AE471A: Undergraduate Project-II

Project topic: Variable Linkage Length Mechanism for Variable Amplitude pitching in Vertical Axis Wind Turbines

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Shrutikirti Singh

DECLARATION

I declare that the project titled, “Variable Linkage Length Mechanism for Variable Amplitude pitching in Vertical Axis Wind Turbines”, is done by me, Shrutikirti Singh, B. Tech, Department of Aerospace Engineering. I have taken reasonable care to ensure that the work is original, and, to the best of my knowledge, does not breach copyright law, and has not been taken from any other sources except the works that have been cited and referred to at the end.

Signature:

Shrutikirti Singh
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CERTIFICATE

The project entitled “Variable Linkage Length Mechanism for Variable Amplitude pitching in Vertical Axis Wind Turbines” was done by Shrutikirti Singh, B. Tech, Department of Aerospace Engineering, under my supervision towards the fulfilment of credits for UGP-II (AE471A).

Abhishek

Signature:

Dr. Abhishek,
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1 ABSTRACT

Vertical-Axis Wind Turbines (VAWTs) are promising renewable energy generation devices with numerous benefits, including being less noisy and safer for the surrounding environment when compared to horizontal-axis wind turbines (HAWTs).
This research project explores a novel approach to enhance the performance of Vertical Axis Wind Turbines (VAWTs) through the integration of a variable-length linkage mechanism. Drawing inspiration from the precision of a screw gauge, the designed mechanism incorporates a crank and rocker system to dynamically adjust the length of the ground link, influencing the pitch amplitude of the turbine blades. Utilizing Fusion 360, the mechanism is meticulously designed to introduce adaptability to varying wind conditions, aiming for increased energy capture efficiency.

The primary objective of this research is to investigate how alterations in the linkage length impact the pitch amplitude of the turbine blades, ultimately optimizing the energy output of the VAWT. The simulation phase employs simple python code with the help of some mathematical derivations of formulas. By systematically varying linkage lengths, the study aims to establish a correlation between linkage parameters and pitch amplitudes, providing crucial insights for the optimization of VAWT performance.

The outcomes of this research are expected to contribute not only to the advancement of vertical axis wind turbine technology but also to the broader field of renewable energy. The designed mechanism, coupled with comprehensive simulation results, is poised to offer a deeper understanding of the intricate dynamics involved in adapting VAWTs to fluctuating wind speeds. This research represents a significant step towards the development of more efficient and adaptable wind energy solutions, with implications for future sustainable energy practices.

2 INTRODUCTIONS

The demand for sustainable and efficient energy sources has intensified the exploration of innovative technologies within the realm of renewable energy. Vertical Axis Wind Turbines (VAWTs) present a compelling solution, offering unique advantages in terms of simplicity, omnidirectional wind capture, and potential scalability. However, optimizing the performance of VAWTs remains a critical challenge, particularly in addressing the dynamic nature of wind conditions.

This research project focuses on a groundbreaking approach to enhance the adaptability and efficiency of VAWTs through the integration of a variable-length linkage mechanism inspired by the precision of a screw gauge. The mechanism, built using Fusion 360, introduces dynamic adjustability to the linkage within a crank and rocker system, allowing for real-time modification of the turbine blade pitch. The goal is to investigate the influence of varying linkage lengths on the pitch amplitude of the turbine blades, ultimately optimizing the energy capture efficiency of the VAWT.

As the global focus on sustainable energy intensifies, innovations such as the proposed variable-length linkage mechanism hold significant promise in advancing the practicality and viability of VAWTs. By bridging the gap between design, simulation, and optimization, this research represents a crucial step towards harnessing wind energy more efficiently and contributing to the broader goals of a sustainable and resilient energy future.

1.1 Renewal Energy Generation

Addressing the contemporary imperative of meeting escalating global energy needs presents a formidable challenge. In the pursuit of sustainable alternatives, wind energy emerges as a frontrunner, demonstrating historical resilience in human utilization since ancient times [1]. The international commitment to harnessing wind power is evidenced by substantial investments, resulting in a steady decline in production costs over recent years. Notably, the U.S. Department of Energy has set a visionary target, aiming for wind power to contribute 20% of the United States' electricity demand by the year 2030 [2]. This strategic emphasis on wind energy underscores its pivotal role in shaping the future landscape of renewable energy sources on a global scale.

Wind power stands out as an environmentally conscious and sustainable energy source, offering a myriad of advantages over conventional counterparts. Primarily, wind energy is a green solution, markedly reducing environmental pollution compared to coal and natural gas combustion for power generation. The operation of wind farms refrains from emitting greenhouse gases, making a significant contribution to mitigating global warming, a pressing threat to the planet's ecosystem and the future of humanity.

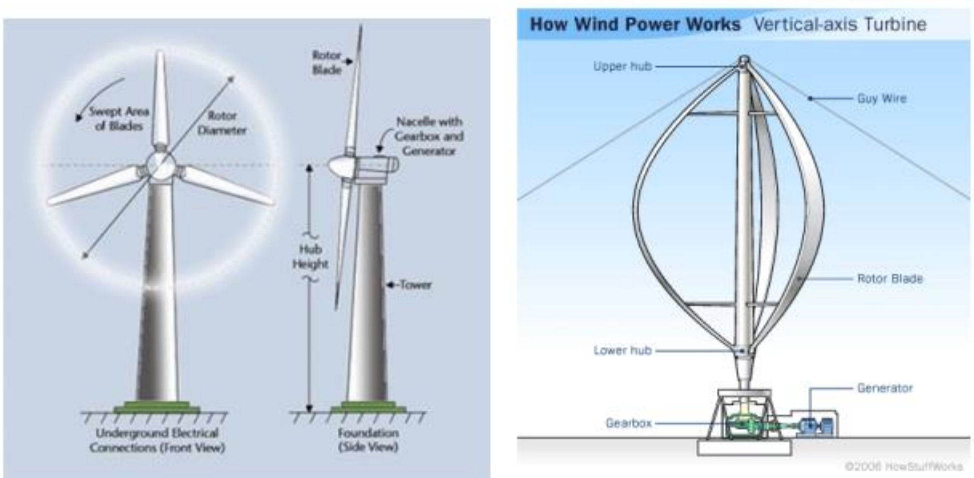
Furthermore, wind energy is inherently renewable, deriving from the Sun, ensuring an everlasting source as long as the Sun continues to radiate energy—an estimated six billion more years. The staggering potential of wind power globally exceeds 400 terawatts [2], with the largest turbines capable of satisfying the energy needs of 600 average U.S. homes [3]. Notably, wind farms exhibit exceptional space efficiency, allowing for the optimal utilization of land, particularly for agricultural purposes, between turbines.

Additionally, wind turbines, especially the vertical-axis variants, boast low operational costs and infrequent maintenance requirements, enhancing their economic viability. The compelling combination of environmental sustainability, renewable abundance, and cost-effectiveness positions wind power as a pivotal player in the quest for efficient and sustainable energy solutions on a global scale.

1.2 Wind Turbines

Wind turbines, pivotal in harnessing kinetic energy from the wind, are instrumental in renewable power generation. Comprising blades that rotate a connected shaft, driving an electrical generator, these turbines efficiently convert wind energy into electricity as the wind propels the rotor into motion.

The classification of wind turbines hinges on the rotation axis of the rotor, leading to two main types: horizontal-axis (HAWTs) and vertical-axis (VAWTs). While HAWTs dominate the wind industry.



(a) HAWT (b) VAWT

Figure 1. Classification of wind Turbines [2]

VAWTs present distinct advantages that merit closer examination. Unlike HAWTs, often situated in rural areas due to noise interaction between towers and blades, VAWTs offer a quieter alternative suitable for populated regions. Additionally, VAWTs exhibit lower assembly and maintenance costs as crucial components are conveniently ground-placed, ensuring easy accessibility. Enhanced safety characterizes VAWTs' operation due to lower rotation speed regimes (TSR), minimizing potential environmental risks.

However, the complexity of VAWTs' aerodynamics, stemming from their non-normal plane of rotation to the flow direction, poses a significant challenge. To optimize VAWTs' performance, efficient programming tools at reasonable computational costs are imperative. A viable approach involves leveraging MATLAB software for calculations and utilizing empirical airfoil data to determine drag and lift forces based on the angle of attack—the angle between the relative velocity and the blade's chord line.

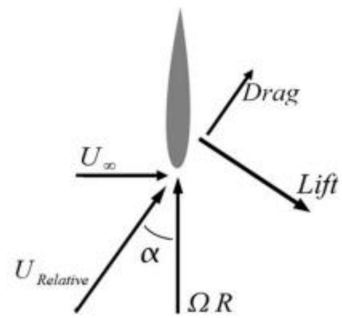


Figure 2. Blade Aerodynamics [2]

Analysing these forces reveals that the lift coefficient initially increases with the angle of attack until reaching the static stall angle. Beyond this point, flow separation occurs, leading to undesirable conditions. Subsequently, the drag coefficient rises, imparting air resistance to the blade motion. Addressing these aerodynamic intricacies is crucial for ensuring the optimal performance and efficiency of VAWTs, underscoring the importance of sophisticated computational tools and empirical data integration in wind turbine design and analysis.

1.3 Pitch Control Mechanism

This study employs a four-bar linkage mechanism to dynamically adjust the blade pitch angle, enabling precise control over the blade orientation concerning the tangential direction and, consequently, modifying the angle of attack. The mechanism comprises four bars interlinked in a closed loop through four joints, constituting the simplest movable closed-chain linkage (Figure 3). This simplicity allows for an array of possible bar combinations by adjusting link lengths.

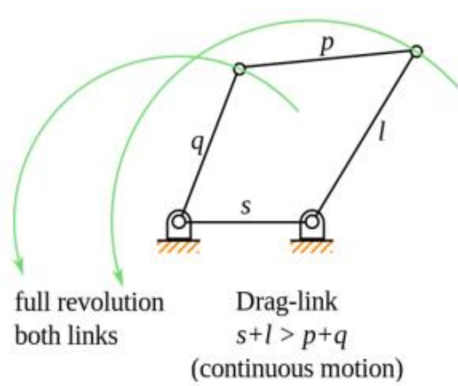


Figure 4. Four-bar linkage mechanism schematics [4]

In the context of a Vertical Axis Wind Turbine (VAWT), the mechanism takes on the form of a crank, featuring all rotational joints with only one fixed point. Consequently, the mechanism exhibits a full 360-degree rotation capability. While certain link lengths are constrained by turbine geometry, at least one must be adjustable to achieve the desired configuration for optimized turbine performance compared to a fixed-pitch counterpart.

This innovative four-bar linkage mechanism represents a pivotal element in the quest for enhancing VAWT efficiency. The ability to dynamically vary the blade pitch angle offers a nuanced approach to optimizing performance, ensuring adaptability to varying wind conditions. The constrained yet adjustable link lengths introduce a degree of flexibility in design, enabling the pursuit of an optimal configuration that aligns with specific turbine requirements and operational contexts.

1.4 Micrometre screw gauge

The screw gauge mechanism is a sophisticated engineering solution employed for precise control and adjustment of lengths, particularly within linkage systems. At its core, this mechanism utilizes the principles of a screw to facilitate controlled linear motion, enabling meticulous changes in the length of a linkage. The primary advantage of the screw gauge lies in its ability to offer fine-tuned adjustments, making it an ideal choice for applications where precision is paramount. [5]

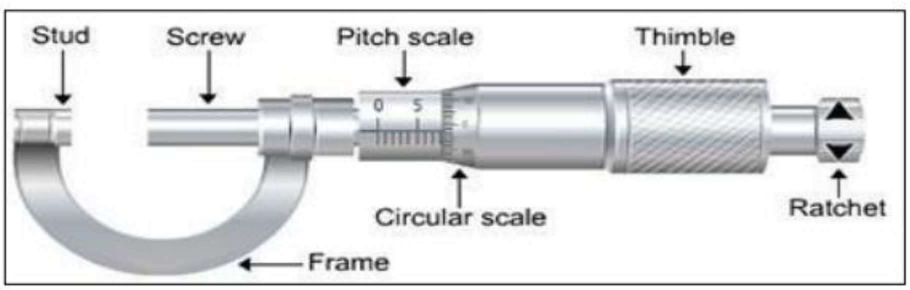


Figure 5. Schematic diagram of screw pitch gauge [5]

The fundamental principle of the screw gauge mechanism revolves around the conversion of rotary motion into linear displacement. This is achieved through the interaction of a threaded screw and a corresponding nut, with the screw featuring a precisely machined helical groove. As the screw is rotated, the nut travels along the screw's threaded length, re sulting in controlled linear motion. This principle forms the basis for the intricate yet effective functioning of the screw gauge.

In the context of a linkage system, the screw gauge mechanism serves as a versatile tool for adjusting the length with exceptional accuracy. The mechanism typically incorporates a threaded rod or screw as one component of the linkage, and a corresponding nut with matching threads as the other. By rotating the screw, the nut moves along the threaded length, exerting controlled linear displacement on the linkage.

This precision in length adjustment is particularly advantageous in scenarios where minute changes in linkage dimensions significantly impact the overall performance of a mechanism. The screw gauge mechanism's ability to provide fine adjustments ensures that the length variations are not only controlled but also reproducible, contributing to the repeatability and reliability of the system.

In the specific context of a vertical axis wind turbine (VAWT) with a linkage system, the screw gauge mechanism can be integrated to dynamically alter the length of the linkage. This capability becomes instrumental in fine-tuning the turbine's blade pitch amplitude, optimizing its performance based on varying wind conditions. The screw gauge mechanism thus stands as a testament to the ingenuity of engineering solutions, offering precision and control in the dynamic adjustment of linkages for enhanced functionality and efficiency.

3 LITERATURE REVIEW

In the exploration led by Moble Benedict et al., a comprehensive investigation was undertaken to unravel the intricacies of a small-scale Vertical Axis Wind Turbine (VAWT) featuring dynamic blade pitching. The key innovation was a blade pitch mechanism allowing instantaneous adjustments to blade pitch phasing, a critical factor in maximizing power extraction, especially in urban settings where wind direction rapidly changes. The study unveiled a strong correlation between turbine efficiency and blade pitching amplitude, identifying an optimal range of ±20° to ±25°. Benedict's work emphasized the potential for substantial enhancements in VAWT performance through novel blade kinematics, reduced chord/radius ratios, and the adoption of cambered blades.

In a parallel study, the aerodynamic performance of Vertical Axis Wind Turbines (VAWTs) with variable amplitude dynamic blade pitching is meticulously examined by Palash Jain and Dr. Abhishek. The research underscores the need to dynamically adjust blade pitch amplitude based on wind speed and tip speed ratio for optimal power extraction. The analysis suggests that higher pitch amplitudes, especially around 35°, are effective at low tip speed ratios, gradually tapering down to 10° beyond a tip speed ratio of 2. The study encourages the optimization of VAWT designs for different sizes and power ratings, emphasizing the advantages of variable pitch VAWTs in addressing wind speed variations in populated areas.

In the paper led by D. Rempfer was based on analysis of blade pitch control mechanism. The study investigates the influence of blade pitch control mechanisms on vertical-axis wind turbine (VAWT) performance. Implementing a pitch control system disrupts symmetry in angle of attack distribution, resulting in diverse torque and power profiles during each cycle. Optimal VAWT operation occurs at low absolute angles of attack, emphasizing the importance of maintaining favourable angles throughout the cycle. The eccentric link, despite size constraints, exhibits notable performance changes. Performance optimization through blade pitch control is effective within specific tip speed ratio (TSR) ranges, necessitating proper linkage design. Future work involves refining models to account for velocity changes and incorporating turbulence effects for comprehensive performance evaluation.

The paper based on the understanding of micrometer by Nivadan Mahato which explores the significance of micrometer screw gauges in precision measurements, particularly in science, technology, manufacturing, and engineering. It delves into the fundamental working principles of micrometers, emphasizing the relationship between screw pitch and rotational movement. The discussion covers construction components, scales, errors, and the importance of precise measurements in various applications. The review concludes by highlighting the meticulous construction and alignment required for accurate micrometer readings, emphasizing their critical role in ensuring uniformity and reliability in diverse fields.

5 VAWT PROTOTYPE

The depicted pitching mechanism, illustrated in Fig. 5(a), is structured on a four-bar linkage system, ensuring automatic cyclic blade pitching during turbine rotation with minimal power loss attributed only to friction. In this schematic, g, b, l, and f represent the four linkage lengths. The pivotal component is the offset link of length g, connecting to pitch links (l) at one end and, at the other end, to a point on the blade, situated f distance behind the pitching axis. Pin joints at both pitch link ends enable rotational freedom. The rotor's radius constitutes the linkage length b. This configuration causes blades to automatically pitch during rotor rotation, with pitching amplitude determined by g when other link lengths remain constant. Fig. 5(b) showcases the actual implementation on the VAWT prototype, emphasizing the evident four-bar linkage system.

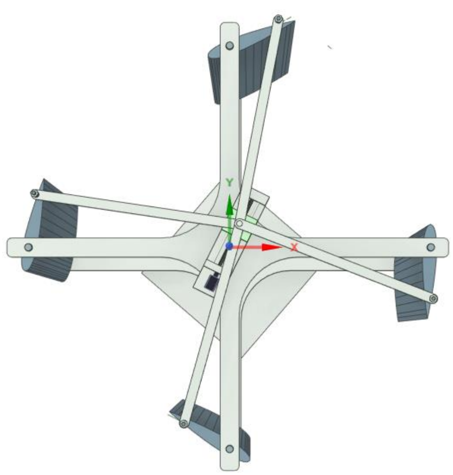


Figure 5. (a)

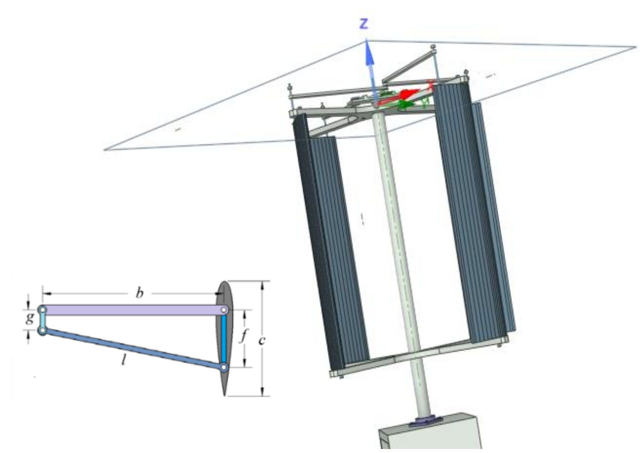


Figure 5.(b)

The VAWT taken for the research purpose is given above here, and measurements are:
g = ground link = 50 mm (maximum)
b = input link = 425 mm
f = floating link = 110 mm
l = output link = 429 mm

5 OBJECTIVES

As elucidated previously, the magnitude of the offset (g) plays a pivotal role in determining the blade pitching amplitude, while the orientation of the offset link governs the cyclic phasing of blade pitching. To dynamically alter the length of the offset (g), a mechanism is essential. Although various mechanisms can serve this purpose, precision and accuracy emerge as critical considerations. While the commonly employed lead screw mechanism may suffice for larger applications, it falls short when dealing with the minute length changes required for the offset link, resulting in an inability to achieve a pitch amplitude within the narrow range of 21° to 22° for small adjustments. It can be seen in given figure 6 that the link g is very small. Consequently, the primary objective of this project is to conduct simulations on the given prototype, exploring the dependency of pitch amplitude on the link length (g) and determining the achievable precision levels. Subsequently, the project aims to design a screw gauge-type mechanism tailored to address this specific challenge. Leveraging the precision and low least count attributes of a screw gauge, this mechanism is poised to provide an optimal solution for precisely altering the length of the offset link and, in turn, adjusting the blade pitch amplitude.

Figure 6. (a) VAWT

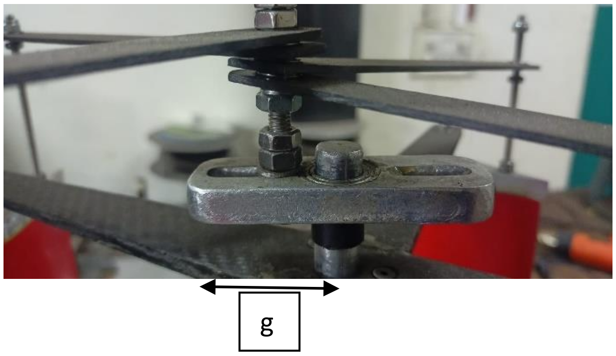


Figure 6. (bThe link

6 SIMULATIONS

I employed the Python programming language to analyze the correlation between the pitch angle and link length across varying azimuthal angles. To streamline the investigation, the offset angle (ε) was set to zero for simplicity.

6.1 Pitch angle calculation:[6]

The angle between the blade chord line and the circular travel path of the blade was referred to as the pitch angle, θ. The pitch amplitude would be varied by adjusting the length of the ground link g. When the blade's leading edge moves outward along the rotating path, the pitch angle is called positive. The necessary geometric relationship of the four-bar link mechanism and the conventions used for the pitch angle are shown in Figure 7. The variable pitch angle Θ can be expressed as:

$$\theta = (\frac{\pi}{2} - \alpha_1 - \alpha_2)$$

Where, the angle α1 and α2 can easily be calculated through trigonometric expressions as;

$\alpha_1 = \sin^{-1}(\frac{g}{d} * \cos(\psi + \varepsilon))$ and $\alpha_2 = \cos^{-1}\frac{(f^2+d^2-l^2}{2df})$

Where, ψ is the azimuthal position of the blade, ε is the offset angle and the diagonal distance d from pitching point 3 to offset point 1. Then, the diagonal distance d is calculated as;

$$d^2 = g^2 + b^2 - 2g * b * \cos{(\psi + \varepsilon + \frac{\pi}{2})}$$

By substituting these two equations in first,

$$\theta = \frac{\pi}{2} - \left[\sin^{-1}(\frac{g}{d} * \cos(\psi + \varepsilon) + \cos^{-1}\frac{(f^2 + d^2 - l^2}{2df})\right]$$

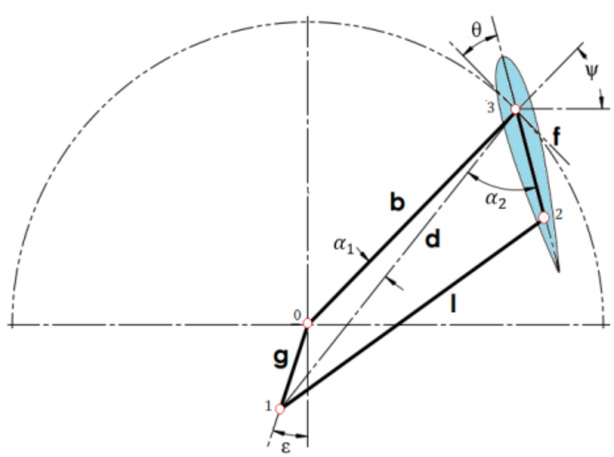


Figure 7. Geometric Relationship of the four-bar link mechanism [6]

6.2 RESULT

The blade pitch angle curve variation in one revolution is shown below.

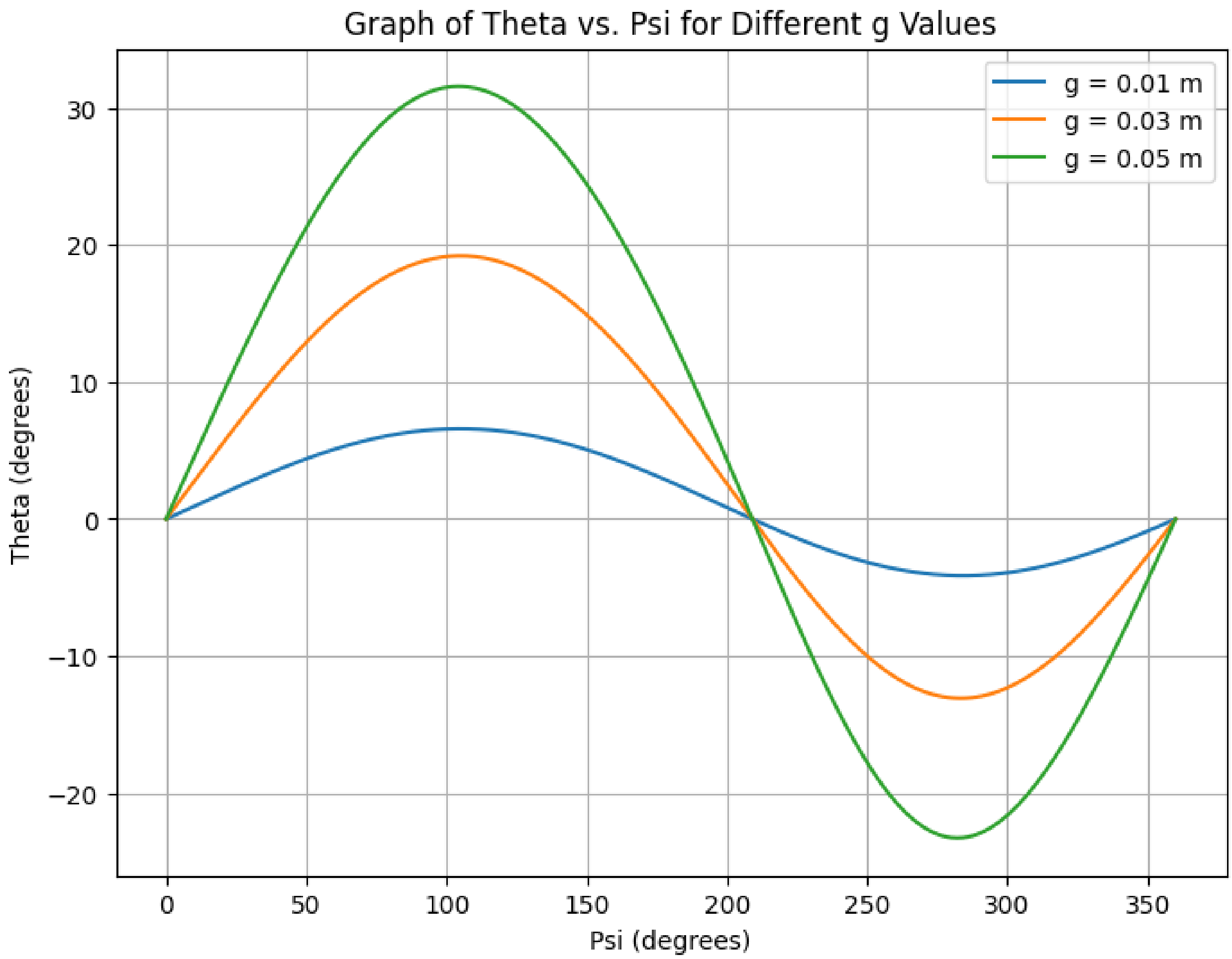


Figure 8. Blade pitch control variation with ground link g

The provided graph illustrates that as the ground link length is systematically adjusted from 10 mm to 30 mm and then to 50 mm, the corresponding amplitude pitch undergoes a variation, ranging approximately from 7° to 19° and further to 32°. Through straightforward calculations, it is deduced that a minimum length variation of 0.833 mm in the link is required to achieve a 1° increase in amplitude pitch. Consequently, the design of a mechanism is imperative, with a stipulated least count not exceeding 0.5 mm to ensure precision.

7 DESIGNS

Leveraging simulation outcomes and precise measurements, the mechanism design has reached its completion using Fusion 360 software. The fundamental principle underlying the design is the screw gauge mechanism, wherein the rotational motion of the nut is efficiently translated into a translational moment. The chosen pitch for the nut is set at 0.5 mm, signifying that a single revolution induces a displacement of 0.5 mm. Consequently, the least count of the screw is calculated to be 0.001 mm, ensuring a high level of precision. The intricacies of the mechanism design are visually depicted in Figure 9.

Figure 9. Variable length mechanism

6 RESULTS

1. The blade pitch angle curve, as depicted in Figure 8, showcases a noteworthy variation throughout one revolution. Systematically adjusting the ground link length from 10 mm to 30 mm and then to 50 mm leads to a corresponding amplitude pitch shift, ranging from approximately 7° to 19° and further to 32°. Crucially, a minimum length variation of 0.833 mm in the link is identified as requisite to achieve a 1° increase in amplitude pitch.
2. The meticulously designed mechanism is seamlessly integrated in place of link g, establishing a pivotal component in the vertical-axis wind turbine (VAWT). This integration is facilitated with the aid of a motor, providing a sophisticated control system for precisely managing the pitch amplitude. The motor-driven control allows for dynamic adjustments, optimizing the performance of the VAWT across varying wind conditions. This innovative integration not only enhances the controllability of the turbine but also contributes to the overall efficiency and adaptability of the system, showcasing the

potential for advanced wind energy solutions.

7 Conclusion-

In pursuit of optimizing the blade pitch control mechanism, this research project successfully employed Fusion 360 software to design a mechanism inspired by the precision of a screw gauge. The mechanism showcased a pitch of the nut at 0.5 mm, translating into a displacement of 0.5 mm per revolution. With a calculated least count of 0.001 mm, the mechanism ensures a high level of precision. The systematic adjustment of the ground link length, as validated through simulation and measurement, substantiates the need for a mechanism with a least count not exceeding 0.5 mm for effective precision in controlling blade pitch. The completion of the project marks a significant step towards enhancing the efficiency of vertical-axis wind turbines through a meticulously designed pitch control mechanism.

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