


Fig.10. Turbine rpm Variation with Wind Speed

4.3 C_P Calculation

In my SolidWorks design, the specification is as follows
Height: 26cm ,Dia:30cm ,Area= H .d =0.078m2
Total kinetic energy developed by air,

$$P_{\text{wind}} = \frac{1}{2}\rho A v^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where,
P wind = Available wind power, ρ = air density,
A = swept area of the turbine blades, v = wind velocity.
For velocity of $5ms^{-1}$, P = 6.09 W For velocity of $8ms^{-1}$, P = 24.09 W
For velocity of $10ms^{-1}$, P = 48.75 W For velocity of $15ms^{-1}$, P = 133.77 W

Table 1. Torque generated at Varying Wind Speeds

Wind speed (m/s)	Torque		
	H-Darrieus	Savonius	helix
5	0.09135	0.15225	0.03045
8	0.50589	0.65043	0.21681
10	0.141375	0.14625	0.063375
15	0.481572	0.414687	0.147147

P out =Torque ×ω and $Cp= P_{wind} / P_{out}$
After conducting calculations, here's a summary of the power coefficient (Cp) variation for three types of turbines (H-Darrieus, Savonius, and helix) at different wind velocities.

Table 2. C_P at Varying Wind Speeds

Wind speed (m/s)	C_P		
	H- Darrieus	Savonius	helix
5	0.15	0.25	0.05
8	0.21	0.27	0.09
10	0.29	0.30	0.13
15	0.34	0.26	0.11

The H-Darrieus VAWT shows an increasing Cp trend with higher wind speeds, indicating improved efficiency in converting wind energy into mechanical power, making it suitable for fluctuating wind conditions. In contrast, the Savonius VAWT peaks at a wind speed of 10 m/s, after which its efficiency declines, suggesting it operates best within a specific wind speed range.[12] The helix VAWT, however, demonstrates lower Cp and torque, indicating reduced efficiency compared to the H-Darrieus and Savonius turbines.

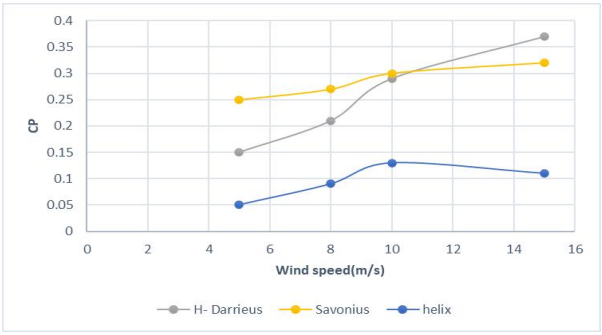


Fig.11. Variation of C_P with wind speed

5. Conclusion

Renewable energy, especially wind power, is a promising solution for future energy demands due to its abundance and eco-friendly nature. A novel project involves developing a vertical axis wind turbine (VAWT) for highways, harnessing wind from passing vehicles to generate electricity. VAWTs are ideal for this due to their low starting torque and quiet operation, fitting well in highway environments. After CFD analysis in ANSYS, the multi-staged H-Darrieus and Savonius turbines showed the best performance. These designs aim to maximize energy efficiency, enabling sustainable wind energy generation along highways for future electricity needs.

6. Acknowledgement

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