Design, Development, and Analysis of Combined Darrieus and Savonius Wind Turbine

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Abstract

This study concerns the design, development, and analysis of the combined Darrieus and Savonius wind turbine. The circumferential placement of three straight Darrieus blades with a NACA 0018 cross-section and a helically twisted Savonius blade ensures an even distribution of torque. Savonius can be used to self-start a wind turbine, something that the Darrieus cannot do on its own due to its unique design. All the wind turbine parts are designed using CAD software, and simulation data is obtained via the CFD approach. Also, the design is imported to FlashForge Finder to 3D print the wind turbine profile, and finally, testing is carried out. The plastic material used for Savonius is ABS, and that for Darrieus is PLA. Equipped with a hybrid design, the fabricated VAWT has exhibited notable characteristics during testing. Its cut-in wind speed, which is the minimum required for operation, is remarkably low, at 3 m/s. Under 6 m/s wind conditions, it achieves a maximum power output of 7.5537 watts. Additionally, the rotor blade has registered a peak rotational speed of 431 rpm at 6 m/s, showcasing its promising potential for wind energy harnessing. Furthermore, a graph plot analysis of the data collected from both processes reveals a comparable slope characteristic. Additionally, mechanical losses have been demonstrated by the discrepancy between the theoretical and experimental data. The study investigates the performance of a novel wind turbine model equipped with an innovative self-starting mechanism, eliminating reliance on external motors, across a range of wind velocities.

Keywords: Wind turbine, VAWT, Darrieus, Helical Savonius, CFD, Flash Forge Finder

1. Introduction

Wind energy extraction is one of the methods used to generate energy from sustainable resources. Vertical Axis Wind Turbines (VAWTs) are compact, silent, and simple to install. They can operate with wind from any angle and perform well in turbulent wind conditions. VAWT's efficiency is lower than that of a horizontal one because of the lower rotor height, and lower wind speed. The shaft is mounted on a vertical axis perpendicular to the ground. Savonius and Darrieus turbines are the two main categories into which VAWTs are often divided.

Savonius turbines are slow-rotating high-torque machines. The difference in drag force that occurs when air strikes the concave and convex portions of the semi-spherical blades rotates the Savonius rotor. Darrieus turbines are high-speed, low-torque machines suitable for generating alternating current (AC) electricity but also lack a self-starting feature. In the case of the Hybrid Vertical Axis Wind Turbine, the lift-type Darrieus rotor provides main power, while the drag-type Savonius rotor provides starting power. The hybrid model is self-starting, as well as the overall efficiency is anticipated to be better than the individual types having a high torque coefficient.

While VAWTs existed before the

1970s, their development gained significant momentum in response to the oil crisis. During the 1970s and 1980s, dedicated research efforts, especially in the USA and Canada, led to a breakthrough: the construction of a 4.2 MW VAWT. This technological leap paved the way for the commercialization of VAWTs (Suprajha & Vijayan, 2007). Numerous researchers have examined the Darrieus turbine's aerodynamic performance. Using 2D ANSYS Fluent simulations, Castelli, Englaro, & Benini performed a numerical analysis of an H-Darrieus turbine. Their findings showed that although the average Cp value was below the Betz limit, it could instantly surpass it. (Castelli, Englaro, & Benini., 2011)

Wang et al. proposed an innovative H-Darrieus turbine with a flexible blade geometry design to achieve higher aerodynamic performance. Turbines with two and three normal and deformable blades were examined. The values of λ between 1 and 4 yielded the highest Cp. However, they demonstrated that Cp values, which are lower than those in a conventional model, may be decreased by higher rotor solidity (σ) (Wang, et al., 2016). The performance of a tilted Darrieus turbine was assessed in a computational study by Bedon, Betta, & Benini and compared with experimental findings from the vertical design. The outcomes demonstrated that efficiency decreases with tilt angle and that the accuracy of the data provided by the URANS models is comparable to that of experimental measurements. (Bedon, Betta, & Benini, 2015)

Numerical analysis by S. Brusca, R. Lanzafame, and M. Messina demonstrated how the rotor blade's Reynolds number has a significant impact on turbine performance. From a geometric perspective, wind turbine performance is enhanced when the aspect ratio decreases and the Reynolds number increases. (Brusca, Lanzafame, & Messina, 2014). S. M. Rassoulinejad-Mousavi, M. Jamil, and M. Layeghi conducted an experimental study of a combined 3-bucket H-rotor with a Savonius Wind turbine. Their study showed the results of testing of VAWT in the subsonic wind tunnel and a comparison between Savonius in the middle of Darrieus and Savonius bottom of the Darrieus rotor. (SM, M, & M, 2013)

The spiral wind turbine was created in the latter part of the 1980s, and its commercial application peaked in the most recent decade. Looking back in time, French scientist George JM Darrieus created the first commercial VAWT. (Suprajha & Vijayan, 2007). A helical Savonius turbine designed for both inland and marine environments, the wind-side wind turbine in Finland operates on sailing engineering principles. It has been operating effectively for the last few decades and can operate at speeds of up to 60 m/s (Suprajha & Vijayan, 2007). Arturo Reza and his friends developed a prototype of VASWT which produced 1500 kW/h per year power at a velocity of 10.2 m/s with a swept area of 1 m^2 (Reza, Tolentino, & Toledo, 2015). The helical Savonius wind turbine at the IOE Pashchimanchal Campus in Pokhara was developed and assessed by P. Bartaula, H. Sigdel, B. Karki, and A. Subedi. Their study presented the superior energy extraction capability of helical Savonius wind turbines over conventional Savonius wind turbines. (Karki, Subedi, Sigdel, & Bartaula, 2019)

2. Methodology

2.1 Complete Background Research:

Brainstorming the possible designs and fabrication techniques of combined Darrieus and helical Savonius wind turbines, the project's foundation is constructed through background research that included examining a related study conducted by individuals in the past, research articles, and books about helical Savonius wind turbines, Darrieus wind turbines, and hybrid VAWTs.

2.2 Design of Helical Savonius and Darrieus Turbine:

Table 1: Savonius Turbine Design Specifications

Descriptions	Windside WS-0, 15 B	Fabricated model
Rotor diameter (D_S)	340 mm	160 mm
Rotor height (H_S)	515 mm	230 mm
Aspect ratio	-	0.6956
Thickness	2 mm	3 mm
Angle of curvature	45°	45°

Table 2: Darrieus Turbine Design Specifications

H – rotor Darrieus Blade	Specifications
Airfoil	NACA 0018
Chord length (C)	70 mm
Diameter (D_D)	800 mm
Blade height (H_D)	240 mm
Aspect ratio	0.6

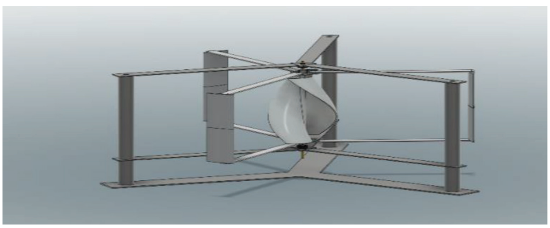

Fig 1: Hybrid model of Darrieus and Savonius VAWT

2.3 Simulation:

A static two-dimensional CFD simulation using the ANSYS is performed for the NACA 0018 blade profile, and the aerodynamic parameters are calculated. To measure the impact of the angle of attack, the simulation is repeated several times at different angles to cover a full rotation. Then, dynamic analysis of the 3-bladed Darrieus turbine is performed by defining a rotating frame of reference and initial conditions. The turbine is simulated at all angles concerning wind flow to study velocity and pressure distribution.

The detailed step-wise process of simulation is as follows:

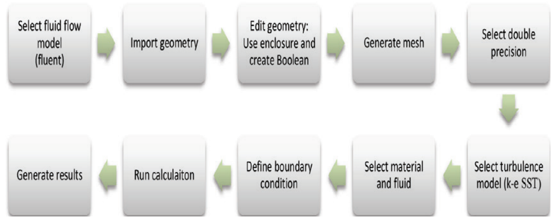

Fig. 2: Steps for Simulation Using ANSYS Fluent

The Navier-Stokes equations for mass conservation and momentum conservation are solved in a frame of reference simulation that moves with the turbine:

Conservation of Mass:

$$\frac{\partial \rho}{\partial t} + \nabla . \rho \vec{v_r} \quad (1)$$

Conservation of Momentum

$$a_{coriolis} = 2\vec{\omega}\, X\, \vec{v_r} \quad (2)$$

$$a_{centrip} = \vec{\omega}\, X \vec{\omega} X\, \vec{r} \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \vec{v_r}) + \nabla . (\rho \vec{v_r} \vec{v_r}) + \rho (a_{coriolis} + a_{centrip}) = -\nabla p + \nabla . \vec{\tau_r} \quad (4)$$

2.3 Fabrication:

CAD design software is used as a reference to fabricate the rotor through FlashForge Finder (3D Printer) and both the Darrieus and Savonius turbine are 3D printed.

Figure 3: Combined Darrieus and Savonius Wind Turbine Project

2.4 Testing:

Rotor rpm is measured concurrently with wind speeds ranging from 3 to 6 m/s to investigate the relationship between the two variables. The motor's power output is estimated using its electrical consumption. The current is gradually increased through a circuit connected to the rotor blade gears, which are identical in size for a fair comparison. The current needed to stop the rotor blade at a certain speed, along with the voltage, is noted. Assuming no energy loss, the motor's output power is estimated as equal to the electrical power it used during this measurement.

2.5 Performance Analysis:

A comprehensive performance analysis of a hybrid Darrieus-Savonius wind turbine is conducted. Through careful plotting of wind speed vs. key parameters like revolution rate, theoretical power output, maximum RPM, and theoretical and actual torque and power at peak RPM, insightful relationships are revealed. Data from experimental testing and ANSYS simulations enlightens these visualizations, ultimately leading to the drawn conclusions.

3. Result and Discussion

3.1 Results Via Testing

The performance evaluation of the turbine system as tested through the experiments yields the following conclusions concerning the performance at varying wind speeds. Observation of the rotor blade rpm is done at intervals of 30 sec from 0 to 3 minutes, and the results obtained indicate that as the wind speed increases, the rpm of the turbine also increases. The maximum rotational speed is determined using a digital tachometer with wind speeds varying from 3 m/s to 6 m/s, implying that higher wind speeds generate higher rpm. Theoretical power calculation for both Savonius and Darrieus turbines using performance coefficients of 0.2 and 0.4 correspondingly demonstrate that the Darrieus model produced the maximum power of 9.3547 watts for wind speeds ranging from 3 m/s to 6 m/s. Analytically calculated torque of the Darrieus turbine also rises as the wind speed increases, thus illustrating higher resisting forces. Additionally, both theoretical and experimental power and torque values for the combined model are calculated at constant rpm, with results showing that power and torque increase with rpm, validating the correlation between wind speed, rotational speed, and turbine performance.

3.2 Results via CFD analysis

The study presented in this paper provides valuable insights into the flow dynamics of a NACA 0018 airfoil at various AoA using CFD analysis. The velocity and pressure distributions are also obtained for AoA of 0°, 5°, 10°, 15°, 20°, and 25°. For each AoA, a required lift coefficient (Cl) and drag coefficient (Cd) are calculated to get the lift-to-drag ratio, and an optimum AoA is selected. This data indicates that an angle of 10° is the most favorable for maximization of lift and minimization of drag, as the highest value of Cl/Cd is equal to 7.6796, obtained at this angle. The lift and drag coefficients start fluctuating as the angle of attack increases beyond 10°, which leads to a reduced Cl/Cd ratio. As the angle of attack is increased to 25°, the lift-to-drag ratio gets further dropped to 1.4128, which means reduced aerodynamic efficiency. The variation in the flow behavior, especially around the airfoil, and the effect it has on lift and drag have been described through contour plots of velocity and pressure for each AoA. Further, the transient flow characteristics of the Darrieus Vertical Axis Wind Turbine (VAWT) blades in a rotating frame are presented qualitatively through velocity and pressure contours, illustrating the intricate fluid dynamics involved in turbine operation.

3.2.1 Contour of aerodynamic behavior of NACA 0018 airfoil for different Angle of Attack (AoA):

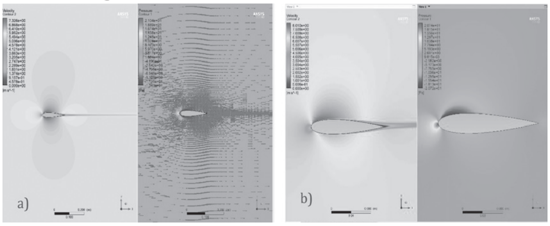

Figure 4: Velocity and Pressure contour at. a) 0^{o} AoA b) 5^{o} AoA

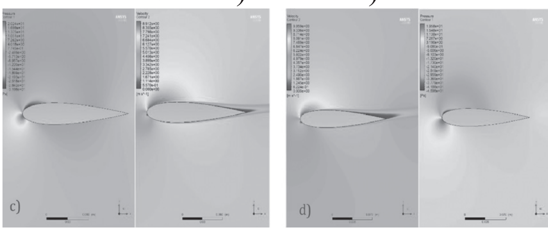

Figure 5: Velocity and Pressure contour at. c) 10^{o} AoA d) d) 15^{o} AoA

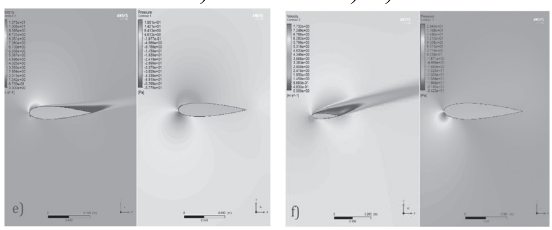

Figure 6: Velocity and Pressure contour at. e) 20^{o} AoA f) 25^{o} AoA

3.2.2 Results of transient flow behavior Darrieus turbine blades in a rotating frame:

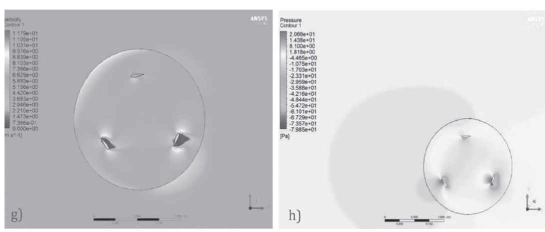

Figure 7: g) Velocity contour and h) Pressure contour of Darrieus turbine transient flow behavior inside a rotating frame

4. Conclusion

VAWTs require low wind speed for power generation and are omnidirectional. So, these are best for harnessing wind energy at lower wind speeds. The Windside WS0, 15B wind turbine for Savonius, and the NACA 0018 wind turbine for Darrieus served as the models for the turbine's rotor design. The combined model is designed and developed to overcome the limitations of individual Savonius and Darrieus turbines. The shape and blade profile are kept almost identical while designing and fabricating. The aspect ratio of the fabricated model is 0.6956 for Savonius and 0.6 for Darrieus wind turbine.

The model is first designed, and the simulation is done in ANSYS Workbench 2020R2. Based on this, the rotor blade is fabricated using FlashForge Finder, and final testing is carried out. The RPM of the rotor blade at various wind speeds and power produced is measured experimentally. After obtaining both theoretical and experimental data, the variation in both sets of data has been analyzed, and similar trends are observed in the curves drawn based on data obtained from both processes. Thus, the experimental data are considered relevant and satisfactory.

Testing of the prototype is done for the speed range of 3–6 m/s. Based on the experimental results, it has been determined that the combined model operated at a low cut-in speed of 3 m/s. The maximum theoretical power for the Savonius and Darrieus rotors is found to be 0.9252 and 9.6547 watts, respectively. Experimental calculations show that the maximum power extracted from the combined model is 7.5537 W at 431 rpm at a constant wind speed of 6 m/s. From the experimental data, it can be concluded that the combined model seems a feasible alternative for power generation for the locations where the wind speed is as low as 3 m/s.

The need for sustainable energy,

especially in developed urbanized areas, can make VAHWTs a reliable source of wind energy. They are also effective in urban locations because of their low starting speed, low visibility impact, and adaptability in small spaces. More research on VAHWT technology will help harness its full potential of generating wind energy that is economically viable and environmentally friendly.

References

Bedon, G., Betta, S. D., & Benini, E. (2015). A computational assessment of the aerodynamic performance of a tilted Darrieus wind turbine. *Journal of Wind Engineering and Industrial Aerodynamics, 145*, 263-269.

Brusca, S., Lanzafame, R., & Messina, M. (2014). Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine's performance. *International Journal of Energy and Environmental Engineering, 5*, 333-340.

Castelli, M. R., Englaro, A., & Benini., E. (2011). The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD. *Energy, 36*(8), 4919-4934.

Karki, B., Subedi, A., Sigdel, H., & Bartaula, P. (2019). Design, simulation, and performance evaluation of vertical axis helical wind turbine. *Journal of Innovations in Engineering Education, 2*, 1-13.

Reza, A., Tolentino, G., & Toledo, M. (2015). Construction of a helical vertical axis wind turbine for electricity supply. *Computer-Aided Design and Applications, 12*, 9-12.

SM, R.-M., M, J., & M, L. (2013). Experimental study of a combined three-bucket H-rotor with Savonius wind turbine. *World Applied Sciences Journal, 28*(2), 205-211.

Suprajha, S. S., & Vijayan, K. (2007). Design and Analysis of Helical Blade Wind Turbine. *International Journal of Innovative Research in Science, Engineering and Technology, 3297*(5), 7924–7931.

Wang, Y., Sun, X., Dong, X., Zhu, B., Huang, D., & Zheng, Z. (2016). Numerical investigation on the aerodynamic performance of a novel vertical axis wind turbine with adaptive blades. *Energy Conversion and Management, 108*, 275-286.