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作品名稱　Development and Comparison of a Small-Scale Toroidal Horizontal-Axis Wind Turbine to a Conventional HAWT Design

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關鍵詞　noise, power, wind energy, wind turbine, toroidal rotor

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Development and Comparison of a Small-Scale Toroidal Horizontal-Axis Wind Turbine to a Conventional HAWT Design

ABSTRACT

Wind energy is one of the most promising and rapidly growing sources of renewable energy, although maximizing its efficiency while minimizing noise remains a challenge and limits its widespread adoption. The emergence of toroidal propellers, which have gained popularity for producing comparable thrust levels to traditional drone propellers while producing less noise, could mitigate this. This study aimed to develop a small-scale toroidal HAWT and compare its power and noise output to a conventional rotor design under similar wind velocity conditions. 15-centimeter diameter models of the toroidal and conventional rotors were created in Fusion 360 and simulated using Ansys Fluent to identify the significant aerodynamic characteristics that positively affect the blades' power coefficient. The toroidal design with the greatest simulated power output at low tip speed ratios (TSRs) was then 3D printed and physically tested in a wind tunnel against the control rotor. The experimental results confirmed that the toroidal design had greater power coefficients at lower TSRs compared to the control rotor. The toroidal rotor started operating at a wind velocity of 3 m/s compared to the control rotor's 6 m/s, which indicates superior start-up characteristics. While the toroidal rotor produced half the power output of the control at the highest tested wind speed of 7 m/s, it emitted 18 decibels less noise and showed a reduction in discernible noise between frequencies of two to five kilohertz. The results from this study show its potential in low-noise wind turbines within low-wind velocity environments.

Keywords: noise, power, wind energy, wind turbine, toroidal rotor

INTRODUCTION

Wind energy is emerging as a mainstream source of renewable energy as awareness grows on the need for a sustainable environment and the demand for power rises (Sohail et al., 2019). From residential use to large-scale grid-connected utilities, wind power has significant potential; as of 2021, wind energy already accounts for 427 megawatts or approximately 1.6% of the country's total capacity for energy sources and continues to grow (Department of Energy, 2022).

However, wind power is highly intermittent as meteorological parameters such as wind speed undergo fluctuations, thereby affecting efficiency and generated energy (Ren et al., 2017). Moreover, although wind energy is a cleaner alternative to fossil fuels, it also imposes risks, particularly noise pollution. The anthropogenic noise generated by wind turbines may exert adverse effects, such as inducing stress, annoyance, and sleep disturbance on communities, which limits its widespread adoption (Zerrahn, 2017; Freiberg et al., 2019).

A possible solution is aerodynamics, as the geometry of the rotor blades have a significant effect on the turbine's overall efficiency and noise emission (Boudis et al., 2023). One such configuration that has garnered attention in a related field is the toroidal propeller, which is a characteristically ring-shaped propeller that has each blade looping onto one another. This design disperses and minimizes the vortices produced over the tips of the propeller, resulting in a more rapid and evenly distributed reduction in noise while producing comparable levels of thrust (Blain, 2023; Ion & Simion, 2023). This may be more utilized in residential areas and contribute to making wind energy more widespread and accessible. Literature on toroidal structures, however, remains limited, and their advantages are not yet fully realized, specifically in the context of a wind turbine rotor.

Thus, this study aims to design and fabricate a toroidal-bladed horizontal-axis wind turbine (HAWT) and compare its energy and noise generation to a standard design HAWT under similar wind velocity conditions. Specifically, the project aims to determine the (1) torque, (2) angular speed, (3) tip speed ratio (TSR), (4) output voltage, (5) current, (6) mechanical power, (7) coefficient of performance, (8) sound pressure levels, and (9) frequencies of the developed toroidal HAWT in comparison to a conventional wind turbine design.

METHODOLOGY

Designing and Modeling of HAWTs

3D models of the three-bladed toroidal wind turbine rotors were created through the computer-aided design (CAD) application Autodesk Fusion 360. Based on the small-scale rotor measurements of Bastankhah and Porté-Agel (2017) and the need for the rotors to remain sufficiently small relative to the cross-sectional area of the wind tunnel, the rotors were designed at a diameter of 15 centimeters. Fifteen toroidal designs in total were modeled, varying by loop diameter (2.5 cm, 5.0 cm, 7.5 cm, 10.0 cm, and 12.5 cm) and angle of attack (15°, 30°, and 45°).

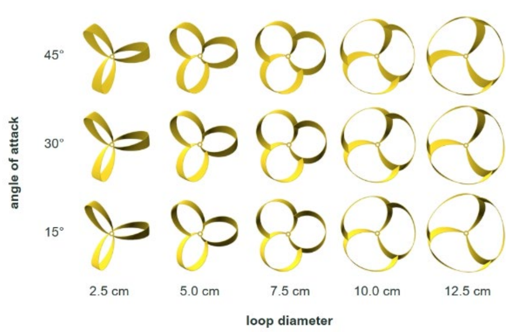

Figure 1. The fifteen toroidal designs with varying angles of attack and loop diameters

The computational fluid dynamics software Ansys Fluent was used to determine the modeled toroidal design that possessed the greatest power coefficients at low wind speeds. The steady state numerical analysis was used to simulate the rotors (Shourangiz-Haghighi et al., 2019). The simulations were run until the residual values and the convergence parameter, which was defined as the aerodynamic torque on the rotor, stabilized and converged.

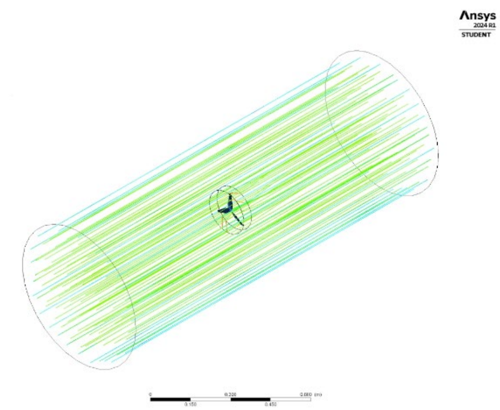

Figure 2. The computational domains of the conventional rotor simulation

The power, TSRs, and power coefficients of the rotors were then calculated. Power is defined as:

$$P = \Gamma\omega \tag{1}$$

where P is the mechanical power generated by the wind turbine in watts (W), Γ is the torque generated by the wind turbine in Newton-meters (Nm), and ω is the angular speed of the rotor in radians per second (rad/s).

The TSR is defined as:

$$\mathrm{TSR} = \frac{R\omega}{U_\infty} \tag{2}$$

where TSR is the tip-speed ratio, R is the radius of the rotor tip blade in meters (m), ω is the angular speed of the rotor in radians per second (rad/s), and U_∞ is the free wind speed in meters per second (m/s).

Lastly, the power coefficient is defined as:

$$Cp = \frac{P}{\frac{1}{2}\rho A U_\infty^3} \tag{3}$$

where P is the mechanical power generated by the wind turbine in watts (W), ρ is the density of the wind in kilograms per meter cubed (kg/m^3), A is the swept area of the rotor in square meters (m^2), and U_∞ is the free wind speed.

The results were then plotted on graphs and analyzed. The toroidal design with a loop diameter of 2.5 cm at a 30° angle of attack was chosen as the most optimal design from the fifteen toroidal models for its high torque and power output at low TSRs.

3D Printing and Construction of HAWTs

The 3D models of the chosen toroidal and conventional rotors were printed using polylactide acid (PLA) filament. A physical device was developed for the verification of the simulated results. The developed turbine used the STELR wind kit for its generator, which was then inserted and screwed perpendicularly into a four-foot, 1.5-inch diameter PVC pipe held on a clamp as seen in Figure 3.

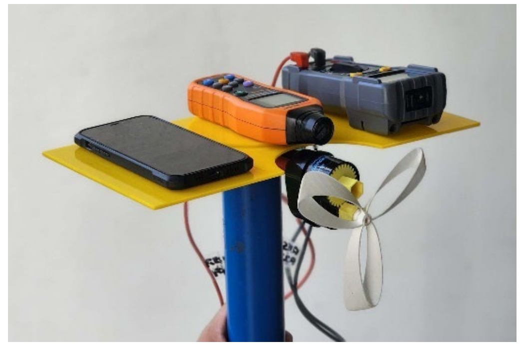

Figure 3. Existing developed wind turbine device

Testing of Toroidal and Conventional HAWTs

The HAWT was tested on its energy and noise production at the PAGASA Wind Tunnel Facility. The wind turbine was tested at wind velocities of 2 m/s to 7 m/s based on the wind speeds measured at a built environment, specifically Nuvali, Laguna, with the NACA 4412 acting as the control. As shown in Figure 4, a setup was developed to measure the angular velocity, noise, and energy production of the wind turbine.

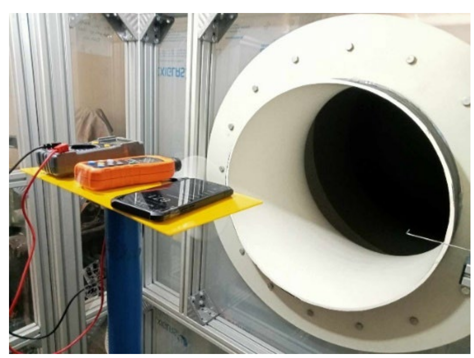

Figure 4. Wind turbine in the wind tunnel

The wind turbines were tested five times at each wind speed in 30-second time blocks at a logging rate of 1 Hz. Data collection was initiated once the system reached a steady state, wherein the readings of the HAWTs exhibited minimal variation.

Data Processing

The means of the readings were taken from the primary data collected across the five replicates and tabulated in Microsoft Excel. The recorded audio of the operating wind turbine noise and the sound pressure levels of the background noise was then post-processed in Audacity.

The power, TSRs, and power coefficients of the rotors were again calculated. The power generated by the wind turbine in the experimental set-up is defined as:

$$P = AV \tag{4}$$

where P is the mechanical power in watts (W), A is the electric current in amperes (A), and V is the output voltage in volts (V). The TSRs and power coefficients of the set-up were calculated using equations (2) and (3).

RESULTS

Simulation of Rotor Designs

The iterations of the toroidal rotors were simulated at TSRs of 0.5 to 4.0, with the objective to maximize the peak power coefficient of the toroidal rotor, as well as maximize its generated power at a given wind distribution, particularly at low wind velocities. Figure 5 shows the results of the best performing iterations.

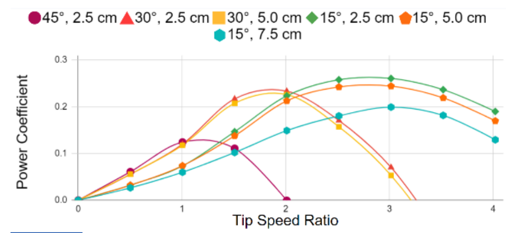

Figure 5. Power coefficient vs. tip speed ratio of the best toroidal rotors (simulation)

Based on its peak power coefficient of 0.26 at TSR 2.75, the toroidal iteration with a loop diameter of 2.5 cm at a 15° angle of attack was the best design. Iterations with similar angles of attack but wider loop diameters, such as 5.0 cm and 7.5 cm, had lower power coefficients. The toroidal iteration with a loop diameter of 2.5 cm at a 30° angle of attack, in particular, peaks early at TSR 1.8 with a power coefficient of 0.24 and has a considerable increase of power at lower TSRs compared to its 15° angle of attack counterpart.

As seen in Figure 6, while the toroidal design is unable to reach peak power coefficients as high as the control rotor, it has increased power coefficients at lower TSRs. Based on the simulation results, the toroidal design with a loop diameter of 2.5 cm at a 30° angle of attack was able to produce 294%, 232%, and 133% of the NACA rotor's power at TSRs 1.0, 1.5, and 2.0 respectively. It then intersected with the control rotor's curve at a TSR of 2.2.

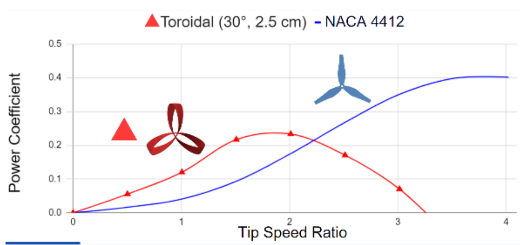

Figure 6. Power coefficient vs. tip speed ratio of ideal toroidal vs. NACA 4412 (simulation).

Experimental Testing of Toroidal Rotor

The experimental results, as seen in Table 1, show that at wind velocities of 3-7 m/s, the toroidal rotor had power coefficients of 0.18 to 0.22 at TSRs of 5.2 to 8.3. The control rotor had power coefficients of 0.36 and 0.41 at TSRs of 10.3 and 14.0 respectively, although it started operating at 6 and 7 m/s.

Table 1. Power coefficients of toroidal vs. NACA 4412 at different wind velocities

	Toroidal		Control	
Wind Velocity (m/s)	Power Coefficient	Tip Speed Ratio	Power Coefficient	Tip Speed Ratio
3	0.18	5	0	0
4	0.23	7	0	0
5	0.23	7	0	0
6	0.22	8	0.36	10
7	0.20	8	0.42	14

Figure 7 shows that the toroidal rotor produced less power compared to the control rotor at 6 and 7 m/s. The control rotor, however, also produced a greater noise output in terms of sound pressure levels compared to the toroidal rotor as displayed in Figure 7. The toroidal design produced 10 and 18 decibels less than the conventional design at a wind velocity of 6 m/s and 7 m/s respectively; the toroidal rotor had a 13% decrease in noise for a 40% decrease in power at 6 m/s and a 21% decrease in noise for a 52% decrease in power at 7 m/s.

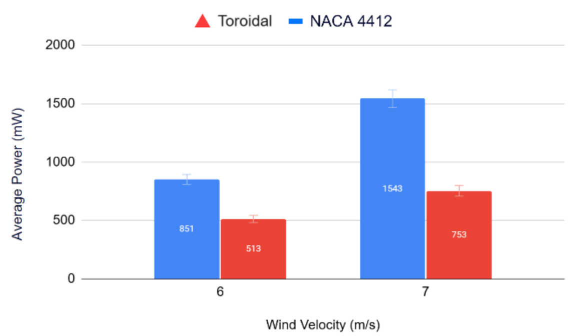

Figure 6. Average power of toroidal vs. NACA 4412 at 6 and 7 m/s ± SD.

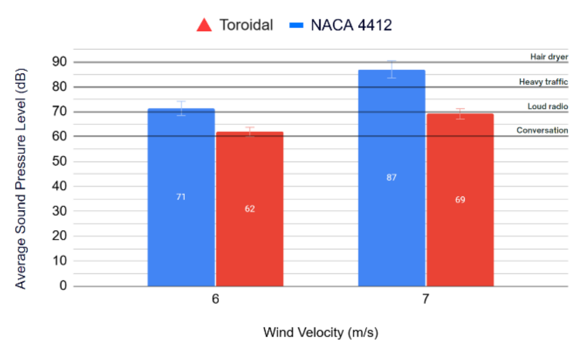

Figure 7. Average decibel levels of toroidal vs. NACA 4412 at 6 and 7 m/s ± SD.

Figure 8 shows the noise spectra of the rotors at 7 m/s, where a reduction in the discernible noise achieved by the toroidal propeller at approximately two to five kilohertz can be observed.

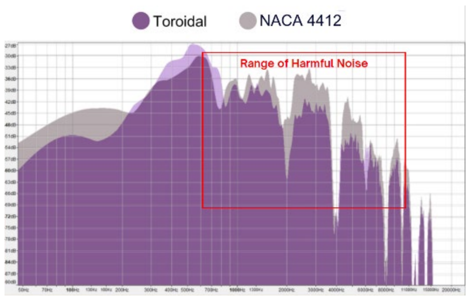

Figure 8. Noise spectra generated by toroidal vs. NACA 4412 rotors.

DISCUSSION

Efficiency of Toroidal Iterations

Based on Figure 5, the toroidal rotors generally produced a greater power coefficient at smaller loop diameters, which indicated better performance and efficiency. Increasing the angle of attack, meanwhile, generally produced greater power coefficients at the lower TSR ranges of 0.5 to 2.0. As shown, a 45° angle of attack produces the greatest amount of torque and power at TSRs less than 1.0. These greater angles of attack, however, quickly induce stall at higher TSRs.

The toroidal design with a loop diameter of 2.5 cm at a 30° angle of attack was chosen for its high torque and power output at low TSRs, which indicates better start-up characteristics and higher efficiencies at low wind velocities. This greater efficiency at lower TSRs can likely be attributed to its stronger structure and wider surface area directly facing the wind, thus creating better conditions to catch the wind at lower velocities as investigated by Jeon et al. (2020) and Kim et al. (2017) in their studies on loop-type wind turbines. These designs' capacity to produce greater torque at low wind speeds makes these designs more suitable for areas with intermittent wind. However, the larger surface area induces drag that slows it down at higher wind speeds.

Performance of Toroidal Rotor

As mentioned previously, the toroidal rotor performs better at low TSRs as shown in Figures 5 and 6 and Table 1, and its superior start-up characteristics compared to the conventional design was demonstrated by the control not operating until a wind velocity of 6 m/s. While the toroidal rotor was only able to produce roughly half of the power generated by the conventional design at the tested wind speeds where both rotors were able to operate, the reduction in noise from the control to the toroidal rotor may be compared to going from a hair dryer to a normal conversation.

Moreover, the reduction in discernible noise seen in Figure 8 falls within the range of frequencies human ears are particularly sensitive to, which is the most significant contributor to overall noise levels in wind turbine operation. This may lead to less annoyance associated with turbine noise (Deshmukh et al., 2019). The enclosed loop structure minimizing vortices generated at the blade tips and increasing solidity, as well as the toroidal rotor operating at lower TSRs compared to the control under similar conditions, may lead to reduced noise generation (Ali et al., 2015; Jeon et al., 2020; Kim et al., 2017; Schubel & Crossley, 2012).

SUMMARY AND CONCLUSION

This study designed and fabricated a toroidal-bladed HAWT and compared its energy and noise production to a conventional design using both simulations and a wind tunnel set-up. The results suggest that the toroidal rotor may be less harmful to human hearing and, therefore, more applicable closer to residential and city areas, where power may be a necessary cost in exchange for human comfort, while the conventional design is more applicable farther away from people. The toroidal design is also suitable for areas with low and intermittent wind velocities, particularly in built environments, where wind speeds are 4 m/s on average.

While the current study may generate data regarding the feasibility of toroidal HAWTs as an alternative energy source and aid in the further development of wind turbine designs, the findings of study will remain limited to the limited iterations of small-scale designs developed. As such, future research could examine larger scale variations of the toroidal design and further experiment with different loop diameters, angles of attack, and thickness of the blades, as well as introduce an airfoil into the toroidal design and utilize glass fiber reinforced polymer.

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1. The research topic matches the global human needs of green technology and the protection of the environment.
2. In addition to describing the engineering process of this research work, it would be good (also required) to present the innovation of this work. A comparison of the proposed system with existing state-of-the-art methods should be provided in the introduction so the advances, contributions, and novelty of the approach can be identified. (For example, why toroidal-bladed?)
3. The findings indicating that the toroidal rotor has better start-up characteristics and lower noise levels are promising. However, the trade-off of reduced power output at higher wind speeds should be discussed in more detail. In addition, the improvement also depends on the specific design of the blade. Perhaps a thorough analysis of the structure dynamics will help quantify the performance better.
4. It is shown that the toroidal blades improve the average noise level. The experimental results show that the proposed design can effectively reduce noise by 18 dB when producing half power output at 7 m/s. It would be good to conduct a

comparative analysis of the noise level when the power output was adjusted to be the same. Specifically, whether the design continues to generate less noise than the control group at a lower wind speed should be validated while maintaining the same power output.

5. Consider discussing the environmental impact of producing and using these rotors, including material sourcing and recyclability.

6. Equation 4 states a simple equation of P=AV to calculate the power output. What was the load during this test? Simply taking the short-circuit current and open-circuit voltage does not reveal the power output.

7. It would be good to compare the simulation and experimental results regarding both power generation efficiency and noise reduction level. In addition, elaborating on the cost efficiency in designing and manufacturing the toroidal blade is helpful.

8. Authors are advised to ensure all abbreviations are written out in full the first time. This is particularly important in the abstract and in the conclusions.