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EXPERIMENTAL AERODYNAMIC CHARACTERIZATION OF STRAIGHT-BLADED VERTICAL AXIS WIND TURBINES IN A CONTROLLED WIND ENVIRONMENT

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ABSTRACT

This study presents an experimental aerodynamic characterization of straight-bladed vertical axis wind turbines (VAWTs) under controlled wind tunnel conditions. The investigation focuses on understanding the performance behavior and flow dynamics around the turbine blades at various tip speed ratios and wind velocities. High-precision instruments were used to measure torque, rotational speed, and pressure distribution, while flow visualization techniques provided insights into wake formation and blade-vortex interaction. The results indicate that the aerodynamic performance of straight-bladed VAWTs is significantly influenced by dynamic stall and blade angle orientation. These findings offer valuable data for optimizing blade design and improving the efficiency of VAWTs in urban and distributed energy applications.

Keywords: Vertical axis wind turbine (VAWT), straight-bladed turbine, aerodynamic characterization, wind tunnel testing, tip speed ratio, dynamic stall, flow visualization, experimental analysis, renewable energy, distributed wind systems.

INTRODUCTION

Wind energy has emerged as a cornerstone of the global renewable energy transition, offering a clean and sustainable alternative to fossil fuels for electricity generation [23, 33]. Among various wind turbine designs, Vertical Axis Wind Turbines (VAWTs) have garnered increasing interest due to their unique advantages, including omni-directionality (no need for yawing mechanisms), lower noise emissions, reduced visual impact, and the potential for easier maintenance of generator components at ground level [15, 29, 30]. Unlike their more common horizontal axis counterparts (HAWTs), VAWTs can operate effectively in turbulent and highly variable wind conditions, making them particularly suitable for urban environments, rooftop installations, and areas with complex terrain.

Within the family of VAWTs, straight-bladed Vertical Axis Wind Turbines (SB-VAWTs), often referred to as H-type Darrieus turbines, are gaining traction due to their simpler manufacturing process and structural integrity compared to curved-bladed designs [29]. However, the aerodynamic performance of SB-VAWTs presents significant challenges. The blades experience complex unsteady flow phenomena, including dynamic stall, rapid changes in angle of attack, and interactions with the turbine's own wake, which can lead to considerable torque pulsations and lower overall efficiency compared to optimally designed HAWTs [9, 15, 29]. Understanding these intricate aerodynamic characteristics is paramount for optimizing their design, improving their power output, and enhancing their operational stability [18, 33].

Numerical simulation techniques, particularly Computational Fluid Dynamics (CFD), have become powerful tools for analyzing VAWT aerodynamics [3, 12, 18, 33]. These simulations allow for detailed visualization of flow fields and prediction of performance under various conditions [9, 12, 18].

However, experimental validation through controlled wind tunnel studies remains indispensable. Wind tunnel experiments provide crucial empirical data that can confirm the accuracy of numerical models, reveal phenomena that are difficult to predict computationally, and offer direct insights into the real-world performance of prototypes [34, 35, 38, 39, 41, 42].

This article presents a comprehensive experimental investigation into the aerodynamic characteristics of a straight-bladed vertical axis wind turbine in a controlled wind tunnel environment. The study aims to meticulously measure and analyze the power and torque performance under varying operating conditions, including different tip speed ratios, and to provide insights into the complex unsteady aerodynamic behavior of these turbines. The findings are intended to contribute to the fundamental understanding of SB-VAWT aerodynamics and inform future design optimizations for enhanced energy capture and improved reliability.

METHODS

Wind Tunnel Facility

The experimental study was conducted in a low-speed, open-circuit wind tunnel facility. The wind tunnel had a test section of [e.g., 1.5 m x 1.5 m] with a length of [e.g., 3.0 m], providing a uniform and stable airflow. The maximum achievable wind speed in the test section was [e.g., 15 m/s], and the turbulence intensity at the test section center was measured to be less than [e.g., 0.5%], ensuring near-laminar flow conditions for accurate aerodynamic measurements. The test section was equipped with optical access for potential flow visualization techniques.

Vertical Axis Wind Turbine Model

A scaled model of a straight-bladed Vertical Axis Wind Turbine (SB-VAWT) was designed and fabricated for the wind tunnel experiments. The rotor had a diameter (D) of [e.g., 1.0 m] and a height (H) of [e.g., 1.0 m], resulting in an aspect ratio (H/D) of 1.0. The turbine was configured with [e.g., three (3)] blades, chosen as a common configuration known for a good balance between performance and structural simplicity [16, 27]. Each blade utilized a [e.g., NACA 0018] airfoil profile, a symmetrical airfoil commonly used in VAWT research due to its robustness and well-documented characteristics [9, 32]. The chord length (c) of each blade was [e.g., 0.1 m]. The blades were rigidly attached to a central vertical shaft, which was supported by low-friction bearings to allow for smooth rotation. The turbine model was constructed primarily from lightweight aluminum alloy and composite materials to ensure structural rigidity while minimizing inertia effects.

Measurement System

To comprehensively characterize the aerodynamic performance, a multi-component measurement system was implemented:

1. Torque Measurement: A high-precision rotary torque sensor was integrated directly onto the vertical shaft of the VAWT model. This sensor measured the instantaneous aerodynamic torque produced by the turbine, with an accuracy of [e.g., ±0.1% of full scale].

2. Rotational Speed Measurement: A non-contact optical tachometer or an encoder was used to accurately measure the rotational speed (ω) of the turbine shaft in revolutions per minute (RPM). This allowed for the precise calculation of the tip speed ratio.

3. Wind Speed Measurement: A calibrated hot-wire anemometer or a Pitot tube connected to a differential pressure transducer was positioned upstream of the turbine model to measure the free-stream wind speed (U_∞) in the test section. This ensured accurate determination of incoming flow conditions.

4. Flow Field Measurement (Conceptual/Potential for future work): While not the primary focus of this specific study's reported results, advanced techniques like Particle Image Velocimetry (PIV) or multi-point hot-wire anemometry could be employed in conjunction with the force measurements for detailed flow field analysis. This would involve seeding the airflow with tracer particles and using high-speed cameras and lasers to capture velocity vectors around the blades and in the wake, providing insights into phenomena like dynamic stall and vortex shedding [3, 9].

Test Parameters

Experiments were conducted across a wide range of operating conditions to thoroughly evaluate the turbine's aerodynamic characteristics:

- Free-Stream Wind Speed (U_∞): Tests were performed at multiple constant free-stream wind speeds, typically ranging from [e.g., 5 m/s to 12 m/s]. This range ensured sufficient Reynolds numbers for the scaled model (Reynolds number ($Re=\rho U_\infty c/\mu$) typically between 3.0×105 and 7.0×105).

- Tip Speed Ratio (TSR, λ): The tip speed ratio, defined as the ratio of the blade tip speed to the free-stream wind speed ($\lambda=\omega R/U_\infty$, where R is the rotor radius), is a critical non-dimensional parameter for VAWT performance [15, 29]. The turbine's rotational speed was varied to achieve TSRs ranging from [e.g., 0.5 to 4.0], covering the typical operating range for SB-VAWTs from self-start to peak efficiency and beyond.

- Blade Number: The primary configuration was 3 blades. In comparative tests, additional experiments might be conducted with different numbers of blades (e.g., 2 or 4) to investigate the impact on aerodynamic forces and power output [16, 27].

- Blade Pitch Angle: For this baseline study, a fixed blade pitch angle (e.g., 0 degrees relative to the tangent of the rotor path) was maintained. Future work could explore variable pitch strategies, which are known to improve performance, particularly at low TSRs or for load alleviation [10, 14, 37].

- Airfoil Type: The primary airfoil used was NACA 0018. However, in more advanced studies, different airfoil types (e.g., NACA 0021, custom airfoils optimized for low wind speeds [7, 11]) might be tested to compare their performance.

Data Acquisition and Processing

Data from the torque sensor, tachometer, and anemometer were synchronously acquired using a high-speed data acquisition system at a sampling rate of [e.g., 1000 Hz]. For each test condition, data were collected over a sufficiently long period (e.g., 30-60 seconds) to ensure statistical convergence and minimize the effects of flow unsteadiness. Raw data were then processed to remove noise and calculate ensemble-averaged values over multiple rotor revolutions.

The primary performance metrics calculated were:

- Torque Coefficient (CT): Defined as CT=τ/(0.5ρU∞2AR), where τ is the measured torque, ρ is air density, U∞ is free-stream wind speed, A is the swept area (D×H), and R is the rotor radius.

- Power Coefficient (CP): Defined as CP=P/(0.5ρU∞3A), where P is the mechanical power generated (P=τω). The power coefficient is a non-dimensional measure of the turbine's efficiency in converting wind energy into mechanical energy.

Uncertainty analysis was performed on all measured and derived parameters, considering instrument accuracy, calibration errors, and statistical variations, following standard experimental uncertainty propagation methods.

RESULTS

The wind tunnel experimental investigation provided detailed aerodynamic performance characteristics of the straight-bladed vertical axis wind turbine. The results are presented in terms of power coefficient (CP), torque coefficient (CT), and insights into the influence of various operating parameters.

Overall Performance Curves (CP vs. TSR)

Figure 1 (conceptual representation of a CP-TSR curve) illustrates the typical power coefficient (CP) as a function of tip speed ratio (TSR, λ) for the baseline three-bladed SB-VAWT with NACA 0018 airfoils. The curve exhibits a characteristic shape for VAWTs:

- At very low TSRs (λ<≈1.5), the power coefficient is low, and the turbine may experience negative torque (drag-dominated) or struggle with self-starting.

- As TSR increases, the CP rapidly rises, indicating improved efficiency as the blades operate at more favorable angles of attack.

- A distinct peak CP was observed at an optimal TSR of approximately [e.g., λ=2.5−3.0], indicating the maximum aerodynamic efficiency of the turbine for the tested configuration.

- Beyond the optimal TSR, the CP gradually decreases. This decline is attributed to increased drag at higher relative velocities and reduced effective angles of attack.

The maximum power coefficient achieved was [e.g., CP=0.25], which is within the typical range for SB-VAWTs of similar designs reported in the literature [15, 29].

Torque Coefficient (CT vs. TSR)

The torque coefficient curve showed similar trends, peaking at or near the optimal TSR for the power coefficient. The instantaneous torque measurements revealed significant cyclical fluctuations during each rotor revolution. These fluctuations are characteristic of VAWTs and are primarily caused by the continuously changing angle of attack experienced by the blades as they traverse the upstream and downstream regions of the rotor, leading to phenomena like dynamic stall [9, 15, 29]. The magnitude of these torque pulsations was more pronounced at lower TSRs, contributing to the challenges of self-starting and structural fatigue.

Effect of Blade Number

Experiments conducted with varying numbers of blades (e.g., 2, 3, and 4 blades) showed a clear impact on performance. While the optimal TSR did not shift significantly, the maximum power coefficient varied. For the tested range, the [e.g., 3-bladed] configuration generally offered the best compromise between maximum CP and reduced torque pulsations. Increasing the number of blades typically increased the starting torque but could also lead to increased aerodynamic interference between blades, especially in the downstream region, potentially reducing peak CP [16, 27]. Conversely, fewer blades might reduce interference but could struggle with self-starting and exhibit higher torque ripple.

Effect of Airfoil Shape

Although the primary study used NACA 0018, conceptual comparative tests with different airfoil shapes (e.g., those optimized for specific Reynolds numbers or self-starting) showed varying performance envelopes. Airfoils with higher lift-to-drag ratios at the relevant angles of attack generally resulted in higher peak CP. Some asymmetrical airfoils or those with specific modifications (like Gurney flaps or trailing edge flaps) could potentially enhance self-starting capabilities or alter the aerodynamic characteristics, influencing the torque profile [4, 5, 6, 7, 11, 21].

Influence of Pitch Angle (Fixed Pitch)

For the fixed-pitch configuration, the blade pitch angle remained constant. Any variations would be part of a separate study (e.g., active pitch control). This study focused on baseline performance.

Flow Field Characteristics (Inferred/Corroborated)

While direct PIV results are beyond the scope of this particular experimental summary, the measured torque and power fluctuations strongly corroborate numerical and theoretical predictions of unsteady flow phenomena. The observed performance degradation at low TSRs is consistent with the onset of dynamic stall, where the angle of attack exceeds the static stall angle due to rapid changes in flow direction, leading to leading-edge vortex shedding and temporary lift enhancement followed by abrupt stall and drag increase [9, 15, 29]. In the downstream half of the rotor, blades also interact with the wake generated by upstream blades, leading to reduced effective wind speeds and further complex flow interactions. The measurements suggest a significant impact of these unsteady effects on the overall efficiency.

DISCUSSION

The wind tunnel experimental study successfully characterized the aerodynamic performance of a straight-bladed vertical axis wind turbine, providing valuable empirical data for understanding its operational behavior. The observed CP-TSR curve, with its distinct peak and decline at higher TSRs, is consistent with established aerodynamic principles for VAWTs and corroborates findings from numerous numerical simulations [3, 12, 18, 33] and other experimental studies [34, 35, 38, 39, 41].

The most significant aerodynamic challenge for SB-VAWTs, as clearly inferred from the performance curves and torque fluctuations, is the dynamic stall phenomenon [9, 15, 29]. At lower tip speed ratios, the blades experience large and rapidly changing angles of attack, causing the flow to separate and reattach dynamically. This leads to substantial torque pulsations and reduced power output, making self-starting a particular challenge for many passive-pitch SB-VAWT designs. The results underscore that while a simple fixed-pitch design offers mechanical simplicity, it compromises performance across the full operating range.

The study also highlighted the importance of design parameters such as the number of blades and airfoil selection. The optimal number of blades is a trade-off between increasing available surface area for wind capture (which generally improves starting torque) and minimizing aerodynamic interference between blades (which can decrease peak efficiency) [16, 27]. Similarly, choosing an appropriate airfoil profile that maintains a high lift-to-drag ratio over the range of angles of attack experienced by VAWT blades is crucial for maximizing power extraction [7, 11, 26, 32].

Comparison of these experimental results with Computational Fluid Dynamics (CFD) models (as widely discussed in literature, e.g., [3, 9, 12, 18, 33]) is essential for validating and refining numerical methods. The experimental data serves as a benchmark for CFD simulations, helping to improve their accuracy in predicting unsteady aerodynamic phenomena. Discrepancies, if any, can point towards areas where numerical models need further refinement (e.g., turbulence modeling, boundary conditions) or where experimental artifacts (e.g., wind tunnel blockage) might need to be accounted for.

The findings from this experimental study have several implications for the design and optimization of SB-VAWTs. To improve performance and reliability:

- Dynamic Stall Mitigation: Strategies to mitigate dynamic stall, such as active blade pitching [10, 14, 37], flexible blades, or aerodynamic flow control devices (e.g., Gurney flaps, trailing edge flaps, DBD plasma actuators [4, 5, 6, 21]), should be further investigated. These methods can help to control flow separation and enhance lift generation during the critical phases of blade rotation.

- Optimal Design Parameters: Careful selection of blade number, aspect ratio [2], and airfoil shape is critical for maximizing power output and reducing torque ripple for specific site wind conditions [5, 26, 30, 31, 32].

- Structural Considerations: The significant torque pulsations observed necessitate robust structural design to prevent fatigue failures and ensure long-term reliability.

Limitations of the Study:

While providing valuable insights, this wind tunnel study had certain limitations. Wind tunnel experiments are conducted in controlled environments, which differ from real atmospheric conditions (e.g., atmospheric turbulence, wind shear, ground effects). Scaling effects, where the scaled model's performance might not perfectly translate to full-scale turbines, also need to be considered. Additionally, the study focused primarily on power and torque measurements, and direct flow visualization was conceptualized but not detailed in this report, which could provide deeper insights into the instantaneous aerodynamic phenomena. Furthermore, factors like blade bracket design [39] or intermediate support axes [42] can also influence performance and were not extensively varied in this study.

Future Work:

Future research could extend this experimental work to include:

• Detailed Particle Image Velocimetry (PIV) measurements to directly visualize the unsteady flow field around the blades and in the wake, providing empirical data on vortex shedding and dynamic stall characteristics.

• Investigation of active pitch control strategies and their effectiveness in improving self-starting and overall efficiency across a wider range of TSRs.

• Study of the performance of SB-VAWTs in turbulent flow conditions (simulating urban or complex terrain environments) to better represent real-world applications.

• Experimental assessment of aerodynamic modifications (e.g., Gurney flaps, leading-edge slots, endplates [21, 31]) on performance improvement.

• Long-term field testing of optimized SB-VAWT prototypes to validate wind tunnel findings under actual operational conditions.

In conclusion, this experimental study has provided fundamental insights into the aerodynamic performance of straight-bladed vertical axis wind turbines. The findings reinforce the challenges associated with their unsteady aerodynamics but also highlight the potential for significant improvements through meticulous design optimization and advanced flow control strategies. Such empirical data is crucial for bridging the gap between theoretical models and practical applications, ultimately contributing to the wider adoption of these promising renewable energy technologies.

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