The Effect of The Blade Pitch Angle of a Small-Scale Vertical Axis Wind Turbine on its Energy Output and Starting Performance

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Abstract

This study investigates the effect of blade pitch angle on energy output and start-up performance in a small-scale vertical-axis wind turbine. The angle of the blade pitch is an important design factor in wind turbines since it directly affects the aerodynamic forces. Therefore, different pitch angles can alter the turbine's efficiency and its ability to start operating independently. A small-scale wind turbine designed in a laboratory environment was used in the study. Experiments were conducted at three different blade pitch angles under constant wind conditions. Energy output was calculated by measuring the voltage and current values produced. Initial performance was evaluated based on the turbine's start-up time. Additionally, the results show a pitch angle increase of 5 to 10.72 degrees, which improves the efficiency of the system. Pitch angle increases from 5 to 10.72 degrees, increasing power output. The power output and the system's associated power efficiency both dropped between 10.72 and 20 degrees.

Keywords: Vertical-axis wind turbine, blade pitch angle, aerodynamic performance, self-starting performance, power coefficient

1. Introduction

Wind turbines are integral to the worldwide transition toward renewable energy sources, providing a sustainable alternative to fossil fuels (Chaudhuri et al., 2022). Among the various design considerations impacting turbine efficiency, the blade pitch angle is especially important, as it directly affects aerodynamic performance and energy production (Hammad et al., 2024; Saathoff et al., 2021). Modifying the pitch serves to optimize lift-to-drag ratios, reduce aerodynamic imbalances, and extend the operational lifespan of the turbines.

Recent research highlights the effect of pitch angle on turbine self-starting performance, particularly near the cut-in wind speed. A turbine with strong starting capability initiates rotation from lower wind velocities, thereby improving capacity factors and reducing the levelized cost of energy (Xu et al., 2024). Despite this, the aerodynamic complexity of vertical-axis wind turbines (VAWTs) has hindered their broader adoption. Their blades are subject to unsteady flow conditions, including dynamic stall at low tip-speed ratios, which reduces efficiency (Le Fouest & Mulleners, 2024).

While the influence of pitch angle has been investigated theoretically, there is limited experimental work assessing its role in the starting and energy performance of small-scale VAWTs. This investigation aims to systematically evaluate how pitch angle affects the energy output and starting performance of a small-scale prototype tested under controlled wind tunnel conditions.

2. BACKGROUND INFORMATION

2.1. Wind Energy Basics

Wind energy harnesses the kinetic energy of moving air masses, which originates from differential solar heating and pressure gradients across the Earth's surface (Burton et al., 2011). The fundamental relationship governing wind power extraction has been extensively studied, with numerous researchers investigating optimal blade configurations for maximum energy conversion efficiency (Manwell et al., 2010).

The classical equation gives the kinetic energy carried by a mass of moving air:

$$E_k = \frac{1}{2}mv^2$$

However, in the context of wind energy, we are concerned with the energy per unit time (power) delivered by the wind to a turbine. The air mass flowing through the swept area A of the turbine blades, over time t is:

$$m = \rho A v t$$

Where ρ is the air density and v is the wind speed. Consequently, the instantaneous power available in the wind is given by:

$$P = \frac{1}{2}\rho A v^3$$

This equation indicates the cubic dependence on wind speed, meaning that even small increases in wind speed can result in significantly greater energy potential (Ragheb & Ragheb, 2011). This is why exact measurements of speed are critical in wind turbine analysis.

2.2. Blade Design Parameters

The performance of a wind turbine is strongly affected by its blade design, with parameters such as blade length, airfoil geometry, and pitch angle determining the efficiency of converting wind energy into mechanical and electrical power. The blade hub is a critical component, as its design must enable effective transformation of wind forces into the torque required for power generation. Blade design, therefore, prioritizes maximizing the rotor's power output while minimizing energy losses to ensure optimal performance.

2.2.1. Blade Length:

The windmill blade length is the fundamental parameter that defines the amount of area swept by the rotor, which in turn determines the kinetic energy capture potential. Since the swept area in an H-axis wind turbine is calculated using the rotor radius (R) and the blade length (L), a larger swept area leads to higher power production under the same wind conditions.

2.2.2. Airfoil Shape:

An airfoil's geometry directly governs the aerodynamic forces on the blade creating lift perpendicular to the flow and drag parallel to it. An optimally engineered airfoil maximizes the lift-to-drag ratio, enhancing overall turbine efficiency. In contrast, non-optimal shapes may trigger aerodynamic stall or increase drag, ultimately diminishing performance (U.S. Department of Energy, 2023).

2.2.3. Pitch Angle:

The pitch angle, defined as the angle between a blade's chord line and the plane of rotation, is a critical parameter in wind turbine performance (Rezaeiha et al., 2017). It determines how wind interacts with the blade surface. Insufficient pitch angles can lead to inadequate lift generation, whereas considerable angles increase aerodynamic drag (Yang et al., 2018). The pitch angle directly influences both the turbine's self-starting performance and its operational power output. Given its impact on both starting performance and energy conversion, this study investigates the effect of blade pitch angle on a small-scale wind turbine.

Individual dynamic blade pitching is a versatile method that can enhance turbine efficiency while maintaining structural integrity (Le Fouest & Mulleners, 2024). In this study, the effect is investigated on a small-scale vertical-axis wind turbine. Turbine performance is quantified using the power coefficient, defined as the ratio of net power generated to the power available in the flow through the blade's swept area.

2.3. Lift and Drag

The forces acting on a wind turbine blade are fundamentally aerodynamic in nature. When wind flows over a blade, it behaves similarly to how air flows over an airplane wing, producing two main forces: lift and drag. Lift is the force perpendicular to the oncoming airflow. It is primarily responsible for initiating and sustaining the rotation of the blades. Drag is the force parallel to the airflow. It acts in opposition to blade motion, resisting rotation. Both forces depend on the shape of the blade (airfoil) and the pitch angle. A blade with an optimized pitch angle generates a favorable lift-to-drag ratio, which enhances rotation. If the pitch angle is too steep, drag becomes dominant and can slow or prevent blade motion, especially at low wind speeds

(Hammad et al., 2024). If the blade is too shallow, it may not generate enough lift to overcome friction and inertia. The balance between lift and drag determines how efficiently a wind turbine captures kinetic energy and converts it to mechanical rotation. This investigation examines how varying pitch angles impact the aerodynamic balance and, consequently, affect both the starting performance and energy output of a small-scale turbine.

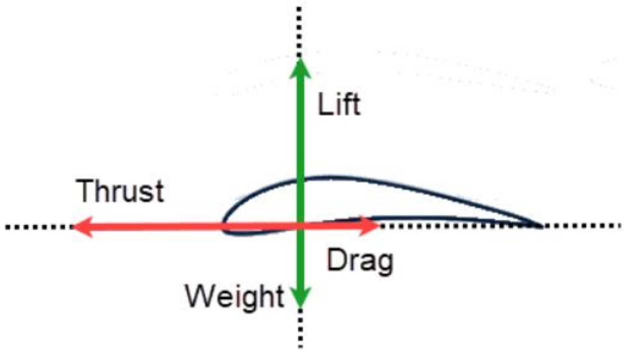

Figure 1: Modelling of lift and drag forces (What is Lift Drag and Pitch?, 2023).

2.3.1. Lift Forces

Lift is the aerodynamic force acting perpendicular to the oncoming airflow over a turbine blade (as shown in Figure 1). It results from a pressure difference between the blade's upper and lower surfaces as wind flows around it. In a wind turbine, lift is the primary force that drives rotational motion. As the pitch angle increases up to its optimal point, lift generally rises. This enhances both startup performance and energy output until drag starts to outweigh the benefits.

2.3.2. Drag Forces:

Drag is an aerodynamic force that acts parallel to and opposite the direction of airflow. It opposes the movement of the blade and increases with both wind speed and the surface area exposed to the flow. Higher pitch angles typically result in increased drag, which can reduce the turbine's rotational efficiency and make startup more challenging, especially in low wind conditions. Increasing the blade pitch angle improves the aerodynamic performance of the H-type Darrieus VAWT by boosting the lift-to-drag ratio, resulting in better startup and overall efficiency (Hammad et al., 2024).

2.4. Betz Limit

The Betz Limit defines the maximum amount of power that can be converted into electrical motion. It indicates the highest theoretical efficiency for a wind turbine (Chaudhuri et al., 2022). While theoretical models such as the Betz limit set an upper bound of 59.3% for energy extraction, this study examines how pitch angle influences the real-world efficiency and startup performance of a small-scale wind turbine (Ranjbar et al., 2019). The results will be compared to this theoretical maximum to evaluate how closely different blade configurations approach ideal conditions.

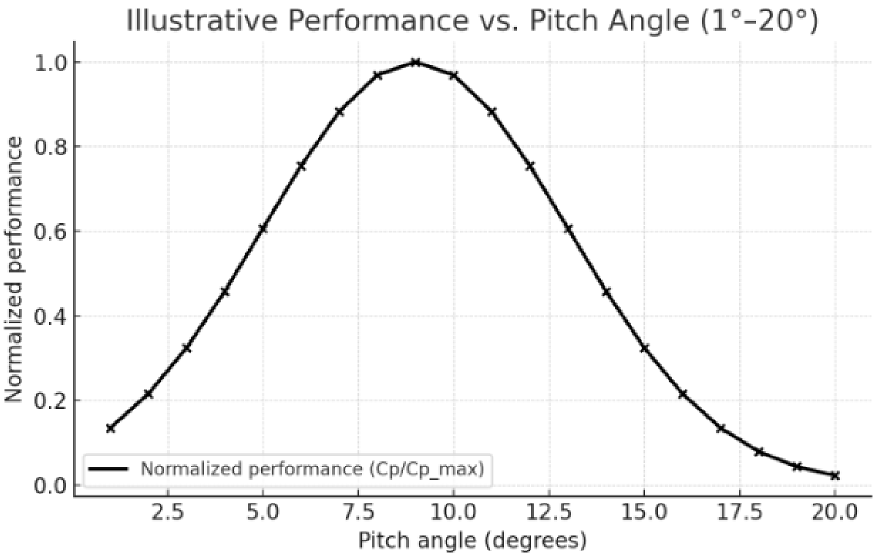

Figure 2: A hypothetical Betz Limit graphic derived from aerodynamic principles

2.5. Electrical Power Output

In a wind turbine, the mechanical energy generated by the rotation of the blades is converted into electrical energy by a generator. The electrical power output is typically measured using the following relationship:

$$P = IV$$

Power value, denoted as P, equals voltage (V) multiplied by current (I). Alternatively, if only voltage and resistance are known, power can be estimated using:

$$P = \frac{V^2}{R}$$

R: the electrical load resistance.

The amount of electrical power generated depends on several factors, including wind speed, blade design, rotor rotational speed, and generator efficiency. Among blade design parameters, the pitch angle directly affects the rotor's torque and angular velocity, which in turn influences the rate at which mechanical energy is transferred to the generator.

A well-optimized pitch angle enables the blades to capture more wind energy with reduced aerodynamic resistance, resulting in higher and more consistent voltage and current outputs. Conversely, suboptimal angles may generate insufficient torque to keep the blades spinning or cause excessive drag, reducing the electrical output.

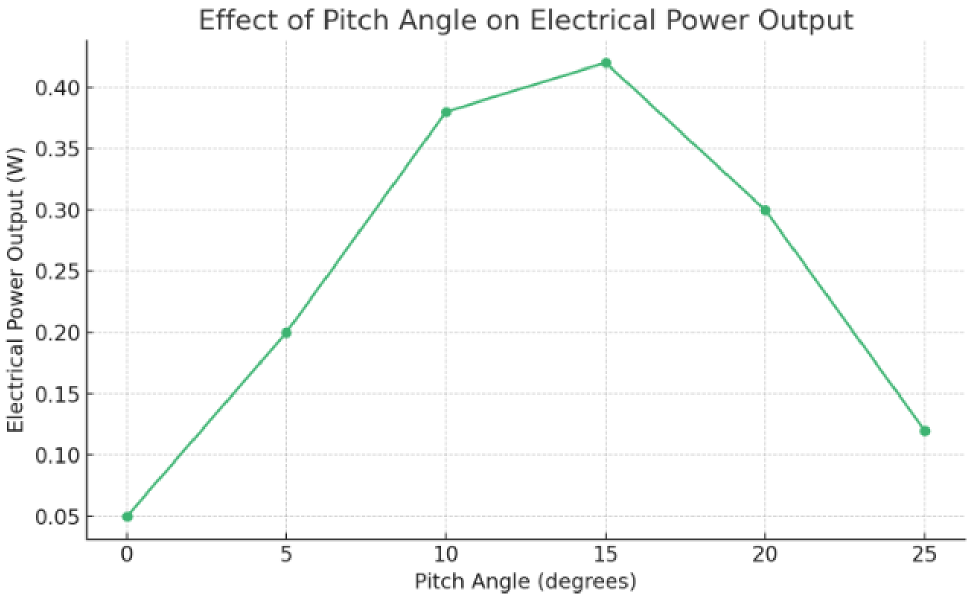

Figure 3: Relationship between electrical power and pitch angle

As the angle between 0° and 15° increases, the electrical power output rises significantly (As shown in Figure 3). After 15°, efficiency declines because of increased drag force.

2.6. Hypothesis

As the pitch angle of the wind turbine blades increases from 0° to an optimal intermediate value (around 10–15°), both the electrical energy output and starting performance improve. However, beyond this optimal angle, further increases in pitch angle lead to increased aerodynamic drag, which reduces torque and lowers both startup efficiency and power output. This prediction is based on aerodynamic principles, especially the lift-to-drag ratio. At low pitch angles, the blades may not generate enough lift to overcome inertia and initiate rotation (Xu et al., 2024). As the angle increases, lift improves, producing more torque and energy. However, at very high angles, drag forces become dominant, decreasing efficiency. This hypothesis will be tested by measuring electrical output (voltage and current) and the time to rotation (startup performance) at different blade pitch angles under controlled wind conditions.

3. VARIABLES

3.1. Independent Variable

The independent variable in this study is the pitch angle of the small-scale wind turbine blades. The pitch angle is defined as the angle between each blade and the rotor plane, which corresponds to the horizontal plane of rotation. This variable directly affects the aerodynamic interaction between the blades and the wind, affecting both torque production and overall turbine performance.

Furthermore, the vertical position or height of the blades relative to the rotor plane can also influence energy capture and may be considered a secondary independent variable. While this factor could be examined in more detailed studies, the main focus of the current experiment remains on the pitch angle to isolate its specific effect on turbine efficiency and starting performance.

$$\theta = arctan\left(\frac{h}{l}\right)$$

In this formula, h represents the vertical height of the blade, and l represents the horizontal length of the blade.

Vertical Height $\boldsymbol{h}$ $(\boldsymbol{h_0} \pm \mathbf{0.02}\boldsymbol{cm})$	*Horizontal Length* $\boldsymbol{l}$ $(\boldsymbol{l_0} \pm \mathbf{0.01}\boldsymbol{cm})$	*Pitch Angle* $\boldsymbol{\theta}$ $(\boldsymbol{\theta} \pm \mathbf{0.37}°)$
$\mathbf{0.26}\boldsymbol{cm}$	$3.01cm$	5.13°
$\mathbf{0.57}\boldsymbol{cm}$	$3.01cm$	10.72°
$\mathbf{1.1}\boldsymbol{cm}$	$3.01cm$	20.21°

3.2. Dependent Variables

The energy output and starting performance are the dependent variables in this investigation of a small-scale wind turbine. The energy output will be measured by recording the electrical current and voltage produced by the turbine with a multimeter. These electrical values enable the calculation of power output using the equation:

$$P = IV$$

Where P represents power in watts, I is the current in amperes, and V is the voltage in volts. This formula provides a direct method for determining the instantaneous electrical power produced by a wind turbine at different blade pitch angles. By keeping the electrical load constant, changes in measured power can be attributed solely to the variation in blade orientation. Additionally, the starting performance of the turbine will be evaluated by observing the time it takes for the blades to begin rotating after the wind source is activated. This offers insight into how the pitch angle influences the turbine's ability to overcome inertia and initiate motion under consistent wind conditions. Together, these two dependent variables, power output and starting time, provide a comprehensive view of the aerodynamic and mechanical performance of the wind turbine as affected by changes in blade pitch angle.

3.3 Controlled Variables

Variable	***Description***
Wind speed	The turbine was placed at a fixed distance from a fan operating at a constant speed.
Blade shape and size	Identical blades with the exact dimensions and aerodynamic profile were used in all trials.
Number of blades	The number of blades was kept constant (three) throughout the experiment.
Turbine shaft friction	The turbine setup remained unchanged and was lubricated to minimize internal friction.
Electrical load (resistance)	A fixed resistive load was connected in each trial to ensure consistent electrical conditions.
Distance from wind source	The distance between the turbine and fan was kept constant to maintain wind consistency.

4. Experimental Design

4.1. Apparatus

Apparatus	***Function of the apparatus***
Small-Scale Wind Turbine	The central apparatus of this investigation, the small-scale wind turbine, converts the kinetic energy from wind into electrical energy. Its structural integrity and consistent performance are crucial for obtaining reliable data. The turbine's design should allow easy adjustment of blade

	pitch angles without compromising stability.
Blade Set	Serving as the independent variable in the experiment, the blade set's pitch angle can be modified to various precise degrees. These adjustments directly affect aerodynamic efficiency, which is hypothesized to influence both the energy output and the starting performance of the turbine.
Multimeter	A digital multimeter is employed to measure both voltage (V) and current (I) generated by the turbine's electrical output. Accurate measurement of these quantities is essential to calculate the power output using the formula $P = V.I$. High precision with a low margin of error is required to capture subtle variations caused by changing blade pitch angles.
Fan or wind source	The wind turbine is driven by a controlled wind source, such as a high-speed fan or wind tunnel cells, providing a consistent and reproducible airflow. This ensures that any observed changes in performance are attributed primarily to variations in blade pitch rather than fluctuations in wind speed.
Digital stopwatch	Timing the turbine's starting performance is significant for understanding how blade pitch affects the ease of start-up. The stopwatch must provide accurate timing to milliseconds for reliable comparison.
Battery	The battery provides electrical power to the system. It is important to replace the battery during each experiment.

4.2. Experiment

The experimental setup comprises a homemade small-scale wind turbine. To investigate the effects of the independent variables, five different scales were employed. Plastic was selected as the blade material owing to its low density, which allows for lightweight construction and facilitates rotation even under low wind conditions. Its flexibility, ease of shaping during manufacturing, and cost-effectiveness also render it a practical choice for this setup. A wooden stand was constructed to provide structural support for the turbine, while a small DC motor fan was used to drive the system under controlled conditions. A 1.5 V cell served as the power source, and insulating bands were utilized to help reduce electrical losses. A digital multimeter was used to measure the voltage across the circuit components.

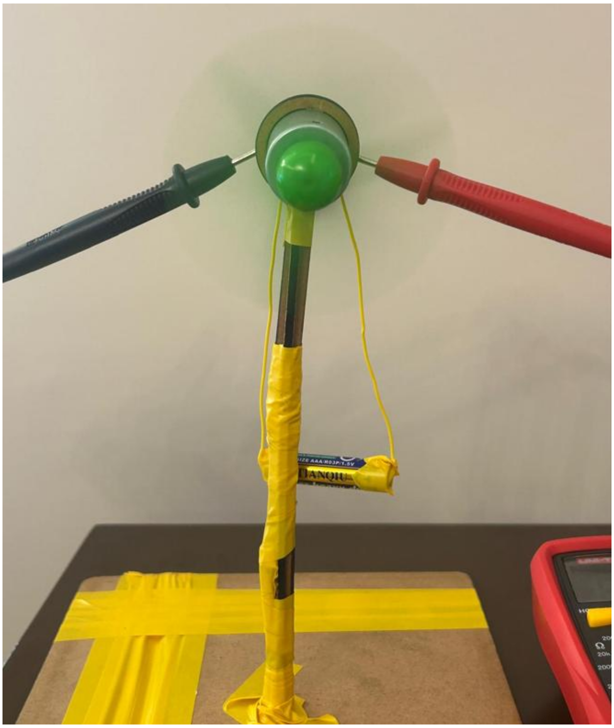

Figure 4: Model of Small-Scale Vertical Axis Wind Turbine with Multimeter

5. Data Analysis

5.1. Pitch Angle

At the beginning of the experiment, the measured voltage was 1.51 V, indicating that the battery was new and fully charged, with a voltage above the nominal rating. In subsequent measures, the voltage values decreased to 1.48 V and 1.47 V, respectively. This reduction can be explained by the current drawn from the battery during operation, which, due to its internal resistance, causes a drop in terminal voltage until equilibrium is reached. Additionally, factors such as the multimeter's internal resistance, temperature variations, and contact conditions between the terminals and probes may have contributed to the observed decrease in voltage throughout the experiment.

The current drawn from the system also decreased slightly, corresponding to the observed voltage drop. Initially, the current measurement reflects the higher initial voltage of the fully charged 1.5 V alkaline cell. As the experiment progressed and the cell discharged, the measured current gradually decreased to 0.25 A. This reduction is primarily due to the battery's internal resistance, which causes the terminal voltage to decrease under load until a steady state is reached. Additional factors influencing the measurement include the multimeter's internal resistance, minor variations in contact conditions, and temperature fluctuations, all of which may subtly affect the current measurement (Linden & Reddy, 2002).

Figure 5: Observed Voltages Slightly Lower Than the Expected 1.5 V Nominal Value

The measured current and voltage corresponding to a blade pitch change of 10.72-degree are presented in the Table 2.

Table 2: Average Data from First Experiment

Trial	***Voltage of Battery (V)***	***Voltage Measured by the Multimeter (V±0.02 V)***	***Pitch Angle (θ)*** $(\theta \pm 0.37°)$	***Current (I)*** $(A \pm 0.13\ A)$
1.	1.50V	1.51V	10.72^0	0.26A
2.	1.50V	1.51V	10.72^0	0.26A
3.	1.50V	1.48V	10.72^0	0.26A
4.	1.50V	1.48V	10.72^0	0.26A
5.	1.50V	1.47V	10.72^0	0.25A
6.	1.50V	1.47V	10.72^0	0.25A
7.	1.50V	1.47V	10.72^0	0.25A
8.	1.50V	1.47V	10.72^0	0.25A

9.	1.50V	1.47V	10.72^0	0.24A

The experiment was carried out at a blade pitch angle of 10.72-degree. Based on the measured voltage and current values, the electrical output is denoted as P, where P equals, I multiplied by V. A blade pitch angle of 10.72-degree. Based on the measured voltage and current values, the electrical output on $P = IV$ (Table 3).

Table 3: Calculation of Each Measurement

Voltage Measured by the Multimeter $(\boldsymbol{V \pm 0.02\ V})$	***Average Current*** $(\boldsymbol{I})$ $(\boldsymbol{A \pm 0.13\ A})$	***Pitch Angle*** $(\boldsymbol{\theta})$ $(\boldsymbol{\theta \pm 0.37°})$	***Power Output*** $(\boldsymbol{W \pm 0.16\ W})$
1.51 V	$0.26\ A$	10.72^0	$0.39\ W$
1.48 V	$0.26\ A$	10.72^0	$0.38\ W$
1.47 V	$0.25\ A$	10.72^0	$0.37\ W$

Average: 0.38 W

These transactions were carried out individually for each selected pitch angle (5.13°, 10, .72°,and 20.21°), ensuring that the experimental process was systematically replicated under comparable conditions. These supplementary tables serve both to illustrate the computational procedure and to enhance the transparency and reproducibility of the study.

The battery was replaced for each different blade; therefore, the current drawn from the battery has been preserved. The system was restarted after adjusting the blade pitch angle to 5.13-degree.

The identical experimental procedure was employed for a blade pitch angle of 5 degrees, and the observations revealed significant differences compared to the 10.72-degree configuration. The measured current at 5-degree was marginally higher than at 10.72-degree, which can be ascribed to the blades being more closely aligned with the wind direction, thereby permitting the turbine to rotate more efficiently even under relatively low wind speeds. At such small angles, flow separation is diminished, resulting in easier initiation of rotation; however, the maximum power output cannot be attained, as the aerodynamic forces acting on the rotor are not exploited with maximum efficiency. Although the current values were somewhat elevated, the measured voltage was comparatively lower than in the 10.72-degree case. This outcome suggests that, while a smaller pitch angle promotes faster rotor acceleration, the aerodynamic torque exerted on the rotor remains suboptimal, thereby restricting the potential for voltage generation relative to the near-optimal configuration (Table 4).

Table 4: Average Data from Second Experiment

Trial	***Voltage of Battery (V)***	***Voltage Measured by the Multimeter (V±0.02 V)***	***Pitch Angle (θ)*** $(\boldsymbol{\theta} \pm \mathbf{0.37}°)$	***Current (I)*** $(\boldsymbol{A} \pm \mathbf{0.13}\ \boldsymbol{A})$
1.	1.50V	1.49V	$5.13^{.0}$	0.24 A
2.	1.50V	1.49V	5.13^{0}	0.24 A
3.	1.50V	1.49V	5.13^{0}	0.24 A
4.	1.50V	1.47V	5.13^{0}	0.24 A
5.	1.50V	1.47V	5.13^{0}	0.24 A
6.	1.50V	1.46V	5.13^{0}	0.23 A
7.	1.50V	1.46V	$5.13^{.0}$	0.23 A
8.	1.50V	1.46V	5.13^{0}	0.23 A
9.	1.50V	1.46V	5.13^{0}	0.22 A

The experiment was conducted at a blade pitch angle of 5.13-degree. Based on the measured voltage and current values, the electrical output is given by P equals I times V. at a blade pitch angle of 5-degree. Based on the measured voltage and current values, the electrical output on $P = IV$ (Table 5).

Table 5: Calculation of Each Measurement

Voltage Measured by the Multimeter $(\boldsymbol{V} \pm \mathbf{0.02}\ \boldsymbol{V})$	***Average Current (I)*** $(\boldsymbol{A} \pm \mathbf{0.13}\ \boldsymbol{A})$	***Pitch Angle (θ)*** $(\boldsymbol{\theta} \pm \mathbf{0.37}°)$	***Power Output (P)*** $(\boldsymbol{W} \pm \mathbf{0.08})$
1.49V	0.24 A	5.13^{0}	0.36 W
1.47 V	0.24 A	5.13^{0}	0.35 W
1.46 V	0.23 A	$5.13^{.0}$	0.34 W

Average: 0.35 W

At a pitch angle of 10.72 degrees, the variation in power output exhibited a partially linear trend, in contrast to the behavior observed at a pitch of 5.13 degrees, where the response was notably less linear. At lower pitch angles, where the blade is positioned nearly parallel to the wind stream, the aerodynamic efficiency diminishes, thereby restricting the conversion of wind kinetic energy into rotor torque. Consequently, both current and voltage values remain relatively low. Furthermore, the initially recorded values were slightly elevated, which can be attributed to the characteristics of the battery or circuit dynamics; however, these values subsequently declined. This decline did not follow a strictly linear pattern, suggesting the influence of additional factors such as internal resistance, transient circuit effects, and the nonlinear aerodynamic response of the turbine.

At a blade pitch angle of 20.21 degrees, the aerodynamic performance of the small-scale wind turbine exhibited a noticeable decline in comparison to lower pitch settings (Table 6). When the blades are oriented at such a steep angle relative to the incoming wind, the flow separation over the blade surface becomes more pronounced, resulting in decreased lift and an increased drag force. Consequently, both current and voltage outputs were lower than those observed at 10.72 degrees, indicating diminished efficiency in converting wind energy into rotational motion and electrical power. Although the larger pitch angle initially permits the blades to intercept more of the wind's force, the aerodynamic losses associated with stall phenomena outweigh these benefits, thereby restricting the turbine's overall power generation capacity.

Table 6: Average Data from Third Experiment

Trial	*Voltage of Battery* ($\boldsymbol{V}$)	*Voltage Measured by the Multimeter (**V**±0.02 V)*	*Pitch Angle* ($\boldsymbol{\theta}$) ($\boldsymbol{\theta \pm 0.37°}$)	*Current* ($\boldsymbol{I}$) ($\boldsymbol{A \pm 0.13\ A}$)
1.	1.50V	1.51V	20.21^0	0.24 A
2.	1.50V	1.50V	20.21^0	0.24 A
3.	1.50V	1.49V	20.21^0	0.23 A
4.	1.50V	1.48V	20.21^0	0.23 A
5.	1.50V	1.47V	20.21^0	0.23 A
6.	1.50V	1.46V	20.21^0	0.23 A
7.	1.50V	1.46V	20.21^0	0.23 A
8.	1.50V	1.46V	20.21^0	0.23 A
9.	1.50V	1.46V	20.21^0	0.23 A

The experiment was conducted at a blade pitch angle of 5.13 degrees. Based on the measured voltage and current values, the electrical output on $P = IV$ (Table 7).

Table 7: Calculation of Each Measurement

Voltage Measured by the Multimeter $(V \pm 0.03\ V)$	***Average Current*** (I) $(A \pm 0.005)$	***Pitch Angle*** (θ)	***Power Output*** $(W \pm 0.01)$
1.51 V	0.24 A	$20.21^{\cdot 0}$	0.36 W
1.50 V	0.24 A	20.21^{0}	0.35 W
1.49 V	0.23 A	20.21^{0}	0.34 W
1.47 V	0.23 A	20.21^{0}	0.34 W
1.46 V	0.23 A	20.21^{0}	0.34 W

Average: 0.35 W

5.2. Starting Performance

Starting performance pertains to the ease with which the system initiates rotation, specifically, the amount of torque required to overcome inertia and friction, and how swiftly it attains operational efficiency (Kesby et al., 2017; Xu et al., 2024). Consequently, a lower value was expected at 20 degrees, which was subsequently confirmed through experimentation. The 20-degree inclination captures more air, resulting in lower starting performance values than predicted. Conversely, the 10.72-degree angle demonstrated the greatest efficiency, as its initiation occurred neither earlier nor later than at 5 and 20 degrees. The average starting time at 10.72-degree aligns with that at 5 and 20 degrees, rendering this pitch angle more efficient and systematically balanced relative to the others (Table 8).

Table 8: Calculation of Each Measurement

Pitch Angle	***Energy Output***
$\mathbf{5.13^{0}}$	0.35 W
$\mathbf{10.73^{0}}$	0.38 W
$\mathbf{20.21^{0}}$	0.35 W

The starting time functions as an indicator of the initial performance of a small-scale wind turbine. It emphasizes that turbines commencing operation at an earlier point exhibit enhanced startup performance; however, it does not offer any information regarding the system's energy efficiency or total energy production.

Table 9: Overall Results for Each Dataset

Pitch Angle	**Power/Energy Output**	**Starting Performance**	**Observations on its efficiency**
5.13	0.35 W	*Higher starting performance because the degree is smallest and the blades are cutting the air.*	*Its efficiency is less than the nominal value because it produces less energy than 10.72 degrees.*
10. 72	0.38 W	*It has an ideal starting performance, neither too low nor too high.*	*It is the most efficient pitch angle for producing energy or designing a blade.*
20.21	0.35 W	*Lower starting performance because it makes a greater angle between blades, hence it keeps more air.*	*Its efficiency is lower than the nominal value because it produces less energy than the 10.72 value.*

6. Conclusion

Reconsidering the research question, the results of this research indicate that the blade pitch angle of a small-scale wind turbine is a key factor in determining the power output and starting performance of the system. The results also demonstrate an increase in pitch angle of 5 to 10.72 degrees, which enhances the system's efficiency. Power output increases when the pitch angle increases from 5 to 10.72 degrees. Between 10.72 and 20 degrees, the power output decreased, and the related power efficiency of the system also decreased. If the starting performance is considered, the one with the highest starting performance was the one with a 5-degree angle of attack; however, this did not make 5 degrees the most efficient angle of attack. The 10.72-degree angle of attack, which had the greatest power output, also had the greatest energy output. However, findings are valid for a small-scale model and may not directly translate to large-scale turbines.

7. Evaluation

The research validated the logic of the experiment by producing results consistent with the general assumption of how pitch angle affects power output and startup performance in a small-scale wind turbine. However, there were some limitations. The model was small, so the results may not apply to the same conditions as large industrial turbines. Furthermore, the tests were conducted under controlled wind conditions that do not fully reflect the variability of natural winds. Specifically, suppose the effects of wind conditions on the energy output and startup performance of wind turbines are to be evaluated. In that case, the prototype experiment may not be remarkably similar to large-scale wind turbines. Wind speed was not included in the experiment, reducing its applicability to real-world applications. Also, only three different blade angles were used for a single blade design, which limited the number of independent variables in the experiment and made the results less generalizable.

8. Further Studies

Investigation of various airfoil configurations and dimensions: The energy generation and initial operational performance of different aerodynamic profiles and airfoil sizes can be broadly generalized, and this objective can be effectively accomplished.

Testing under realistic, variable wind conditions: Conducting wind tests at different speeds and directions outdoors, instead of in a wind tunnel, enables more accurate application of results to real-world scenarios.

The utilization of dynamic pitch control in conjunction with models featuring larger options involves testing adjustable airfoil angles and conducting trials on larger models. This approach enhances the applicability to industrial turbines and augments the reliability of measurements.

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