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The effects of inertia on a straight-bladed vertical axis wind turbine

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Abstract. The application of vertical axis wind turbines (VAWTs) is gaining increasing attention, particularly in urban areas with highly turbulent wind conditions. The airfoil blade is a critical component of a wind turbine which determines its overall performance. However, Darrieus turbines often suffer from self-starting issues which are closely related to inertia. Since blade inertia is influenced by their material, lightweight materials are typically used for blade manufacture. Nevertheless, experimental study on the blade inertia of VAWTs remain limited. This paper investigates the effects of blade inertia on a straight-bladed VAWT. A two-bladed NACA0018 VAWT with a 700 mm diameter and an aspect ratio of 1 was fabricated and tested in a wind tunnel at an incoming wind speed of 5.61 m/s. To compare the effects of inertia, two different blade coatings—epoxy and thin film were used. The difference in the coating material density resulted in varying blade inertia. The study focused on self-starting behavior, maximum rotational speed, and power output. The coefficient of power (C_P) was analyzed across a wide range of tip speed ratios (TSRs) under various load conditions. The results indicate that as inertia increases, the turbine takes longer to reach its maximum rotational speed, exhibiting lower angular acceleration and greater fluctuation in the transient state before stabilizing. Additionally, the VAWT with 2.3 times higher blade inertia exhibited lower maximum rotational speed and power output. In contrast, the turbine with lower blade inertia achieved a 30% higher rotational speed and a 69.75% increase in maximum C_P.

Keywords: Vertical axis wind turbine, Darrieus turbine, Inertia, Wind tunnel testing, Coefficient of Power (C_P)

1. Introduction

Wind energy is one of the main sources of clean and renewable energy. According to the Global Wind Energy Report, the total cumulative installed wind capacity reached 1021 GW in 2023. Compared to 319 GW in 2013, this represents a more than threefold increase over a decade. Forecasts suggest that from 2024 to 2030, wind capacity will grow by approximately 1210 GW [1].

The iconic horizontal axis wind turbines (HAWTs) have long dominated the market due to their efficiency. However, vertical axis wind turbines (VAWTs) are gaining increasing attention for their omni-directional characteristics. One of the main challenges with VAWTs, particularly H-rotor designs, is their low self-starting ability. Numerous studies have been conducted to address this issue and enhance turbine efficiency. These studies focus on turbine parameter optimization, configurations, power augmentation devices, variable mechanisms, and more [2-6].

Research also shows that the self-starting ability of the H-rotor VAWT is related to its inertia. Tigabu et al. [7] conducted computational simulations to explore how inertia affects the self-starting behavior of vertical axis hydrokinetic turbines by varying blade density. They found that at minimal inertia, the added mass has a significant impact on the turbine's dynamics, causing the greatest overshoot in blade speed. As inertia increases, the peak is dampened, but the acceleration slows. Moreover, reducing inertia results in a shorter starting time. A fluid-structure interaction simulation was conducted by Liu et al. [8] on a hybrid H-type and Savonius turbine. A large inertia in the VAWTs leads to slow acceleration, resulting in low angular velocity. This causes the blades to experience significant dynamic stall, which greatly reduces the aerodynamic moment of the turbine. As a result, the startup process takes longer for VAWTs with higher inertia. A CFD simulation by Huang et al. [9] on a variable solidity VAWT revealed that both solidity and moment of inertia have a significant impact on the self-starting capability. Similarly, Arab et al. [10] investigated the effects of inertia on the self-starting characteristics of a Darrieus turbine. Their results indicated that as turbine inertia increases, it takes longer to reach the final velocity, and in some cases, the turbine may fail to reach this condition, causing the rotation to stop. Maalouly et al. [11]performed a transient CFD analysis of an H-rotor VAWT and found that minimizing the inertia of a steady-optimized turbine significantly improves its startup characteristics, making it superior to its steady-optimized counterpart. Cheng and Yao [12] optimized a U-type VAWT using machine learning and found that, due to its smaller moment of inertia, the U-shaped VAWT can rotate at a higher angular velocity, allowing it to capture and convert wind energy at a higher TSR. In contrast, Celik et al. [13] reported a contradictory observation when investigating the start-up process of an H-rotor using CFD. They found that increasing turbine inertia had minimal effect on the start-up behavior and final rotational speed. However, it increased the instantaneous turbine power during the start-up process, and the optimum TSR was observed with decreasing turbine inertia.

The literature review reveals a lack of experimental studies on the effects of inertia in straight-bladed vertical axis wind turbines. Only one experimental study by Davari et al. [14] investigated the self-starting characteristics of a Darrieus VAWT. However, their study focused on overcoming friction and inertia rather than analyzing the direct effects of inertia in the VAWT.

This paper investigates the effect of different turbine blade inertias on the aerodynamic performance of the VAWT. Section 2 details the VAWT model, blade variations in inertia, and experimental procedures. Section 3 presents the results and corresponding discussions, while the final section provides the study’s conclusion.

2. Methodology

For a vertical axis wind turbine, several important parameters define its operation and performance. One such parameter is the tip speed ratio, a dimensionless quantity defined as:

$$\lambda = \frac{\omega R}{U_\infty} \tag{1}$$

where ω is the rotational speed of the turbine in rad/s, R is the rotor radius, and U_∞ is the incoming wind speed, The turbine's performance can be obtained by the coefficient of torque (C_T) and coefficient of power (C_P) as follows:

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

where T and P are the torque and power respectively, ρ is the air density and A is the swept area. The inertia, I, of a blade with a mass, m, from the turbine rotational axis is defined as:

$$I = mR^{\,2} \tag{3}$$

2.1 VAWT model and blade inertia

The VAWT used in the experiment is a straight-bladed H-rotor consisting of a rotating shaft and four struts made of carbon fiber rods. Table 1 presents the specifications of the VAWT. The turbine's shaft is mounted in the wind tunnel, with its top and bottom supported by bearings, as shown in figure 1. The airfoil blades are attached to the struts using end caps.

The airfoil blades of the turbine are made of expanded polystyrene foam (EPS). Two different coatings were applied to the blades: epoxy and thin-film as shown in figure 1. The epoxy-coated blades (light blue) were produced by covering the EPS blade with paper and applying a thin layer of epoxy, while the thin-film coating was applied using a heated iron. Both methods result in a smooth blade surface. The mass of an epoxy blade is approximately 210 g, whereas the thin-film-coated blade weighs about 91.5 g. This corresponds to inertias of 0.026 kgm^2 and 0.011 kgm^2 for

Table 1. Wind turbine specification.

Specification	Symbol	Value
Airfoil	-	NACA0018
Number of blades	N	2
Chord length	c	0.15 m
Pitch angle	B	6°
Turbine diameter	D	0.7 m
Turbine height	H	0.7 m
Swept area	A	0.49 m^2
Aspect ratio	AR	1

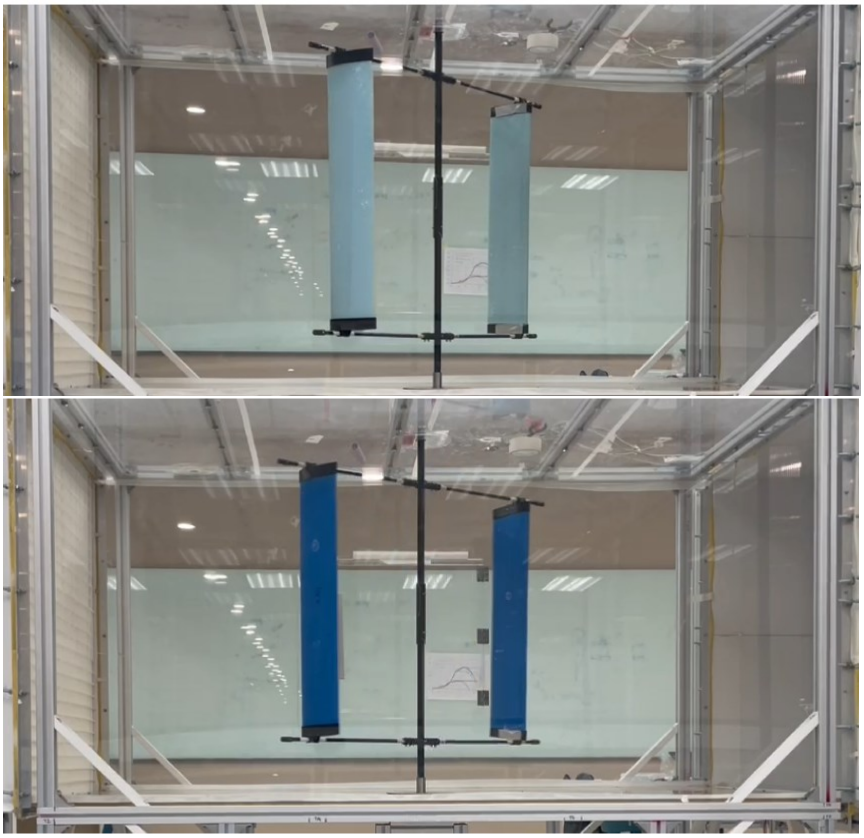

Figure 1. The VAWT which is affixed in the wind tunnel for the testing, the left turbine with light blue epoxy blades whereas the right turbine with navy blue thin film blades.

the epoxy blade and the thin-film blade respectively. The inertia of each epoxy-coated blade is about 2.3 times higher than the thin-film blade.

2.2 Experiment setup and procedure

The testing was conducted in an open-type, low-velocity suction wind tunnel with a test section measuring 1 m in height, 1 m in width, and 2.5 m in length as shown in figure 1. Further details on the wind tunnel can be found in [15].

The experiment was conducted at an incoming wind speed of 5.61 m/s with a turbulence intensity of 3.14%. A torque transducer (FUTEK TRS605) was installed between the turbine shaft and a motor to measure the rotational speed and torque of the VAWT. The data were collected and analyzed using SENSIT software.

The experiment began with an assessment of the turbine's self-starting behavior. The wind tunnel was set to operate with both turbines initially stationary, allowing them to accelerate to their maximum rotational speed. To capture high-resolution data on the self-starting, measurements were recorded at 0.005-second intervals (200 Hz) for approximately one minute. The experiment then proceeded with the turbine performance test, where various loads were applied to the rotor shaft to measure mechanical torque. This was achieved using a motor and pulley system, which provided counter-torque to the rotating shaft. Torque and rotational speed readings were recorded every 0.5 seconds for each loading condition. The average values of the recorded data were then calculated.

Since the turbine size is relatively large compared to the tunnel test section, the blockage effect must be considered. The blockage ratio (Br) is defined as the ratio of the turbine swept area (As) to the test section area (At), as shown in equation 4 [16].

$$Br = \frac{As}{At} \tag{4}$$

The corrected wind speed (Uc) can be obtained from equations 5 and 6 as shown below:

$$Uc = U\infty\,(1 + \mathcal{E}) \tag{5}$$

$$\mathcal{E} = \frac{1}{4} Br \tag{6}$$

$\mathcal{E}$ is the correction factor. After collecting the results, the blockage correction was applied to determine the actual performance, specifically the corrected coefficient of power based on the adjusted wind speed.

3. Results and discussions

3.1 Rotational speed

Figure 2 shows the rotational speed of the turbine as a function of time. As mentioned earlier, the data were recorded at 0.005 s intervals. Both turbines accelerated from rest to their maximum rotational speed.

As shown in the figure, both turbines exhibited similar performance before time step 2000. Between time steps 2000 and 8000, the turbines accelerated, with the thin-film-bladed VAWT displaying a steeper gradient on the graph, indicating greater angular acceleration. Both the epoxy-bladed and thin-film-bladed turbines reached a stable rotational speed around time step

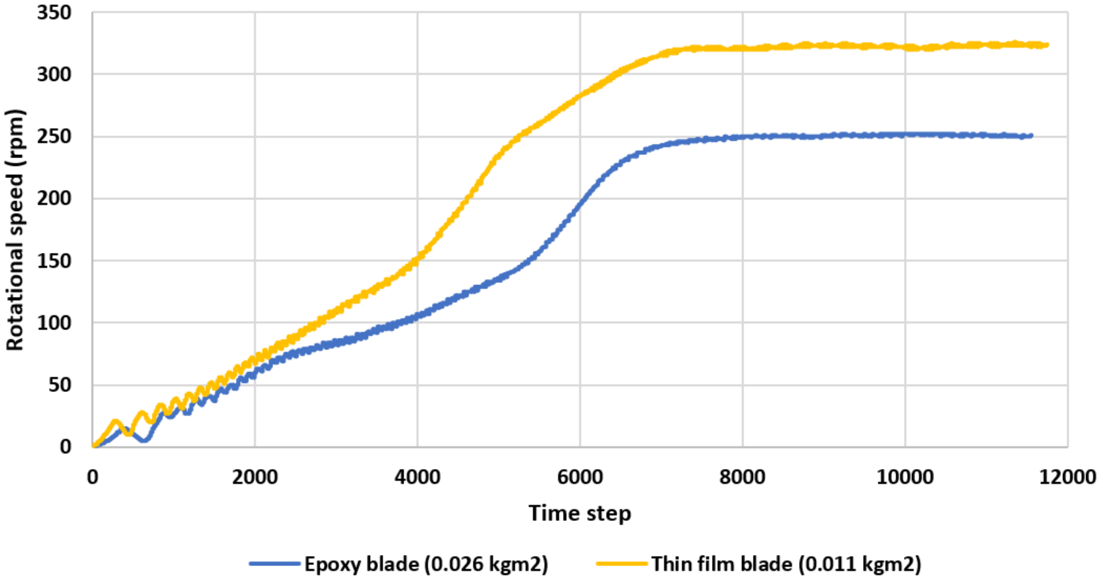

Figure 2. The starting behaviour of the VAWT with different blade inertias.

8000, corresponding to approximately 40 s. The maximum rotational speed of the thin-film-bladed turbine was about 325 rpm, which is 30% higher than the epoxy-bladed turbine's maximum of about 250 rpm. This result suggests that a turbine with a heavier blade and higher inertia more difficult to self-start and attains a lower maximum rotational speed. Additionally, the higher-inertia turbine takes longer to reach the same rotational speed. A similar trend was observed in the simulation results reported by Liu et al. [8].

When analyzing the turbine’s starting behavior, both graphs initially exhibit fluctuating curves. This fluctuation occurs because the blades experience high net torque at the upwind position and low net torque at the downwind position. During the operation of a straight-bladed VAWT, the wind flow interacts with the airfoil blade, generating both lift and drag. These aerodynamic forces produce a tangential force on the blade, which in turn provides torque to spin the turbine. Unlike a horizontal-axis wind turbine, where the blade generates a relatively consistent torque at all azimuthal angles; as shown in figure 3, the force vector in a VAWT continuously changes with the azimuthal angle as the turbine rotates. In the upwind region (Quadrants 1 and 2), the resultant flow impinges on the airfoil at a more favorable angle of attack, with the optimum occurring at approximately a 90° azimuthal angle. Consequently, the torque generated at this position is the highest. In the downwind region (Quadrants 3 and 4), although a symmetrical airfoil is used, the wake generated upstream propagates toward the downstream region, causing the rotor blades to spin more slowly and reducing the energy extracted in this region. Additionally, when the rotor blades are parallel to the incoming flow at 0° and 180° azimuthal angles, almost no torque is generated. This explains the fluctuations observed in the graph before 2000 time steps. As the turbine accelerates and stabilizes its rotational speed, these fluctuations subside. It is also observed that the thin-film-bladed VAWT exhibits more pronounced ripples with shorter time intervals compared to the epoxy-bladed VAWT, indicating that it accelerates more quickly.

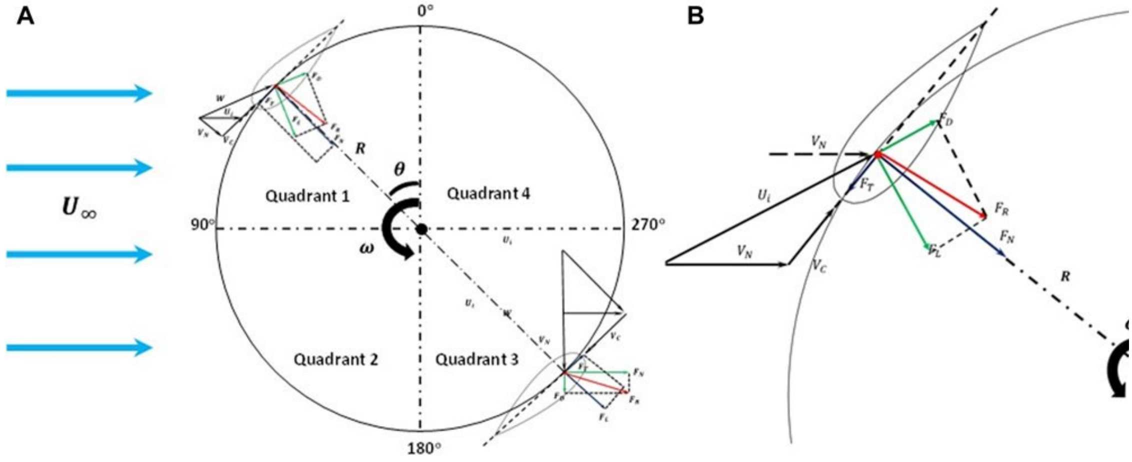

Figure 3. Forces on the airfoil blade at different azimuthal angle of a VAWT.

3.2 Coefficient of power

A turbine's performance can be quantified using the coefficient of power (C_P). A comparison between both turbines is presented in figure 3. The turbine's swept area is 0.49 m^2, and the crosssectional area of the test section is 1 m^2, resulting in a blockage ratio of 0.49. Therefore, the results must account for the tunnel blockage effect, and the corrected results are included.

Figure 4 shows both the uncorrected and corrected data for the VAWTs. The uncorrected $C_{P,max}$ for the thin-film-bladed turbine is 0.388 at a TSR of 1.93. After applying blockage correction, the $C_{P,max}$ is reduced to 0.275 at a TSR of 1.72. Similarly, for the epoxy-bladed VAWT, the uncorrected and corrected $C_{P,max}$ are 0.237 and 0.162 at TSRs of 1.35 and 1.23 respectively.

Comparing the corrected results of the epoxy and thin-film-bladed VAWTs, the lower-inertia thin-film-bladed VAWT achieved a higher maximum C_P of about 69.75%. When analyzing the graph, both turbines exhibited similar gradients before reaching their maximum C_P. This occurs because the higher-inertia blades limit the angular velocity, reducing the tangential velocity interacting with the blade.

At a constant incoming wind speed, the wind strikes the blade at an increased angle of attack, exceeding the optimal value and causing stall. This limits the lift force and reduces the torque generated on the turbine blade. Conversely, for the same turbine specifications, a lighter blade with lower inertia maintains the same lift force while generating sufficient torque to spin the turbine. With the same angular acceleration but lower inertia, the turbine achieves a higher angular velocity, resulting in a greater blade tangential velocity. This leads to a higher TSR and a better angle of attack which is closer to the optimum lift-to-drag ratio, being achieved by the VAWT blades. Consequently, more torque is generated, enhancing turbine performance. A similar observation was reported by [12].

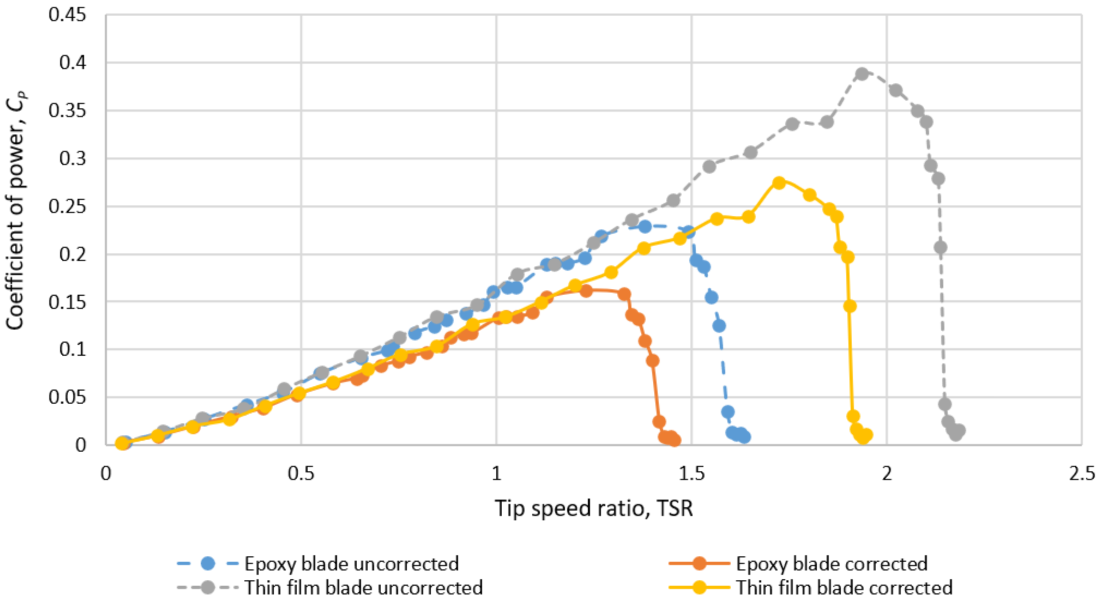

Figure 4. Corrected and uncorrected coefficient of power against tip speed ratio for the epoxy-bladed VAWT and thin film-bladed VAWT.

4. Conclusion

A wind tunnel test was conducted to investigate the effect of blade inertia on a straight-bladed vertical axis wind turbine (VAWT). Identical airfoil blades with two different coatings were used to vary the turbine blade's inertia, while all other parameters of the VAWT remained constant.

The epoxy-coated blade had an inertia 2.3 times higher than the thin-film-coated blade. The results showed that blade inertia significantly affects the aerodynamic performance of the VAWT. The lower-inertia blade turbine achieved a higher rotational speed, reaching approximately 75 rpm more than the epoxy-bladed turbine, representing a 30% increase. The improved performance of the turbine is attributed to the lower blade inertia, which allows for greater angular acceleration and tangential velocity, leading to a better angle of attack and higher turbine torque. For future studies, instead of varying blade inertia through different-density coatings, the mass will be strategically added to the same VAWT to further examine the correlation between inertia and turbine performance.

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