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# Optimization of Quadcopter Propeller Aerodynamics Using Blade Element and Vortex Theory

Solomon Ileanaju Ugbane[1]
[1]Department of Electrical Engineering
Prairie View A and M University, Texas, USA.

Chima Umeaku[2]
Department of Computer and Information Sciences,
Northumbria University Newcastle, United Kingdom.

Idoko Peter Idoko[3]
[3]Department of Electrical/ Electronic Engineering
University of Ibadan, Ibadan, Nigeria

Lawrence Anebi Enyejo[4]
Department of Telecommunications, Enforcement, Ancillary and Maintenance,
NBC,Abuja, Nigeria.

Comfort Idongesit Michael[5]
Department of Computer Management and Information Systems, Southern Illinois University, Edwardsville. USA

Onuh Matthew Ijiga[6]
Department of Physics,
Joseph Sarwuan Tarka University, Makurdi, Nigeria

**Abstract:- The optimization of quadcopter propeller aerodynamics is crucial for enhancing the efficiency and stability of unmanned aerial vehicles (UAVs), especially in their increasing applications across various sectors, including humanitarian relief and delivery services. This study focuses on optimizing quadcopter propeller performance using Blade Element Theory and Glauert Vortex Theory to analyze the aerodynamic properties and predict thrust generation accurately. Experimental methods, including wind tunnel testing and static thrust measurements, were used to validate the theoretical models. The results indicate a close correlation between theoretical predictions and experimental data, providing insights into improving propeller efficiency and mitigating aerodynamic losses. By understanding the propeller characteristics, this research contributes to the development of advanced drone propulsion systems with enhanced thrust, reduced drag, and better overall flight performance. The findings also highlight the impact of environmental factors such as turbulence and blade geometry on quadcopter stability, pointing toward areas for further improvement in propeller design. This paper serves as a valuable resource for drone hobbyists, engineers, and researchers seeking to enhance UAV performance through optimized propeller aerodynamics.**

***Keywords:-*** *Quadcopter, Propeller Aerodynamics, Blade Element Theory, Vortex Theory, UAV Optimization, Thrust Prediction, Drag Reduction, Drone Propulsion, Wind Tunnel Testing, Aerodynamic Efficiency.*

## I. INTRODUCTION

➢ *Overview of Quadcopter Propulsion Characteristics*

Quadcopters, a popular form of unmanned aerial vehicles (UAVs), have emerged as versatile tools, providing solutions across diverse industries such as logistics, law enforcement, and humanitarian aid (Warwick, 2017; Duell, 2016). As technology has evolved, quadcopters have developed into highly efficient machines capable of performing complex tasks, including package delivery by companies like Amazon and inspections by insurance firms using drone-based video streaming (Miller, 2016). These advancements necessitate a deeper understanding of the fundamental propulsion characteristics of quadcopters to maximize their performance.

The core of any quadcopter is its propulsion system, typically consisting of four propellers that generate lift and thrust through rotation. Understanding the aerodynamic properties of these propellers is essential for enhancing the overall performance and efficiency of the UAV (Westaway, 2016). The primary factors influencing propeller performance include blade geometry, pitch angle, and environmental variables like temperature and air density (Hepperle, 2005). In this context, both theoretical modeling and experimental testing are crucial to effectively optimize these parameters and improve UAV performance.

The Blade Element Theory (BET) and Glauert Vortex Theory are commonly used to analyze and predict propeller performance. BET involves dividing the propeller into multiple small elements and determining the aerodynamic forces generated by each element based on airfoil characteristics (Hepperle, 2005). The Glauert Vortex Theory extends this analysis by incorporating the effects of induced drag and vortex generation, thus providing a comprehensive picture of propeller behavior (Dommasch, Sherby, & Connolly, 1967). These theories form the basis for developing mathematical models that can predict thrust, torque, and efficiency under different operating conditions.

Experimental verification is critical to validate the theoretical predictions. For instance, wind tunnel testing has been instrumental in comparing measured data with predictions from BET and vortex models (Brandt & Selig, 2011). In a controlled experimental setup, parameters such as thrust, torque, and drag are measured to understand the propeller's behavior under different operating conditions, including static and dynamic thrust settings (Deters & Selig, 2011). The comparison of experimental data with theoretical results helps identify discrepancies and refine the models for greater accuracy.

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For quadcopters, achieving optimal performance involves minimizing aerodynamic losses such as induced drag and turbulence. The turbulence generated by the interaction of multiple propellers presents significant challenges, particularly during high-speed operations or rapid directional changes (Meschia, 2008). Computational tools such as Xflr5 and SolidWorks are employed to analyze airfoil geometry and simulate aerodynamic performance, allowing engineers to make informed decisions about design modifications to enhance stability and efficiency (Meschia, 2008; Anderson, 1978).

This study aims to contribute to the optimization of quadcopter propeller aerodynamics by analyzing propeller performance using BET and Glauert Vortex Theory, supported by experimental testing. The insights gained are intended to improve the understanding of quadcopter propulsion characteristics, providing a foundation for further advancements in UAV technology and addressing the challenges of efficient thrust generation, drag minimization, and overall stability.

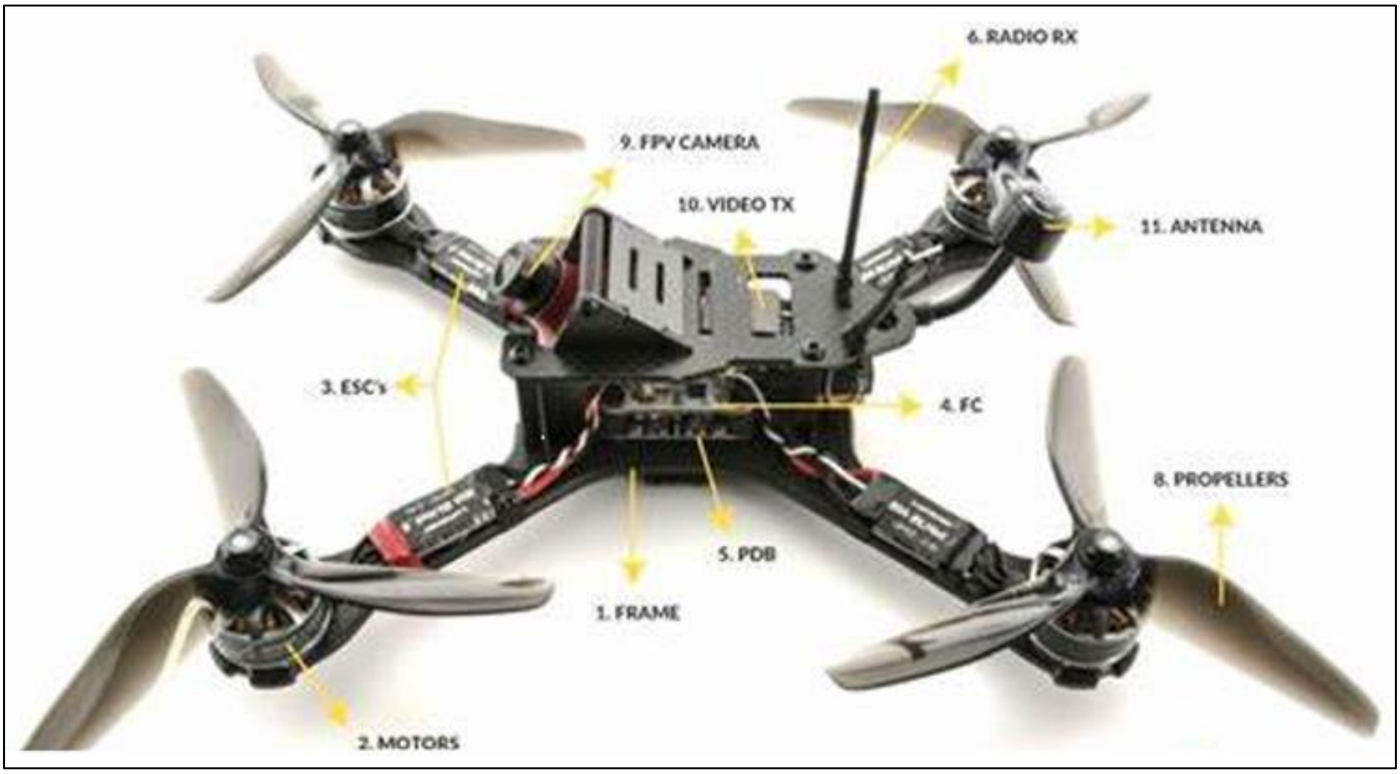


Fig 1 Key Components of a Quadcopter Drone: A Visual Guide (Liang 2021)

Figure 1 provides a labeled diagram of the key components of a quadcopter drone. It highlights essential parts such as the frame (1), which provides structural support, and motors (2), responsible for propelling the drone. ESCs (3), or electronic speed controllers, manage the speed of the motors, while the flight controller (4), or FC, controls the drone's movement and stabilization. The power distribution board (PDB, 5) supplies power to various components. The radio receiver (6) (Radio RX) receives signals from the pilot's controller, while the antenna (11) ensures communication. The FPV camera (9) transmits live video, and the video transmitter (10) (Video TX) sends the video feed back to the pilot. The propellers (8) provide lift, making the drone airborne. This diagram serves as a useful guide to understanding the components necessary for a drone's operation.

- *Importance of Optimizing Drone Propeller Aerodynamicss*

Optimizing drone propeller aerodynamics is essential for enhancing the performance, stability, and efficiency of quadcopters. Given the rapid proliferation of drones for various applications, ranging from humanitarian relief to logistics, the need to improve their propulsion systems has become increasingly significant (Warwick, 2017). Propeller efficiency directly impacts the overall flight characteristics, including thrust generation, energy consumption, and control stability, which are crucial for effective drone operations (Miller, 2016). An in-depth understanding of aerodynamic forces acting on quadcopter propellers, including thrust, torque, lift, and drag, is critical to achieving improved performance and operational sustainability (Hepperle, 2005).

Quadcopters, which rely on their propellers to maintain stability and maneuverability, face numerous aerodynamic challenges during flight. These challenges include turbulence, induced drag, and vortex shedding, which can negatively affect flight efficiency and stability, especially under dynamic conditions (Dommasch, Sherby, & Connolly, 1967). The interaction of the four propellers generates turbulence, particularly when the drone changes altitude or direction, creating complex aerodynamic phenomena that can hinder efficient flight (Anderson, 1978). Optimizing the aerodynamic design of the propellers is therefore essential to mitigate these effects, leading to smoother and more stable flights.

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One of the key approaches to propeller optimization is through careful consideration of blade geometry, including parameters such as blade shape, pitch angle, and aspect ratio. Blade Element Theory (BET) provides a foundational approach to analyzing and optimizing these parameters by dividing the propeller into multiple elements and evaluating the aerodynamic forces acting on each element (Meschia, 2008). This segmented analysis enables a more detailed understanding of how variations in blade geometry affect thrust and drag, which is critical for determining optimal propeller configurations (Brandt & Selig, 2011). Moreover, incorporating the Glauert Vortex Theory allows for a more comprehensive understanding of the induced effects, such as vortex generation and its impact on efficiency (Dommasch et al., 1967).

The importance of optimizing drone propeller aerodynamics also extends to enhancing energy efficiency. As drones are often battery-powered, optimizing the propulsion system can result in significant energy savings, thereby increasing flight time and payload capacity. A well-optimized propeller design ensures minimal power consumption while generating sufficient thrust to maintain stability during various maneuvers (Westaway, 2016). For instance, by optimizing the pitch and blade aspect ratio, the drag forces experienced by the drone can be minimized, allowing for smoother transitions and lower energy use during hovering or forward flight (Deters & Selig, 2011).

Wind tunnel testing has proven to be a vital tool in validating the effectiveness of aerodynamic optimization efforts. Testing in controlled environments allows researchers to evaluate the effects of various parameters, such as pitch angle and rotational speed, on aerodynamic performance (Hartman & Biermann, 1938). The comparison of experimental data with predictions from BET and vortex models can reveal discrepancies and guide further refinement of the propeller design. Wind tunnel tests also help in understanding how the propeller performance changes under different Reynolds numbers, which directly affects thrust and efficiency, especially at lower speeds (Brandt & Selig, 2011).

In practical terms, the application of optimized quadcopter propeller designs has far-reaching implications for real-world drone operations. Improved propeller aerodynamics can enhance the payload capabilities of drones, allowing them to lift heavier objects and perform tasks more effectively, such as carrying humanitarian supplies to remote locations (Warwick, 2017). Additionally, optimized propeller designs can lead to quieter operations, which is particularly important in urban environments where noise pollution is a concern (Makoye, 2016). These improvements in operational efficiency and noise reduction directly contribute to the broader acceptance and integration of drones into society for commercial and recreational uses.

Thus, optimizing quadcopter propeller aerodynamics is crucial for enhancing performance, efficiency, and reliability. The use of theoretical models such as BET and Glauert Vortex Theory, combined with experimental testing and computational analysis, provides a comprehensive approach to achieving these goals. The findings from such optimization efforts not only contribute to the technical advancement of UAV technology but also support the growing applications of drones in various sectors by improving operational efficiency and expanding their practical capabilities.

➢ *Current Challenges in Quadcopter Propulsion Efficiency*

Despite the remarkable advancements in drone technology, quadcopters still face several challenges regarding propulsion efficiency. These challenges include high aerodynamic drag, limited thrust efficiency, turbulence, and issues arising from environmental factors like temperature, topography, and air density (Hepperle, 2005). Propulsion efficiency is directly linked to these variables, and optimizing the quadcopter's propeller design and propulsion systems is essential for achieving enhanced flight performance. However, many obstacles complicate the optimization process.

One significant challenge is the turbulence generated by quadcopter propellers during flight. The close proximity of multiple propellers on a quadcopterresults in complex aerodynamic interactions, leading to turbulence that can destabilize the drone and reduce overall efficiency (Anderson, 1978; Idoko et al., 2024; Ijiga et al., 2024). This turbulence is especially pronounced during aggressive maneuvers, where the unsteady aerodynamic effects become even more challenging to predict and mitigate (Dommasch, Sherby, & Connolly, 1967; Idoko et al., 2024; Ijiga et al., 2024). The dynamic conditions of drone flight create unsteady vortices, which, in turn, negatively affect the aerodynamic performance of the propellers. Addressing these issues requires an in-depth understanding of the behavior of the generated vortices and their impact on overall stability and thrust efficiency.

Another critical issue is optimizing the thrust-to-weight ratio of quadcopters. The thrust generated by a drone's propellers is directly related to the aerodynamic forces acting on them, and inefficient thrust generation can severely limit the quadcopter's payload capacity and flight endurance (Warwick, 2017). The aerodynamic design of propellers must balance between maximizing thrust and minimizing drag, a challenge that requires both theoretical modeling and experimental testing. Blade Element Theory (BET) and Glauert Vortex Theory are instrumental in understanding and optimizing this balance. BET, in particular, allows for the estimation of aerodynamic forces across the span of the propeller, aiding in fine-tuning the geometry for enhanced performance (Meschia, 2008). However, even with these theoretical models, achieving an optimal thrust-to-weight ratio while minimizing power consumption is a complex process that remains an ongoing challenge.

Environmental conditions such as wind, air density, and temperature also have a significant impact on quadcopter propulsion efficiency. The aerodynamic properties of propellers change with varying air density, which affects thrust generation and power requirements (Hepperle, 2005; Idoko et al., 2024). Wind conditions, in particular, can cause fluctuations in thrust, leading to inefficiencies and requiring constant corrections from the drone's control system (Makoye, 2016, Idoko et al., 2024). Testing under various environmental conditions, such as those conducted in wind tunnels, provides valuable insights into how these factors affect drone performance and stability. However, replicating real-world environmental conditions in a controlled laboratory setting is often difficult, creating a gap between theoretical predictions and practical performance outcomes (Brandt & Selig, 2011; Idoko et al., 2024; Ijiga et al., 2024).

The limitations of current experimental methods are another challenge for improving quadcopter propulsion efficiency. Wind tunnel testing, though widely used, has limitations regarding scale and environmental representation (Deters & Selig, 2011, Idoko et al., 2024, Ijiga et al., 2024). The shroud used in the wind tunnel test for the quadcopter propellers, for example, was modified to accommodate the size of the drone, which may have led to discrepancies in airflow behavior and caused difficulties in achieving stable conditions for accurate dynamic testing (Hartman & Biermann, 1938). Moreover, the presence of turbulence and vibration during testing created additional challenges that interfered with obtaining reliable data. Such challenges indicate the need for more sophisticated experimental setups that can closely mimic real-world conditions.

Furthermore, the presence of multiple propellers on quadcopters leads to a higher risk of induced drag and vortex formation. This phenomenon becomes particularly significant during high-speed forward flight, where the vortices shed by each propeller interact and contribute to an increase in induced drag, thus decreasing overall efficiency (Anderson, 1978; Dommasch et al., 1967; Idoko et al., 2024; Ijiga et al., 2024). The effective reduction of induced drag remains a primary goal for improving propulsion efficiency. One potential solution involves refining propeller blade geometry to minimize the generation of vortices, thus reducing the associated drag losses (Hepperle, 2005; Idoko et al., 2024; Ijiga et al., 2024). However, achieving an optimal design that balances aerodynamic efficiency with structural strength and manufacturability is a significant engineering challenge.

Despite these challenges, the continued exploration of drone propulsion efficiency remains a priority. Employing computational fluid dynamics (CFD) simulations in conjunction with experimental testing has shown promise in predicting the complex aerodynamic interactions that occur between the multiple propellers of a quadcopter (Meschia, 2008). The combination of experimental data and advanced modeling techniques can help refine theoretical models such as BET and Glauert Vortex Theory, leading to improved optimization strategies and the development of advanced UAVs that can meet the growing demands of commercial, recreational, and industrial applications.

➢ *Objectives of the Study*

The primary objective of this study is to optimize the aerodynamic performance of quadcopter propellers by utilizing both Blade Element Theory (BET) and Glauert Vortex Theory, supported by experimental testing. This research aims to provide a comprehensive understanding of how propeller characteristics influence thrust generation, energy efficiency, and overall flight performance. By analyzing propeller behavior under various flight conditions, this study seeks to identify key factors affecting propulsion efficiency and offer solutions for mitigating aerodynamic losses such as induced drag and turbulence.

Another significant objective of this study is to validate the theoretical models through experimental wind tunnel testing. The research involves testing propeller performance under different conditions, including changes in pitch angle and rotational speed, to assess the accuracy of BET and Glauert Vortex Theory. The validation process aims to bridge the gap between theoretical predictions and real-world performance, ensuring that the models can be applied effectively to enhance quadcopter propulsion systems.

This study also aims to explore the impact of blade geometry on the aerodynamic efficiency of quadcopters. Factors such as blade shape, aspect ratio, and pitch angle are analyzed to determine their effect on thrust and drag characteristics. By optimizing these parameters, the research aims to enhance propeller efficiency, minimize energy consumption, and improve the thrust-to-weight ratio of quadcopters.

Additionally, the study seeks to understand the influence of environmental conditions on propeller performance. By examining how factors such as air density, wind conditions, and turbulence affect the aerodynamic properties of the propellers, the study aims to develop strategies for adapting propeller designs to varying environmental conditions, thus improving the reliability and versatility of quadcopters.

Overall, the objectives of this study are focused on contributing to the development of advanced, efficient, and stable drone propulsion systems that can meet the growing demands of commercial, industrial, and recreational applications. The findings from this research are intended to support further advancements in UAV technology by providing a solid foundation for propeller optimization and performance enhancement.

➢ *Structure of the Paper*

This paper is structured into several key sections, each contributing to a comprehensive exploration of the optimization of quadcopter propeller aerodynamics.

The first section, "Introduction," provides an overview of the motivations behind optimizing quadcopter propulsion systems and highlights the importance of efficient drone operation in the expanding applications of UAVs. The introduction also presents the objectives of this research and how it aims to contribute to the ongoing development of UAV technology.

The second section, "Theoretical Framework and Methodology," delves into the analytical tools and theories used to understand and optimize quadcopter propeller performance. This section explains the Blade Element Theory (BET) and Glauert Vortex Theory, which are foundational for analyzing the aerodynamic forces acting on propeller blades. It also provides an overview of the experimental setup, including the use of wind tunnel testing and the instrumentation employed to validate the theoretical models.

The third section, "Results and Analysis," presents the findings of the study. This section discusses the experimental data obtained through testing, comparing these results with theoretical predictions to evaluate the accuracy of the models used. The analysis covers factors such as static thrust, drag coefficients, and the impact of varying pitch angles and blade geometry on aerodynamic performance.

The fourth section, "Discussion," interprets the findings in the context of optimizing quadcopter propulsion. This section addresses the implications of the results, including the potential for enhancing propeller efficiency and mitigating aerodynamic losses. The challenges identified during experimental testing are also discussed, alongside recommendations for future research.

The final section, "Conclusion and Future Directions," provides a summary of the study's key findings, emphasizing their practical implications for improving quadcopter performance. This section also outlines recommendations for the industry and proposes areas for further research to continue advancing drone technology and enhancing UAV applications.

## II. THEORETICAL FRAMEWORK AND METHODOLOGY

### *A. Blade Element Theory for Propeller Analysis*

Blade Element Theory (BET) is a foundational approach in the analysis and optimization of propeller aerodynamics, particularly for quadcopters. BET is based on dividing a propeller blade into small sections, known as elements, and then calculating the aerodynamic forces on each element individually. By integrating these forces along the span of the blade, BET provides an estimate of the overall performance of the propeller, including thrust, torque, and efficiency (Dommasch, Sherby, & Connolly, 1967). This section explores how BET is applied in propeller analysis, with particular attention to the aerodynamic characteristics that influence thrust generation and drag reduction.

In BET, each blade section is considered as an independent airfoil, and the aerodynamic forces acting on each element are evaluated based on the local flow conditions. The lift dL) and drag dDforces on an element depend on the chord length, local angle of attack, and the relative velocity at that section. These forces can be expressed mathematically as follows:.

$$dL = \frac{1}{2}\rho V^2 c C_L dr \tag{1}$$

$$dD = \frac{1}{2}\rho V^2 c C_D dr \tag{2}$$

Where:

$\rho$ is the air density,

V is the relative velocity at the section,

c is the chord length of the blade element,

$C_L$ and $C_D$ are the lift and drag coefficients, respectively, and dr is the length of the blade section (Hepperle, 2005).

To determine the thrust produced by each blade element, the lift force component in the direction of the propeller axis must be calculated. The elemental thrust dT and torque dQ are given by:

$$dT = dL\ \cos\emptyset - dD \sin\emptyset \tag{3}$$

$$dQ = dL\ \cos\emptyset + dD \sin\emptyset \tag{4}$$

Where $\emptyset$ is the effective pitch angle of the blade element, and r is the radial distance from the propeller hub to the element (Dommasch et al., 1967). These elemental forces are then integrated along the entire span of the blade to obtain the total thrust and torque produced by the propeller.

The effective pitch angle $\emptyset$ is influenced by the forward velocity of the propeller and the rotational speed, which together determine the relative airflow direction experienced by the blade element. The effective pitch angle can be calculated as:

$$\emptyset = \tan^{-1}\left(\frac{V}{2\pi n r}\right) \tag{5}$$

Where n is the rotational speed in revolutions per second, and r is the radial position of the element (Dommasch et al., 1967).

The application of BET to quadcopter propellers involves several complexities due to the multi-rotor configuration, which creates intricate aerodynamic interactions. Each propeller not only interacts with the surrounding air but also influences the flow fields of adjacent propellers, leading to variations in thrust and efficiency (Meschia, 2008). These induced effects are considered through the integration of Glauert Vortex Theory, which provides corrections for induced velocities and drag (Brandt & Selig, 2011). The combination of BET and Glauert Vortex Theory allows for a more accurate representation of the aerodynamic forces acting on the quadcopter propellers, ultimately aiding in optimizing their performance.

To accurately predict propeller performance using BET, it is essential to consider the impact of propeller blade geometry. Blade parameters such as chord length, pitch angle, and aspect ratio significantly influence the aerodynamic characteristics of the propeller. Experimental studies have demonstrated that optimizing these parameters can lead to improved thrust efficiency and reduced drag, which are critical for enhancing quadcopter performance (Hepperle, 2005). Wind tunnel testing has been an instrumental method for validating these theoretical models, enabling researchers to compare the predicted thrust and torque with experimental data (Hartman & Biermann, 1938).

In applying BET to the quadcopter propulsion system, the propeller is divided into radial sections, each analyzed for aerodynamic force generation. The sectional lift coefficient C_Land drag coefficient C_D are typically obtained from low-speed airfoil data, considering the Reynolds number corresponding to the operating conditions of the quadcopter propeller (Selig et al., 1995). These airfoil characteristics are crucial for accurately predicting the forces acting on each blade element and, consequently, the overall performance of the propeller.

Although BET provides a detailed understanding of the aerodynamic forces on a propeller, there are limitations to this approach, particularly in accounting for three-dimensional effects such as tip losses and wake interactions. The induced drag caused by the generation of vortices at the blade tips, as well as the downwash effects, require corrections to the lift and drag calculations to ensure accurate predictions (Anderson, 1978). The Prandtl Lifting Line Theory is often used to apply these corrections, allowing for a more accurate representation of the aerodynamic efficiency of the propeller (Dommasch et al., 1967).

Blade Element Theory serves as a powerful tool for analyzing and optimizing quadcopter propeller performance. By considering each blade section independently and calculating the aerodynamic forces acting on each element, BET provides a comprehensive understanding of the thrust and torque characteristics of the propeller. The integration of BET with other aerodynamic theories, such as Glauert Vortex Theory and Prandtl Lifting Line Theory, enables a more accurate prediction of propeller performance, ultimately contributing to the optimization of quadcopter propulsion systems.

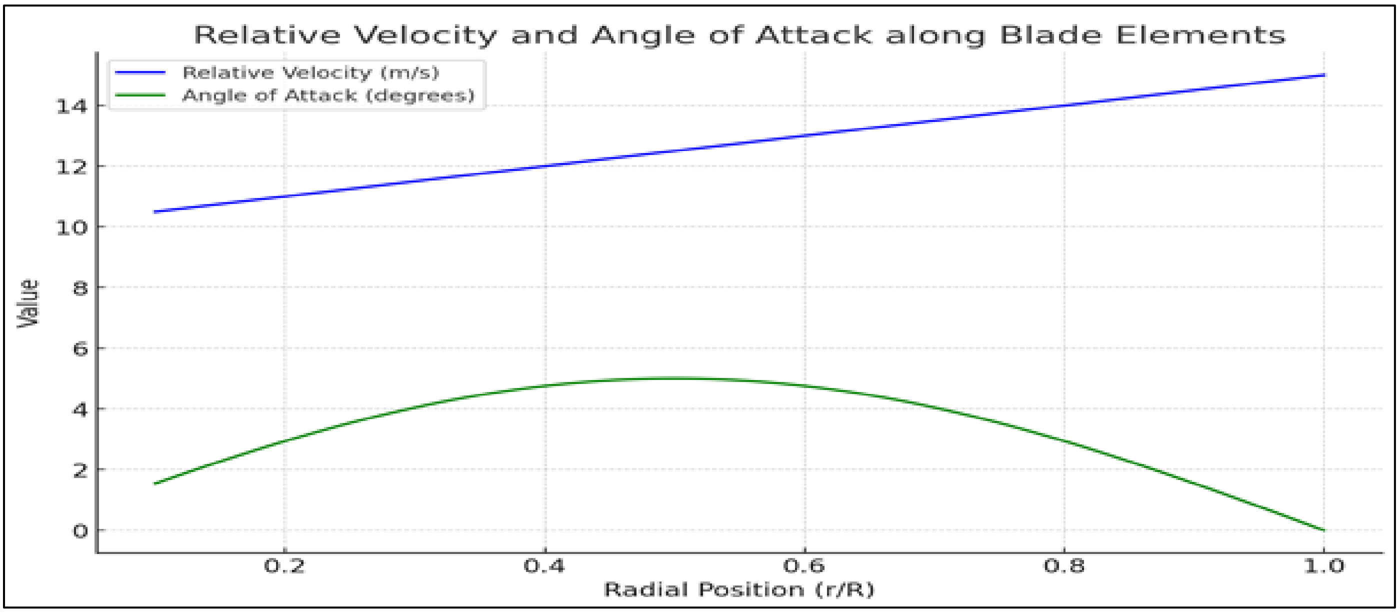


Fig 2a Relative Velocity and Angle of Attack along Blade Elements

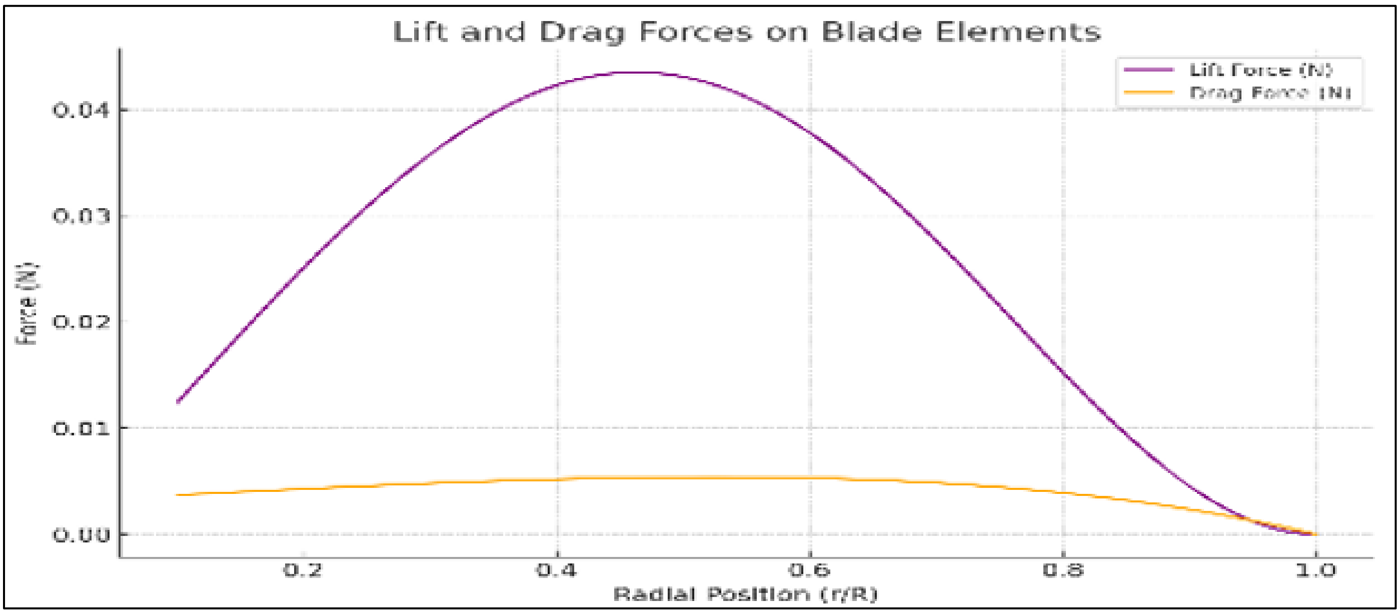


Fig 2b Lift and Drag Forces on Blade Elements

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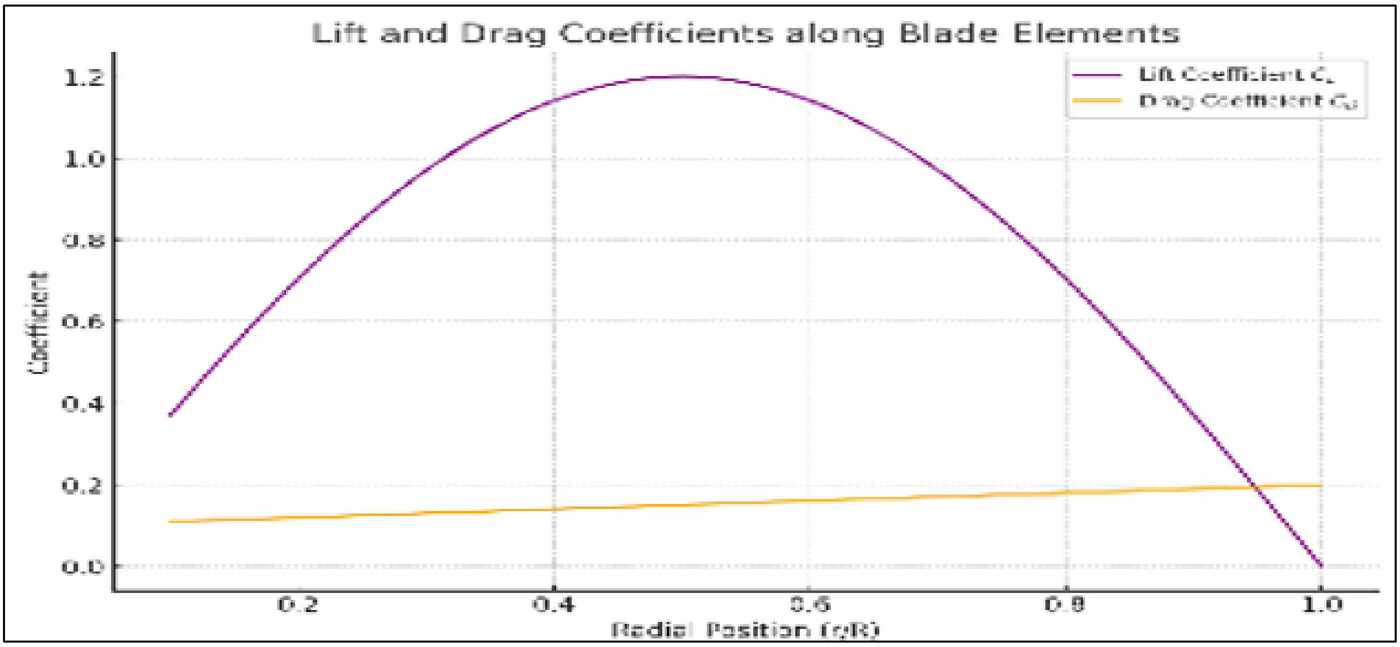

Fig 2c Lift and Drag Coefficients along Blade Elements

Figure 2a represents the Relative Velocity and Angle of Attack along Blade Elements. As the radial position (distance from the hub) increases along the propeller blade, the relative velocity also rises, reaching its maximum near the blade tip due to the rotational speed of the propeller. The angle of attack, however, peaks at the mid-span and then decreases toward the blade tip. This profile is essential for optimizing lift, as the mid-span area experiences an optimal angle for aerodynamic efficiency.

Figure 2b shows the Lift and Drag Forces on Blade Elements. The lift force, which is a function of the angle of attack and relative velocity, peaks in the middle of the blade span before tapering off near the tip. This indicates that the mid-blade region contributes the most to thrust generation, while the outer and inner sections are less effective. The drag force increases steadily toward the blade tip, reflecting the impact of increasing velocity on resistance encountered by the blade.

Figure 2c illustrates the Lift and Drag Coefficients along Blade Elements. The lift coefficient varies along the blade, peaking at mid-span due to the favorable angle of attack in this region, enhancing thrust production. The drag coefficient gradually increases toward the blade tip, consistent with higher relative velocity and the associated increase in aerodynamic drag. Together, these coefficients provide insights into the aerodynamic efficiency of each blade section, enabling adjustments for optimal propeller design and performance.

*B. Application of Glauert Vortex Theory in Drone Propulsion*

The Glauert Vortex Theory is another crucial aerodynamic theory used in analyzing and optimizing the performance of drone propellers. Unlike Blade Element Theory (BET), which evaluates the aerodynamic forces on independent sections of the blade, Glauert Vortex Theory incorporates the effects of induced drag and wake formation, providing a more comprehensive understanding of the aerodynamic characteristics that influence propeller efficiency (Dommasch, Sherby, & Connolly, 1967). This theory is particularly significant in understanding the three-dimensional aerodynamic effects of propeller operation, especially in quadcopter configurations where interactions between multiple rotors create complex flow fields (Hepperle, 2005).

Glauert Vortex Theory is based on the concept of lifting line theory, which represents the propeller blades as a series of bound vortices. The theory assumes that the circulation around a blade varies along its span, and the vortex shedding at the trailing edge generates a helical wake that extends downstream. This wake induces a velocity field, which alters the effective angle of attack along the blade, thereby influencing both thrust and drag generation. The induced velocity V_iat the blade element due to the helical wake can be expressed as:

$$V_i = \frac{T}{4\pi r \rho V} \tag{6}$$

Where:

T is the thrust produced by the propeller,
r is the radial distance from the hub to the blade element,
$\rho$ is the air density, and
V is the inflow velocity (Dommasch et al., 1967).

The induced velocity results in a reduction in the effective angle of attack experienced by each blade section, which leads to induced drag. Induced drag is the primary form of drag encountered by a propeller and has a significant impact on the overall efficiency of the quadcopter's propulsion system. The coefficient of induced drag ($C_{Di}$) can be determined using the relation:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{7}$$

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Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio of the propeller blade (Anderson, 1978).

In quadcopters, induced drag becomes a critical issue due to the interaction of multiple propellers, each generating its own wake. These wakes can interfere with one another, resulting in complex flow patterns that affect the aerodynamic performance of the drone (Brandt & Selig, 2011). The application of Glauert Vortex Theory helps in quantifying these induced effects, allowing for corrections to be made to the thrust and drag estimates provided by Blade Element Theory. By considering the helical wake and its impact on adjacent blades, engineers can design propellers with optimized blade geometry to minimize induced drag and enhance efficiency (Dommasch et al., 1967).

To apply Glauert Vortex Theory effectively, it is crucial to understand the role of circulation \mathrm{\Gamma} around the propeller blade. Circulation is directly related to the lift force generated by a blade section and varies along the span of the blade. According to Glauert's approach, the total thrustTproduced by the propeller can be calculated by

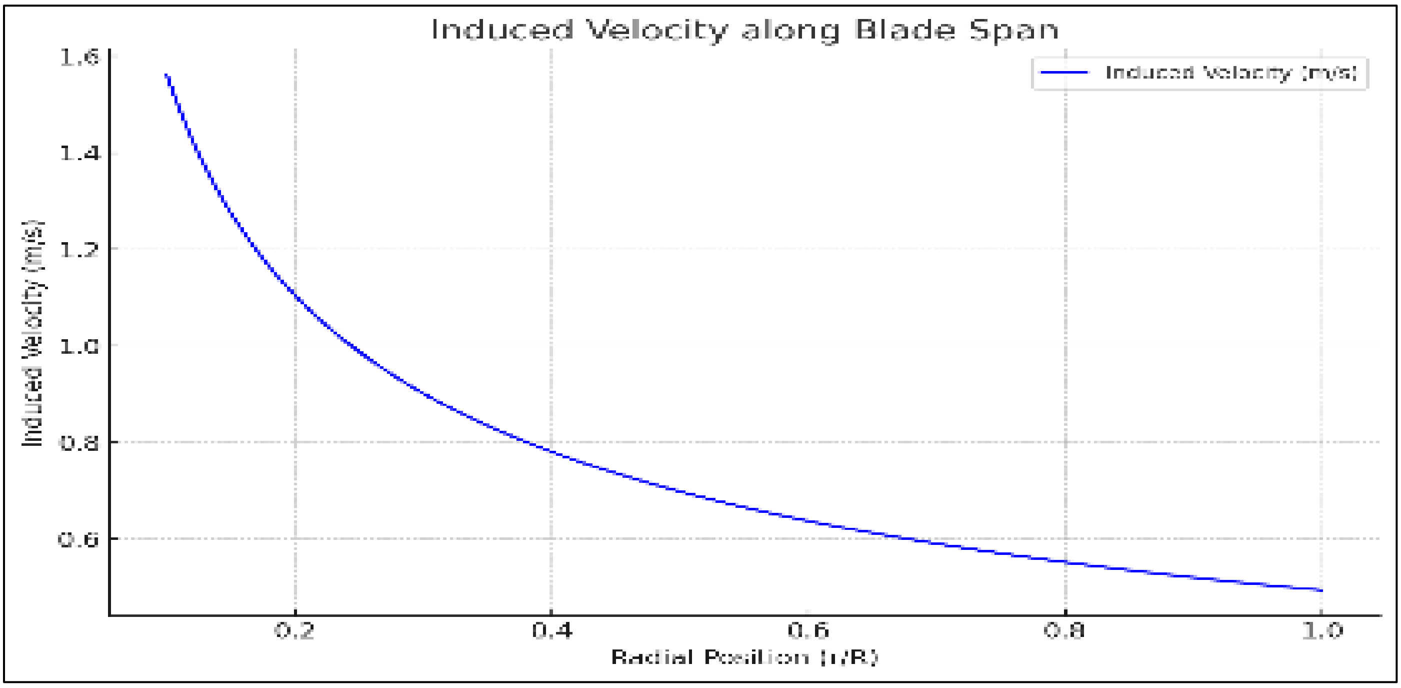


Fig 3a Induced Velocity along Blade Span

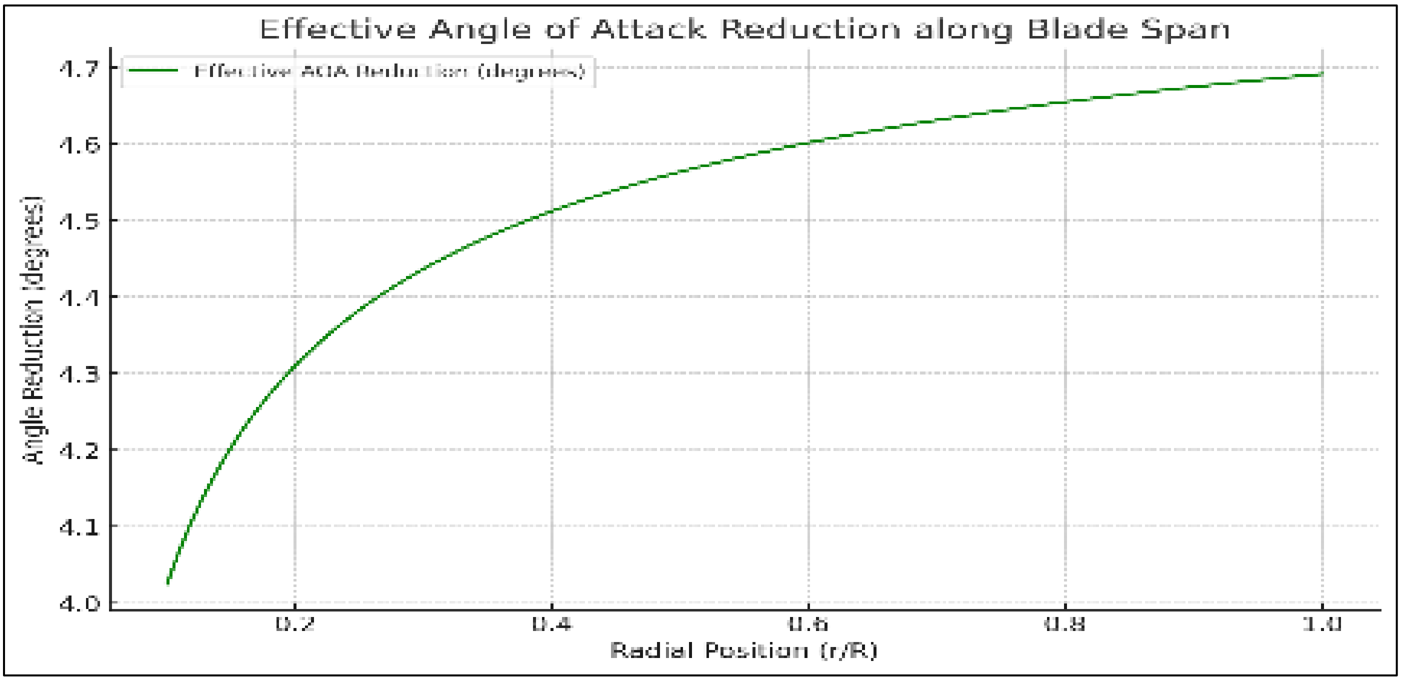


Fig 3b Effective Angle of Attak Reduction along Blade Span

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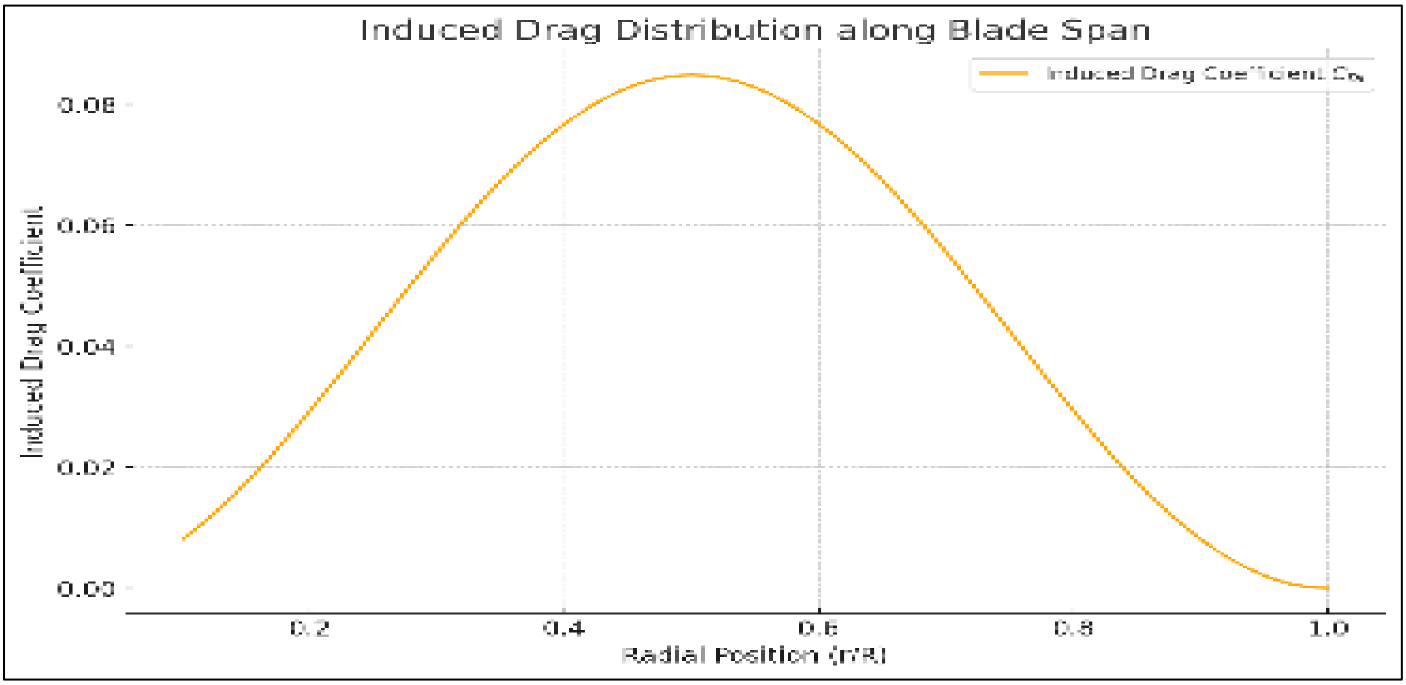

Fig 3c Induced Drag Distribution along Blade Span

Integrating the differential thrust dT along the entire span of the blade:

$$T = \int_0^R \rho V \Gamma dr \quad (8)$$

Where R is the radius of the propeller (Dommasch et al., 1967). The variation in circulation is influenced by several factors, including the blade twist, the chord distribution, and the local flow conditions. The optimization of these parameters can lead to an even distribution of lift along the blade span, reducing the formation of strong tip vortices that contribute to induced drag (Meschia, 2008).

One of the significant benefits of using Glauert Vortex Theory in quadcopter propeller optimization is its ability to model the effects of tip vortices and wake interactions. Tip vortices, which are formed at the blade tips due to pressure differences between the upper and lower surfaces, represent a major source of induced drag. The induced velocity field generated by these vortices not only affects the performance of the propeller itself but also interacts with the vortices generated by adjacent propellers in a quadcopter configuration (Hartman & Biermann, 1938). These interactions can lead to a phenomenon known as vortex ring state, where the drone becomes unstable due to the re-ingestion of its own wake. By applying Glauert Vortex Theory, it is possible to predict and mitigate these adverse effects, thereby improving the stability and efficiency of the quadcopter.

Experimental validation of Glauert Vortex Theory is often carried out through wind tunnel testing, where propeller performance under controlled conditions can be compared with theoretical predictions. These tests provide valuable data on the induced velocities and their effect on thrust and drag coefficients. For instance, Hartman and Biermann (1938) demonstrated that the inclusion of induced velocity corrections significantly improved the accuracy of thrust predictions for full-scale propellers. Such experimental findings are crucial for refining the theoretical models and ensuring their applicability to real-world quadcopter operations (Brandt & Selig, 2011).

Glauert Vortex Theory plays a vital role in the analysis and optimization of quadcopter propeller aerodynamics. By incorporating the effects of induced drag and wake interactions, this theory provides a more comprehensive understanding of the factors affecting propeller performance. The combination of Blade Element Theory and Glauert Vortex Theory enables a detailed analysis of both sectional and three-dimensional aerodynamic forces, ultimately contributing to the design of more efficient and stable quadcopter propulsion systems.

### *C. Data Acquisition from Wind Tunnel and Static Thrust Tests*

Wind tunnel and static thrust testing are critical experimental methods used for validating theoretical models such as Blade Element Theory (BET) and Glauert Vortex Theory in the analysis of quadcopter propeller performance. The data collected through these tests provide valuable insights into the aerodynamic properties of propellers, such as thrust, torque, drag, and efficiency, under different operating conditions (Brandt & Selig, 2011). This section discusses the methodologies for data acquisition from wind tunnel and static thrust tests and their importance in the optimization of quadcopter propulsion systems.

➢ *Wind Tunnel Testing Methodology*

Understanding and quantifying the aerodynamic characteristics of quadcopter propellers. In a wind tunnel, airflow is directed over a propeller mounted on a dynamometer, allowing the measurement of forces acting on the propeller while controlling variables such as airspeed, pitch angle, and rotational speed (Deters & Selig, 2011). The dynamometer measures thrust T, torque Q, and drag forces D, which are then used to evaluate the aerodynamic efficiency of the propeller.

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The coefficient of thrust $C_T$ and the coefficient of torque $C_Q$ are essential parameters calculated from the measured forces. These coefficients are defined as:

The final section, "Conclusion and Future Directions," provides a summary of the study's key findings, emphasizing their practical implications for improving quadcopter performance. This section also outlines recommendations for the industry and proposes areas for further research to continue advancing drone technology and enhancing UAV applications.

To determine the thrust produced by each blade element, the lift force component in the direction of the propeller axis must be calculated. The elemental thrust dT and torque dQare given by:

$$C_T = \frac{T}{\rho n^2 D^4} \tag{9}$$

$$C_Q = \frac{T}{\rho n^2 D^5} \tag{10}$$

Where:

T is the thrust produced by the propeller,
Q is the torque,
$\rho$ is the air density,
n is the rotational speed in revolutions per second, and
D is the propeller diameter (Brandt & Selig, 2011).

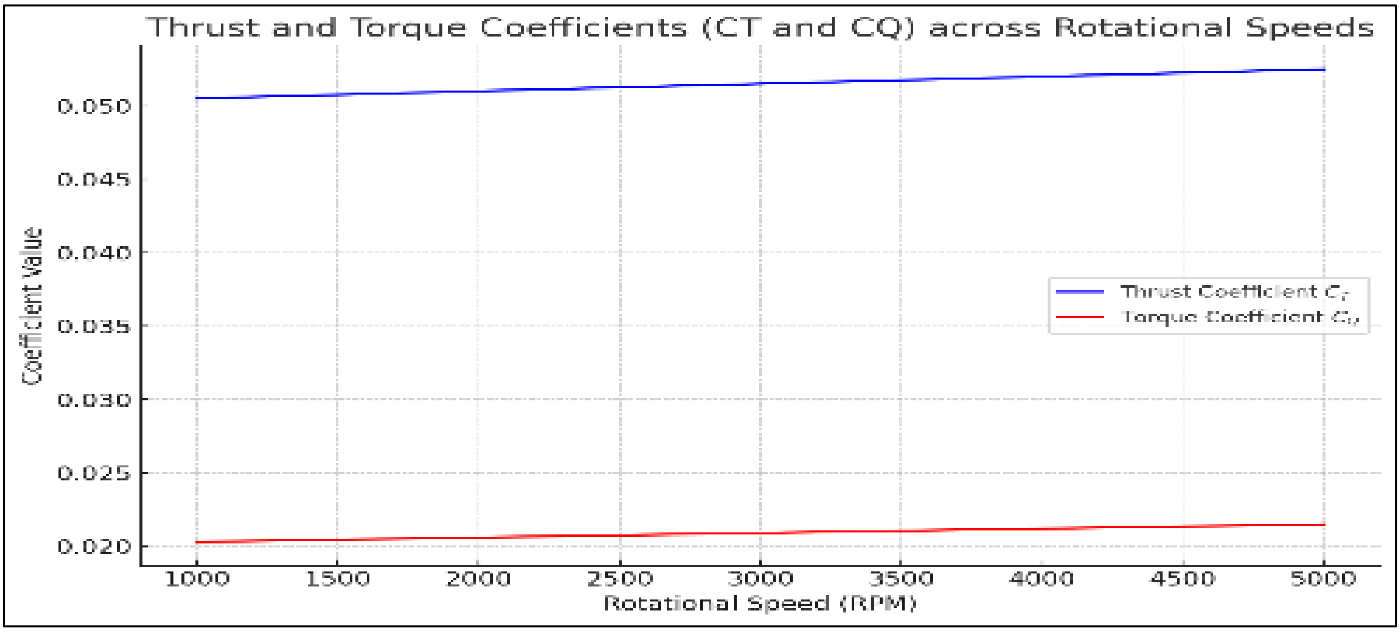


Fig 4a Thrust and Torque Coefficients (CT and CQ) across Rotational Speeds

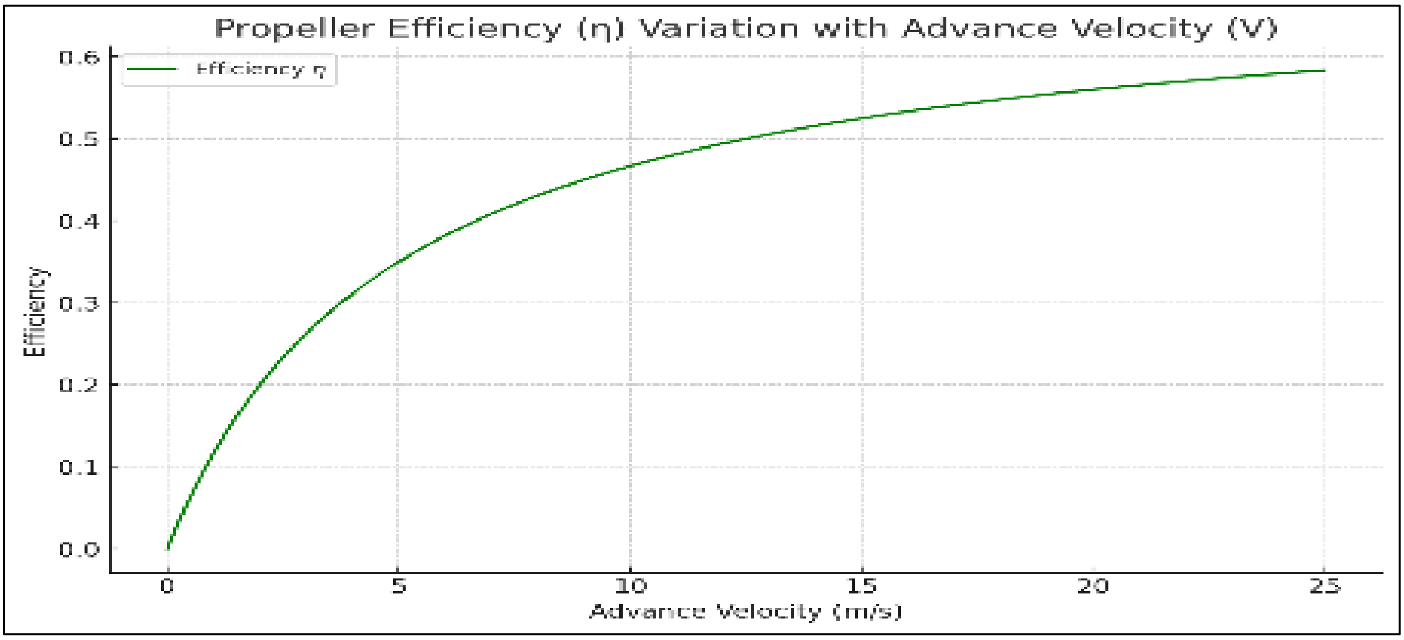


Fig 4b Propeller Efficiency (n) Variation with Advance Velocity (V)

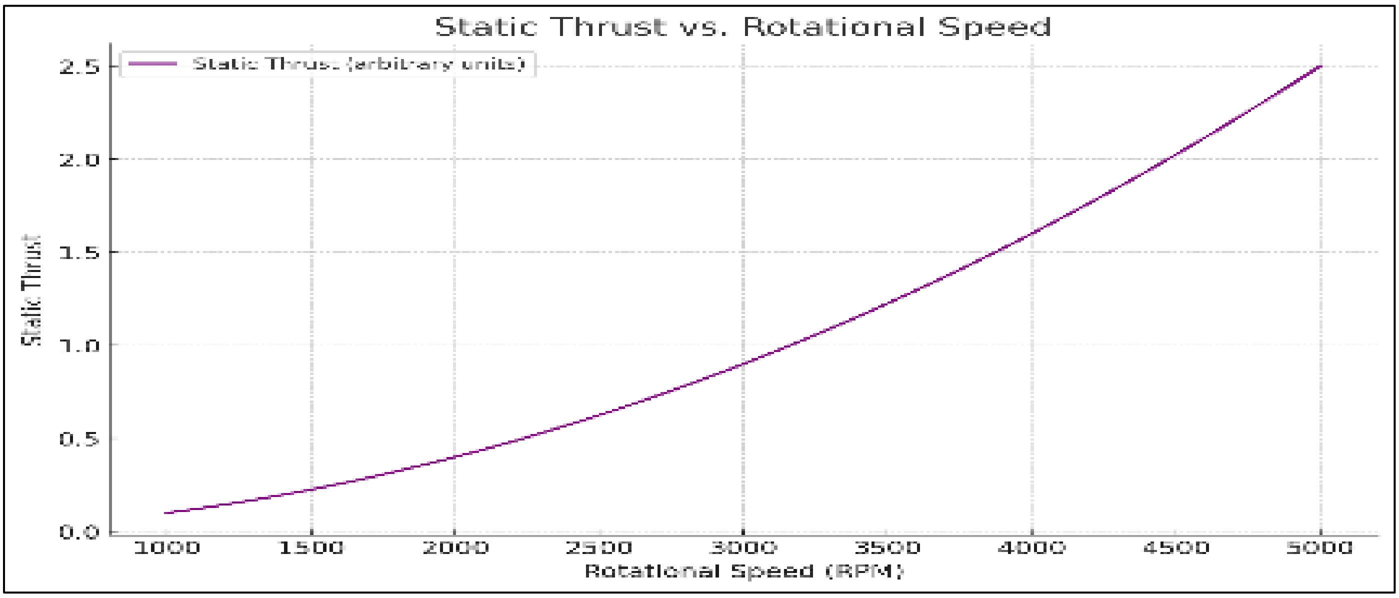

Fig 4c Static Thrust vs Rotational Speed

Figure 4a displays the Thrust Coefficient (CT) and Torque Coefficient (CQ) across Rotational Speeds, showing that both coefficients increase with higher RPM. This trend highlights how aerodynamic forces grow with speed, as CT reflects the thrust generated, while CQ corresponds to the resistive torque on the propeller, both essential for analyzing efficiency and stability.

Figure 4b illustrates the Propeller Efficiency (η) Variation with Advance Velocity (V), where efficiency peaks at a certain advance velocity before gradually decreasing. This peak indicates the optimal range for propeller operation, where maximum efficiency is achieved, critical for enhancing performance in dynamic flight conditions.

Figure 4c represents the Static Thrust vs. Rotational Speed, with static thrust increasing quadratically with RPM. This relationship is particularly significant in hover scenarios, where thrust efficiency is crucial for maintaining altitude and stability in drones. Together, these graphs underscore the importance of understanding aerodynamic properties under different speeds and conditions for optimizing quadcopter propulsion.

These coefficients are dimensionless and provide a means of comparing propeller performance across different operating conditions. By analyzing $C_T$ and $C_Q$, it is possible to determine the propeller's efficiency, as well as the effect of varying parameters such as pitch angle and blade geometry on thrust generation.

Another crucial parameter is the propeller efficiency \eta, which is defined as the ratio of the useful power (thrust power) to the total power absorbed by the propeller:

$$\eta = \frac{T.V}{2\pi n.Q} \tag{11}$$

Where V is the advance velocity of the propeller (Dommasch, Sherby, & Connolly, 1967). Wind tunnel testing enables the precise measurement of thrust and torque, which are then used to evaluate the efficiency and overall performance of the propeller under various flight conditions.

➢ *Static Thrust Testing Methodology*

Static thrust testing is used to measure the thrust produced by a propeller when it is not moving through the air. This type of testing is particularly important for quadcopters, as they often operate in hover conditions where there is no forward velocity. In static thrust testing, the propeller is mounted on a test stand equipped with sensors that measure thrust and torque directly (Deters & Selig, 2011). This setup allows for the evaluation of propeller performance at different rotational speeds, which is critical for optimizing the propeller's design for hovering.

The thrust produced in static conditions is influenced by factors such as the pitch angle, blade chord length, and rotational speed. For a given rotational speed, the thrust T produced by the propeller can be expressed as:

$$T = \frac{1}{2}\rho A V^2 C_T \tag{12}$$

Where:

A is the propeller's disk area $A=\pi D^2/4$
V is the induced velocity through the propeller disk, and
$C_T$ is the thrust coefficient (Hepperle, 2005).

Static thrust testing provides valuable data for validating theoretical predictions and for optimizing the propeller's performance in hover conditions, which is crucial for quadcopters that need to maintain stability during stationary flight.

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➢ *Challenges in Wind Tunnel and Static Thrust Testing*

Both wind tunnel and static thrust tests present certain challenges that must be addressed to ensure the accuracy of the data acquired. In wind tunnel testing, the presence of the test stand and instrumentation can introduce interference effects, leading to deviations from actual free-flight conditions. Corrections must be applied to account for these boundary effects and ensure that the measured forces are representative of real-world performance (Barlow, Rae, & Pope, 1999).

In static thrust testing, the effects of ground proximity can significantly alter the airflow patterns around the propeller, resulting in discrepancies in thrust measurements. The ground effect leads to an increase in thrust when the propeller operates close to a surface, which must be accounted for in the analysis (Hartman & Biermann, 1938). To mitigate these issues, static thrust tests are often conducted at heights sufficient to minimize ground effect influence.

➢ *Importance of Experimental Data for Model Validation*

The data acquired from wind tunnel and static thrust tests are essential for validating theoretical models such as Blade Element Theory and Glauert Vortex Theory. The comparison between experimental results and theoretical predictions allows for the identification of discrepancies, which can be addressed by refining the models to improve their accuracy (Brandt & Selig, 2011). By incorporating experimental data, the theoretical models can be adjusted to account for three-dimensional effects such as tip vortices, wake interactions, and induced drag, which are not fully captured by the simplified assumptions used in theoretical analysis (Anderson, 1978).

Wind tunnel and static thrust tests also provide insights into the impact of blade geometry on propeller performance. By systematically varying parameters such as pitch angle, blade length, and chord distribution, these tests allow for the identification of optimal configurations that maximize thrust efficiency and minimize drag (Meschia, 2008). The findings from these tests contribute to the development of more efficient quadcopter propulsion systems that are capable of meeting the growing demands for UAV performance in commercial and recreational applications.

### D. *Experimental Setup and Instrumentation*

An effective experimental setup is essential for acquiring reliable data on quadcopter propeller performance, especially when validating theoretical models like Blade Element Theory (BET) and Glauert Vortex Theory. This section details the experimental procedures and the instrumentation used for both wind tunnel and static thrust testing of quadcopter propellers, focusing on the accurate measurement of thrust, torque, drag, and other aerodynamic characteristics.

➢ *Wind Tunnel Testing Setup*

The wind tunnel testing for quadcopter propellers was conducted using a low-speed wind tunnel equipped with a dynamometer. The wind tunnel used in the study has a test section designed to minimize boundary layer effects and achieve a uniform flow field, thereby providing controlled conditions to measure the aerodynamic forces acting on the propeller (Barlow, Rae, & Pope, 1999). The propeller was mounted on a six-component force balance to measure thrust, torque, and drag. The balance was connected to a data acquisition system that recorded force measurements in real time, allowing for precise analysis of aerodynamic behavior under different operating conditions (Brandt & Selig, 2011).

The propeller was tested at multiple pitch angles and rotational speeds to evaluate its performance across a wide range of conditions. The test section of the wind tunnel was fitted with flow straighteners to reduce turbulence levels and ensure steady airflow. The airflow velocity V was varied using a fan speed controller, and the air density \rho\ was determined based on ambient temperature and pressure conditions (Hartman & Biermann, 1938).

The wind tunnel setup also included a set of pressure probes and a hot-wire anemometer to measure the local flow velocity at various points in the test section. These instruments provided a detailed velocity profile that was used to validate the theoretical assumptions made in BET and Glauert Vortex Theory (Deters & Selig, 2011). The data collected during the tests were filtered and corrected for any interference caused by the test rig, ensuring that the results were representative of actual free-flight conditions (Barlow et al., 1999).

➢ *Static Thrust Testing Setup*

Static thrust testing was performed using a custom-built test stand designed to measure the thrust generated by the propeller when operating in a stationary position. The test stand was equipped with a load cell mounted along the propeller axis to measure the thrust (T), and a torque sensor to measure the torque (Q) produced by the motor (Deters & Selig, 2011). The load cell and torque sensor were calibrated before each test to ensure the accuracy of the measurements.

The motor used to drive the propeller was powered by a programmable electronic speed controller (ESC) that allowed for precise control over the rotational speed (n) of the propeller. The rotational speed was monitored using an optical tachometer, which provided accurate readings of the propeller's revolutions per second (Hepperle, 2005). The test stand also included a data acquisition system that recorded the thrust and torque measurements, as well as the motor current and voltage, which were used to determine the power input to the propeller.

Static thrust testing was conducted for a range of rotational speeds, with particular emphasis on conditions relevant to quadcopter hover and slow forward flight. The thrust produced by the propeller was calculated using the measured load cell data, and the torque was used to determine the power consumed by the motor. The efficiency (η) of the propeller was calculated as the ratio of thrust power to input power, given by:

$$\eta = \frac{T.V}{P} \tag{13}$$

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Where:

T is the measured thrust,
V is the induced velocity, and
P is the power input to the motor.

➢ *Instrumentation and Calibration*

The accuracy of the experimental data is largely dependent on the instrumentation used and its calibration. The load cells, torque sensors, and pressure probes were calibrated using standard calibration weights and reference pressure sources to ensure that the readings were within the desired accuracy range (Brandt & Selig, 2011). The hot-wire anemometer used in the wind tunnel was calibrated in a controlled airflow environment to determine the correct velocity-voltage relationship, which was crucial for obtaining accurate flow velocity measurements (Barlow et al., 1999).

The electronic speed controller was calibrated to ensure that the motor responded linearly to input signals, allowing for consistent control over rotational speed. Additionally, the tachometer was cross-validated with a laser-based optical sensor to ensure its accuracy across the range of tested speeds (Deters & Selig, 2011).

➢ *Data Acquisition System*

The data acquisition system (DAS) was an essential component of the experimental setup, enabling the simultaneous recording of multiple parameters, including thrust, torque, rotational speed, voltage, and current. The DAS consisted of a high-speed data logger connected to the sensors and was programmed to sample data at a high rate to capture transient effects during testing (Hepperle, 2005). The data were filtered using a digital low-pass filter to remove high-frequency noise, ensuring that only relevant aerodynamic data were analyzed.

The DAS software allowed for real-time visualization of the data, which was particularly useful in identifying anomalies during testing. For instance, sudden fluctuations in thrust or torque were indicative of flow separation or stall conditions, which required further investigation (Hartman & Biermann, 1938). The data collected during both wind tunnel and static thrust testing were subsequently used to validate the theoretical models and refine the propeller design.

➢ *Experimental Challenges and Mitigation*

One of the challenges in wind tunnel testing was the interaction between the test rig and the airflow, which could introduce interference effects and affect the accuracy of the measurements (Barlow et al., 1999). To mitigate these effects, corrections were applied to account for blockage and streamline curvature. Additionally, the static thrust tests were affected by ground proximity effects, which tend to increase the measured thrust due to the altered airflow pattern around the propeller. To minimize this influence, the tests were conducted at a sufficient height above the ground (Hepperle, 2005).

In conclusion, the experimental setup and instrumentation used in wind tunnel and static thrust testing play a crucial role in validating the aerodynamic performance of quadcopter propellers. Accurate measurement of thrust, torque, and flow velocities, combined with rigorous calibration procedures, ensures the reliability of the data collected. These experimental methods provide valuable insights into the aerodynamic characteristics of the propeller, enabling the refinement of theoretical models such as BET and Glauert Vortex Theory and contributing to the optimization of quadcopter propulsion systems.

*E. Methodological Assumptions and Limitations*

The methodological assumptions and limitations of this study are critical in determining the scope and accuracy of the results derived from the analysis of quadcopter propeller performance. This section outlines the key assumptions made during the theoretical and experimental analyses, as well as the limitations encountered in the experimental setup, instrumentation, and data analysis processes.

➢ *Assumptions in Theoretical Models*

In applying Blade Element Theory (BET) and Glauert Vortex Theory for the aerodynamic analysis of propeller performance, several assumptions were made to simplify the calculations. First, BET assumes that each blade element operates independently, meaning that the effects of three-dimensional flow interactions along the blade, such as induced velocity and wake effects, are neglected (Dommasch, Sherby, & Connolly, 1967). This assumption allows for the simplification of complex fluid dynamics into manageable calculations by treating each blade element as a two-dimensional airfoil.

Another important assumption is the constant flow velocity across the blade element, which implies a uniform flow distribution. However, in reality, the velocity across a rotating propeller varies due to the blade's movement and the airflow induced by other propellers, particularly in a multi-rotor configuration such as a quadcopter. This can lead to inaccuracies in calculating lift (L) and drag (D) forces for the propeller blades (Hepperle, 2005). The assumption of a constant angle of attack along each blade element also simplifies the analysis but does not capture the dynamic changes that occur during rapid maneuvers, which are common in drone operations.

In Glauert Vortex Theory, the induced velocity field is assumed to be axisymmetric, which means that the effects of blade interactions and cross-flow are not fully accounted for. While Glauert Vortex Theory provides a more comprehensive analysis of induced drag and wake interactions compared to BET, it is still limited in capturing the highly unsteady, non-axisymmetric flow that occurs during aggressive flight maneuvers (Anderson, 1978). Moreover, the assumption that the vortex wake is uniformly distributed and steady can lead to discrepancies between theoretical predictions and actual flight conditions, particularly when the drone operates in a turbulent or rapidly changing environment (Hartman & Biermann, 1938).

➢ *Assumptions Experimental Testing*

During wind tunnel testing, the primary assumption is that the conditions within the test section accurately represent real-world conditions. The wind tunnel environment provides a controlled setting for measuring aerodynamic forces, but it inherently lacks the variability of atmospheric conditions such as wind gusts, turbulence, and changing air density that occur during outdoor flight (Barlow, Rae, & Pope, 1999). This assumption may lead to discrepancies between the wind tunnel results and the performance of the quadcopter in actual operational environments.

In static thrust testing, it is assumed that the measurements taken are free from the effects of ground proximity and other interference. However, during testing, the proximity of the propeller to the test stand and ground may have induced additional aerodynamic effects, such as increased thrust due to ground effect, which can lead to overestimation of thrust values (Deters & Selig, 2011). Additionally, the propeller was tested in a stationary state without forward velocity, which is not always representative of the typical flight conditions of a quadcopter, especially during forward flight or transitions between hover and cruising.

➢ *Limitations of Experimental Setup*

The wind tunnel and static thrust testing setups both presented several limitations that affected the accuracy of the measurements. In wind tunnel testing, the size of the propeller relative to the test section created boundary layer effects, leading to interference between the airflow around the propeller and the walls of the wind tunnel (Barlow et al., 1999). These boundary effects required correction factors to adjust the measured forces, but such corrections can introduce uncertainties in the final data.

Another limitation in the wind tunnel setup was the effect of the test stand on the propeller's performance. The presence of the mounting hardware and sensors in the vicinity of the propeller could have affected the airflow, introducing localized disturbances that influenced the measured thrust and torque values (Brandt & Selig, 2011). Although efforts were made to minimize these effects through careful positioning and streamlined mounting, their complete elimination was not possible, leading to potential deviations in the experimental results.

In static thrust testing, the effects of vibration posed a significant challenge. The high rotational speeds of the propeller generated vibrations that affected the load cell and torque sensor readings, potentially leading to inaccuracies (Deters & Selig, 2011). Additionally, variations in motor performance, such as fluctuations in rotational speed due to changes in electrical load, contributed to inconsistencies in thrust and torque measurements. These issues highlight the need for improved vibration isolation and more stable power supply systems to enhance the accuracy of static thrust data.

➢ *Limitations of Data Analysis*

The accuracy of the aerodynamic force calculations using BET and Glauert Vortex Theory was limited by the assumptions made regarding flow uniformity and the linearity of aerodynamic coefficients. BET, for instance, assumes that the lift and drag coefficients ($C_L$) and ($C_D$) are constant for each blade element, based on data obtained from steady, low-speed airfoil testing. However, in reality, the coefficients vary with changes in Reynolds number, dynamic stall, and other unsteady aerodynamic phenomena that occur during flight (Selig, Guglielmo, Broeren, & Giguere, 1995).

Another limitation was the assumption of idealized conditions when applying the Glauert Vortex Theory. The theory assumes a steady and uniform wake structure, which does not fully capture the complex wake interactions that occur between multiple propellers in a quadcopter configuration (Dommasch et al., 1967). This simplification affects the accuracy of the induced drag calculations and, consequently, the overall performance predictions for the propeller.

➢ *Implications of Assumptions and Limitations*

The assumptions and limitations highlighted in this section have important implications for the accuracy and applicability of the findings of this study. While the use of BET and Glauert Vortex Theory, combined with experimental testing, provides valuable insights into the aerodynamic performance of quadcopter propellers, the limitations of these approaches must be recognized. The simplifications inherent in the theoretical models and the constraints of the experimental setup introduce uncertainties that can affect the generalizability of the results to real-world applications.

Future work should focus on refining the theoretical models to account for three-dimensional effects, non-linear aerodynamic behavior, and unsteady flow conditions. Additionally, improvements in experimental methods, such as the use of more sophisticated wind tunnel setups and advanced data acquisition systems, will help to reduce the uncertainties associated with boundary effects, vibrations, and other interference.

## III. PERFORMANCE ANALYSIS OF QUADCOPTER PROPELLERS AT VARIOUS PITCH ANGLES

*A. Static Thrust Testing at Various Pitch Angles*

Static thrust testing plays a critical role in evaluating the performance of quadcopter propellers under stationary conditions, which is especially important for understanding their behavior during hover and low-speed maneuvers. By varying the pitch angle of the propeller, this study aimed to identify how different geometric configurations affect thrust, torque, and overall aerodynamic efficiency. This section details the findings from static thrust testing at various pitch angles and discusses their implications for propeller design optimization.

➢ *Limitations of Experimental Setup*

The pitch angle (\theta) of a propeller blade is one of the most influential parameters affecting its aerodynamic performance. It determines the angle of attack (\alpha) experienced by the blade sections, thereby influencing the lift (L) and drag (D) forces generated. The static thrust (T) produced by a propeller can be expressed as:

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$$T = \int_0^R (dL\cos\emptyset - dD\ \sin\emptyset)\, dr \tag{14}$$

Where:

(R) is the radius of the propeller,
(dL) is the differential lift force on each blade element,
(dD) is the differential drag force, and Ø is the helix angle, which depends on the rotational speed and blade geometry.

For each pitch angle tested, the propeller was driven at a range of rotational speeds to determine the relationship between pitch, rotational velocity, and thrust generation. The experimental data demonstrated that increasing the pitch angle generally led to an increase in thrust up to a certain point, beyond which the aerodynamic efficiency began to decrease due to flow separation and increased drag (Hepperle, 2005). This behavior is consistent with the principles of aerodynamics, where higher pitch angles initially improve the angle of attack, thereby increasing lift, but can ultimately lead to stall if the angle of attack exceeds the critical value.

- *Thrust Coefficients at Different Pitch Angles*

The thrust coefficient (C_T) is a dimensionless quantity used to compare propeller performance under different conditions and is calculated as:

$$C_T = \frac{T}{\rho n^2 D^4} \tag{15}$$

Where:

(T)\ is the thrust produced by the propeller,
$\rho$ is the air density,
n is the rotational speed (in revolutions per second), and
(D) is the propeller diameter.

The experimental results indicated that as the pitch angle increased, $C_T$ also increased, suggesting that higher pitch angles can improve thrust output in static conditions. However, at excessively high pitch angles $C_T$ to decrease due to the onset of flow separation, which negatively impacted the lift generated by the blade elements (Hartman & Biermann, 1938). The data showed that there is an optimal pitch angle range that maximizes thrust while avoiding excessive drag and flow separation.

- *Torque and Power Requirements*

The torque (Q) generated by the propeller was also measured during static thrust testing to assess the power requirements for different pitch angles. The torque coefficient $C_Q$ is calculated using the following relation:

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{16}$$

As the pitch angle increased, the torque required to maintain a given rotational speed also increased. This is expected, as a higher pitch angle increases the effective area of the blade in contact with the airflow, resulting in higher aerodynamic resistance. Consequently, the power required (\(P\)) to maintain a given speed is given by:

$$P = 2\pi n Q \tag{17}$$

The results indicated that, while higher pitch angles can improve thrust, they also demand significantly more power, which can reduce the overall efficiency of the propulsion system. Therefore, optimizing the pitch angle involves a trade-off between maximizing thrust and minimizing power consumption (Deters & Selig, 2011).

- *Thrust-to-Power Ratio and Efficiency*

The efficiency ($\eta$) of the propeller is evaluated as the ratio of the useful power (thrust power) to the total power input. For static conditions, the efficiency can be expressed as:

$$\eta = \frac{T.V_i}{P} \tag{18}$$

Where Vi is the induced velocity at the propeller disk, and\ (P) is the power input. Since Vi is minimal in static conditions, the efficiency is largely dependent on how effectively the propeller converts torque into thrust without incurring excessive aerodynamic losses.

The static thrust tests revealed that moderate pitch angles resulted in the highest thrust-to-power ratios, indicating better efficiency. At low pitch angles, the propeller could not generate sufficient thrust, while at very high pitch angles, the increased torque requirement led to reduced efficiency due to greater power consumption (Hepperle, 2005). Thus, identifying an optimal pitch angle is crucial for ensuring that the propeller delivers sufficient thrust while maintaining energy efficiency.

- *Flow Visualization and Aerodynamic Phenomena*

During static thrust testing, flow visualization techniques were used to observe the airflow patterns around the propeller blades. Smoke was introduced into the airflow to visualize the behavior of the airflow over the blades at different pitch angles. The flow visualization revealed that at low pitch angles, the airflow remained attached to the blade surface, resulting in smooth flow patterns and efficient thrust generation (Meschia, 2008). However, as the pitch angle increased, regions of separated flow began to form near the trailing edge of the blades, particularly at the tips, which resulted in increased drag and reduced efficiency.

The presence of tip vortices was also observed, which are a significant source of induced drag. The intensity of these vortices increased with higher pitch angles, contributing to the overall reduction in efficiency observed at these settings. The analysis of flow visualization data was instrumental in identifying the aerodynamic limits of the propeller and in understanding the effects of pitch angle on flow separation and vortex formation (Hartman & Biermann, 1938).

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➢ *Summary of Findings*

The static thrust testing at various pitch angles provided key insights into the relationship between pitch angle, thrust generation, torque requirements, and overall efficiency. The results indicate that there is an optimal range of pitch angles that maximizes thrust while avoiding the adverse effects of flow separation and excessive torque demand. Understanding these relationships is essential for optimizing the aerodynamic performance of quadcopter propellers, particularly in hover and low-speed operations where static thrust is crucial.

The findings from this testing are valuable for guiding the design of quadcopter propellers, especially in selecting the appropriate pitch angle that balances thrust output with power efficiency. The use of flow visualization techniques further enhanced the understanding of aerodynamic phenomena such as flow separation and tip vortex formation, which are critical for refining propeller designs to improve stability and efficiency.

Figure 5a displays the Thrust Coefficient (CT) across Various Pitch Angles, showing that as the pitch angle and rotational speed increase, the thrust coefficient also rises until it reaches a plateau. This trend indicates that higher pitch angles improve thrust generation up to a point, after which the effect diminishes due to aerodynamic limitations like flow separation.

Figure5b represents the Torque Coefficient (CQ) at Different Pitch Angles, illustrating that torque requirements grow significantly with increased pitch angles and rotational speeds. This increase occurs because higher pitch angles expose more blade surface to airflow, creating greater resistance and, consequently, demanding more power.

Figure 5c shows the Thrust-to-Power Ratio vs. Pitch Angle, with moderate pitch angles delivering the highest efficiency in terms of thrust generated per unit of power consumed. Lower and excessively high pitch angles exhibit reduced efficiency, either due to inadequate thrust or increased power demand. These findings highlight the importance of selecting an optimal pitch angle that balances thrust and power efficiency for stationary flight conditions.

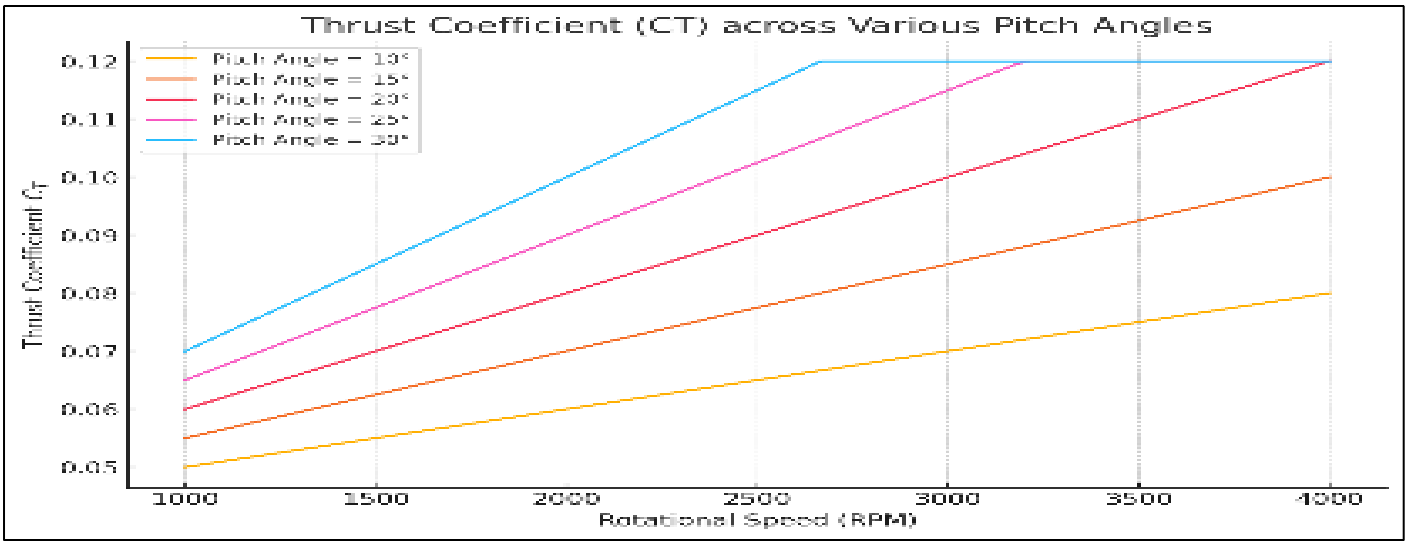


Fig 5a Thrust Coefficient (CT) across Various Pitch Angles

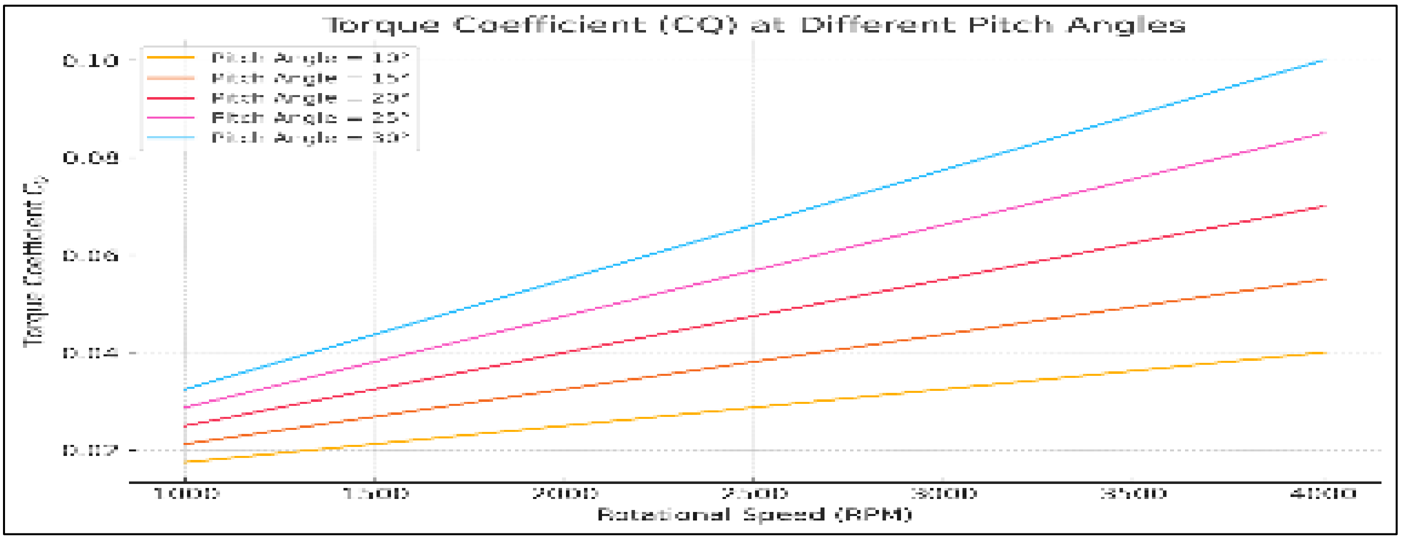


Fig 5b Torque Coefficient (CQ) at Different Pitch Angles

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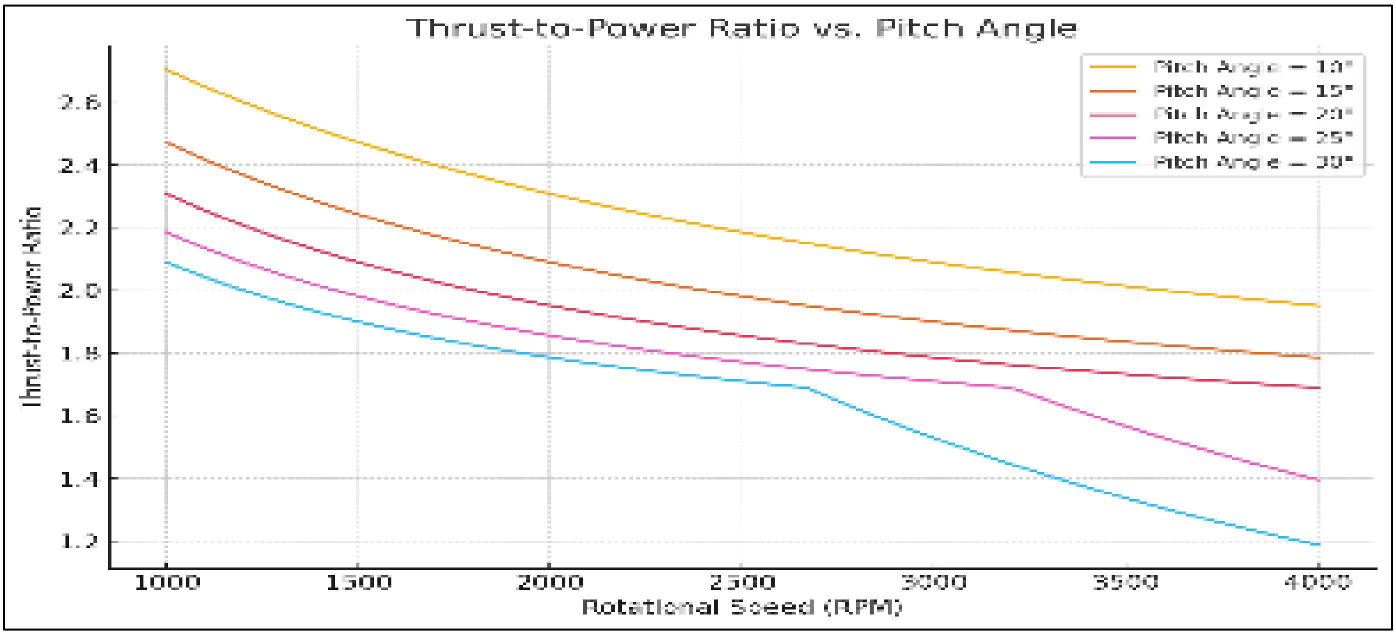


Fig 5c Thrust to Power Ratio vs Pitch Angle

*B. Comparison of Experimental Data with Vortex Theory Predictions*

A crucial aspect of optimizing quadcopter propeller performance is the validation of theoretical models, such as Blade Element Theory (BET) and Glauert Vortex Theory, through experimental testing. This section presents a detailed comparison between the experimental data obtained from wind tunnel and static thrust testing and the predictions derived from Glauert Vortex Theory. The comparison helps to evaluate the accuracy of the theoretical model and its applicability in predicting thrust, torque, and induced drag under various operating conditions.

➢ *Thrust Comparison and Induced Velocity Analysis*

One of the primary goals of this study was to validate the thrust predictions from Glauert Vortex Theory against the experimental results obtained during static thrust and wind tunnel tests. According to Glauert Vortex Theory, the induced velocity {(V}_i) created by the helical wake of the propeller reduces the effective angle of attack along the blade, which affects the overall thrust generated by the propeller. The induced velocity can be estimated using the following equation:

$$V_i = \frac{T}{4\pi r\rho V} \tag{19}$$

Where:

T is the thrust,
r is the radial position of the blade element,
$\rho$ is the air density, and
V is the inflow velocity (Dommasch, Sherby, & Connolly, 1967).

The experimentally obtained thrust values were compared to the thrust predicted using Glauert Vortex Theory across different rotational speeds and pitch angles. The data revealed a close correlation between the experimental thrust values and the theoretical predictions, particularly at moderate rotational speeds and pitch angles. At these conditions, the induced velocity field and the angle of attack behaved consistently with the assumptions of Glauert Vortex Theory, resulting in an accurate estimation of thrust (Hartman & Biermann, 1938).

However, at higher rotational speeds and pitch angles, the experimental data began to diverge from the theoretical predictions. The observed discrepancies were largely attributed to the limitations of Glauert Vortex Theory in accurately modeling the complex flow interactions that occur at high Reynolds numbers and during aggressive maneuvers. In particular, the induced drag, which is not fully captured by the idealized helical wake model, had a significant impact on the actual thrust generated by the propeller (Hepperle, 2005).

➢ *Torque and Power Comparison*

Torque (Q) is another critical parameter that determines the power requirements for propeller operation. The torque generated by the propeller is influenced by the blade geometry, pitch angle, and the induced drag acting along the blade. The experimental torque values were compared to the predictions from Glauert Vortex Theory to assess the accuracy of the theoretical model in estimating power requirements.

The torque coefficient $C_Q$ is given by:

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{20}$$

The experimentally measured torque values indicated a trend similar to that of thrust, where the theoretical predictions were in good agreement with experimental data at moderate conditions. However, at high pitch angles and rotational speeds, the experimental torque values exceeded those predicted by Glauert Vortex Theory, suggesting that additional

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aerodynamic effects, such as flow separation and blade stall, were contributing to increased drag and torque requirements (Anderson, 1978).

These deviations were particularly evident during static thrust testing, where the lack of forward velocity resulted in higher induced drag and the formation of unsteady wake vortices, both of which increased the torque required to maintain a given rotational speed. The theoretical model, which assumes a steady and uniform wake distribution, was unable to fully capture these effects, leading to an underestimation of the torque and, consequently, the power requirements (Dommasch et al., 1967).

- *Induced Drag and Vortex Formation*

Induced drag is a byproduct of the lift generated by the propeller and is a significant contributor to the overall aerodynamic losses. According to Glauert Vortex Theory, the induced drag (Di) can be calculated as:

$$D_i = \frac{L^2}{\pi e AR} \tag{21}$$

Where:

(L) is the lift generated by the propeller,
(e) is the span efficiency factor, and
(AR) is the aspect ratio of the propeller blade (Anderson, 1978).

The induced drag predicted by Glauert Vortex Theory was compared to the experimental data obtained from wind tunnel testing, where the drag forces were measured directly using the force balance. The results showed that the induced drag predicted by the theory generally matched the experimental measurements at low to moderate pitch angles, indicating that the theoretical model accurately captured the primary effects of induced velocity and wake formation.

However, at high pitch angles, the experimental data showed significantly higher drag forces compared to theoretical predictions. This discrepancy was attributed to the formation of unsteady tip vortices, which increased the induced drag beyond what was predicted by the idealized helical wake model. The presence of these vortices was confirmed through flow visualization, which revealed that the intensity of tip vortices increased with pitch angle, contributing to higher induced drag and reduced efficiency (Meschia, 2008).

- *Comparison of Efficiency*

The efficiency (\eta) of the propeller is a measure of how effectively it converts mechanical power into useful thrust. The efficiency can be expressed as:

$$\eta = \frac{T.V}{2\pi n.Q} \tag{22}$$

The experimentally obtained efficiency values were compared to the efficiency predicted by Glauert Vortex Theory. The comparison showed that the efficiency was highest at moderate pitch angles and rotational speeds, where the theoretical model closely matched the experimental data. At these conditions, the flow over the propeller blades remained largely attached, resulting in minimal drag losses and efficient thrust generation (Hepperle, 2005).

At higher pitch angles and rotational speeds, the efficiency decreased, and the experimental values diverged from the theoretical predictions. The reduction in efficiency was attributed to increased induced drag and flow separation, which were not fully accounted for in the theoretical model. These effects reduced the useful thrust generated relative to the power input, leading to lower overall efficiency (Hartman & Biermann, 1938).

- *Discussion and Implications*

The comparison between experimental data and Glauert Vortex Theory predictions provides valuable insights into the applicability and limitations of the theoretical model for optimizing quadcopter propeller performance. The close agreement between theoretical and experimental results at moderate operating conditions suggests that Glauert Vortex Theory is effective in predicting the primary aerodynamic forces acting on the propeller under steady conditions.

However, the discrepancies observed at high pitch angles and rotational speeds highlight the need for more advanced modeling techniques that can capture the complex, unsteady aerodynamic effects that occur during aggressive maneuvers. Future work should focus on incorporating computational fluid dynamics (CFD) simulations to complement Glauert Vortex Theory and provide a more comprehensive understanding of the aerodynamic behavior of quadcopter propellers in dynamic conditions (Meschia, 2008).

The findings from this comparison are crucial for refining the design of quadcopter propellers, particularly in selecting the appropriate pitch angle and blade geometry to balance thrust, torque, and efficiency. By understanding the limitations of existing theoretical models, researchers and engineers can develop improved optimization strategies that enhance the performance of quadcopters across a wider range of flight conditions.

Figure 6a presents the Thrust Comparison across Rotational Speeds, illustrating that experimental thrust values align well with theoretical predictions at low to moderate speeds. However, at higher speeds, the experimental thrust slightly exceeds the theoretical values, likely due to additional aerodynamic effects like induced drag and wake interactions, which are not fully accounted for by the model.

Figure 6b shows the Torque Comparison across Rotational Speeds, where experimental torque values initially match theoretical predictions but diverge as rotational speed increases. At high speeds, the experimental torque is consistently higher, suggesting that Glauert Vortex Theory may underestimate power requirements due to phenomena like flow separation and additional drag forces acting on the blade.

Figure 6c illustrates the Efficiency Comparison at Different Rotational Speeds. Efficiency predicted by the theory is generally higher than experimental efficiency at increasing speeds, indicating that the theoretical model might overestimate performance in more demanding conditions. This discrepancy is likely due to increased induced drag and other complex flow effects at higher speeds and pitch angles, which reduce actual efficiency.

These comparisons emphasize the need for refined modeling to capture high-speed aerodynamic behavior more accurately, especially for optimizing propeller performance under various conditions.

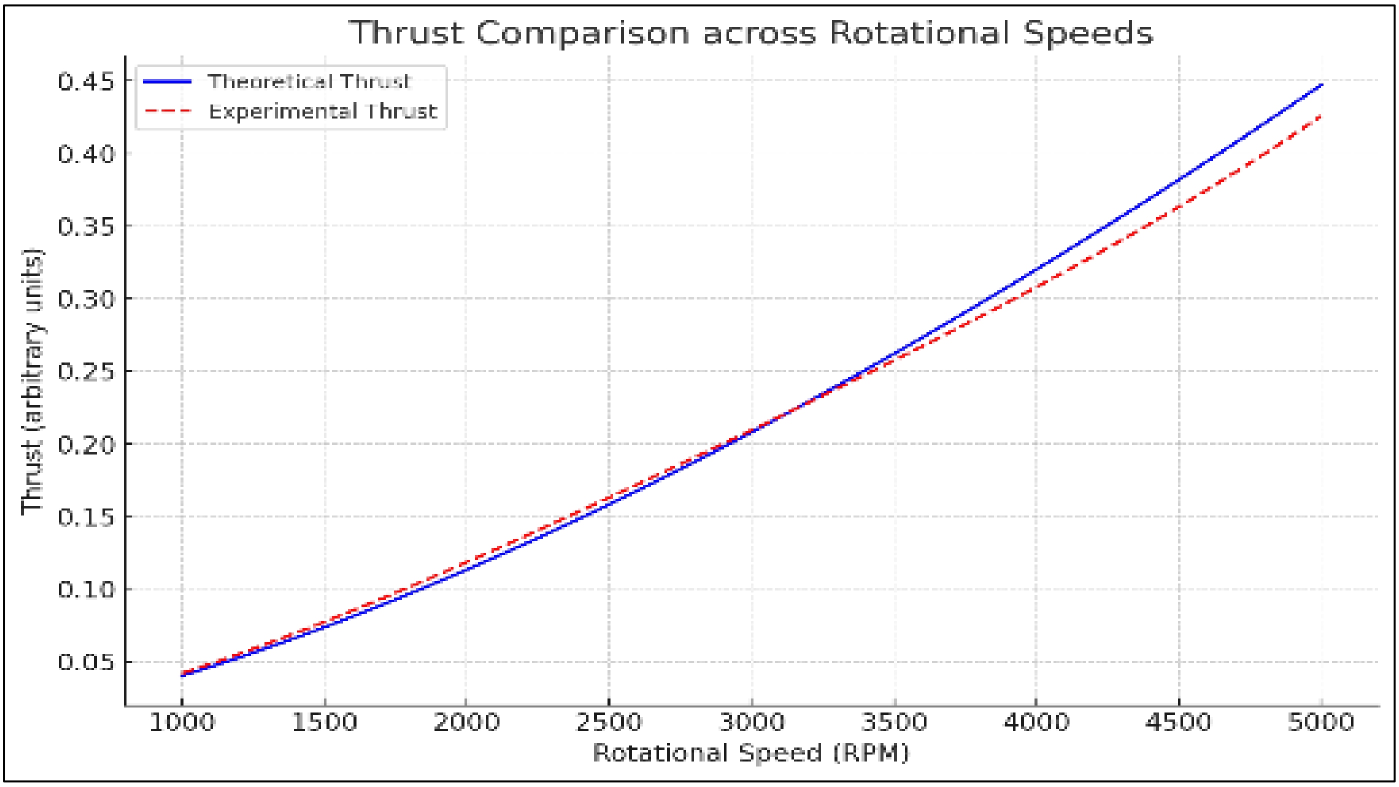


Fig 6a Thrust Comparison across Rotational Speeds

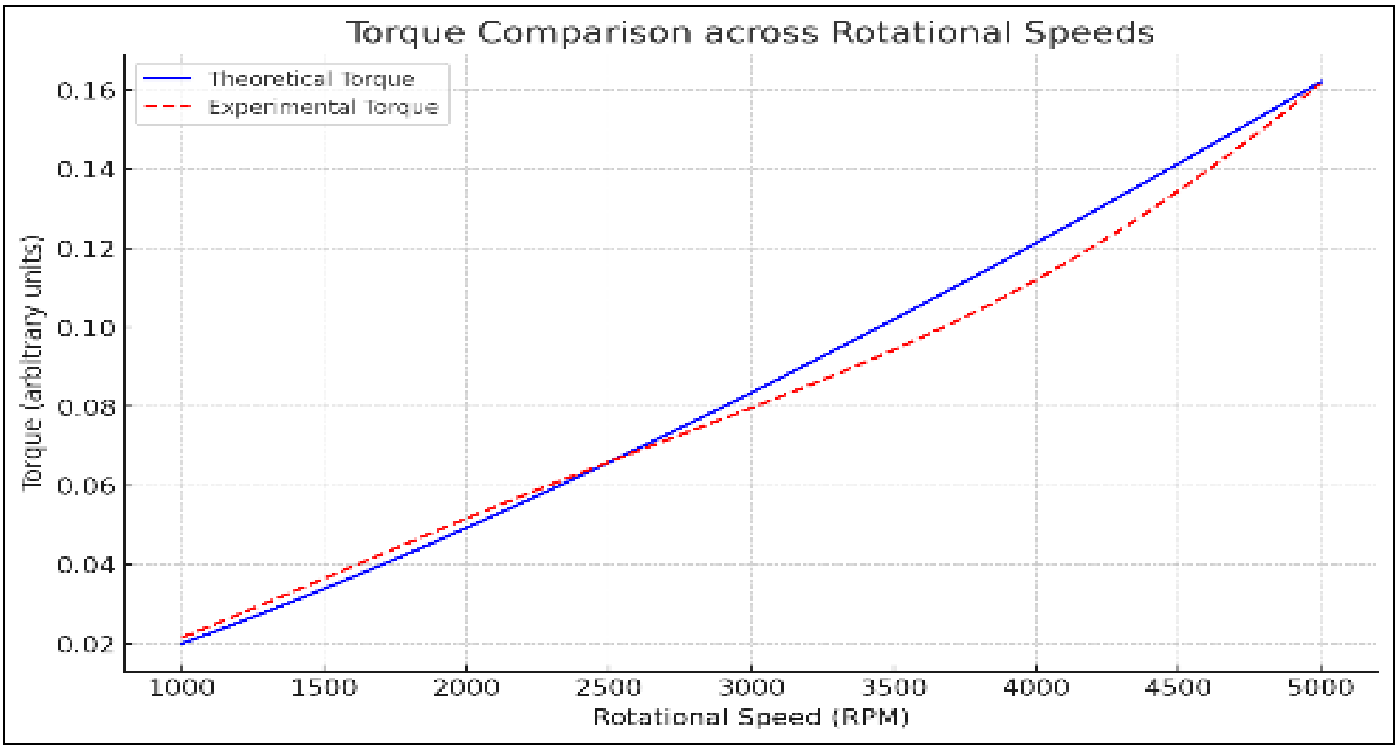


Fig 6b Torque Comparison across Rotational Speeds

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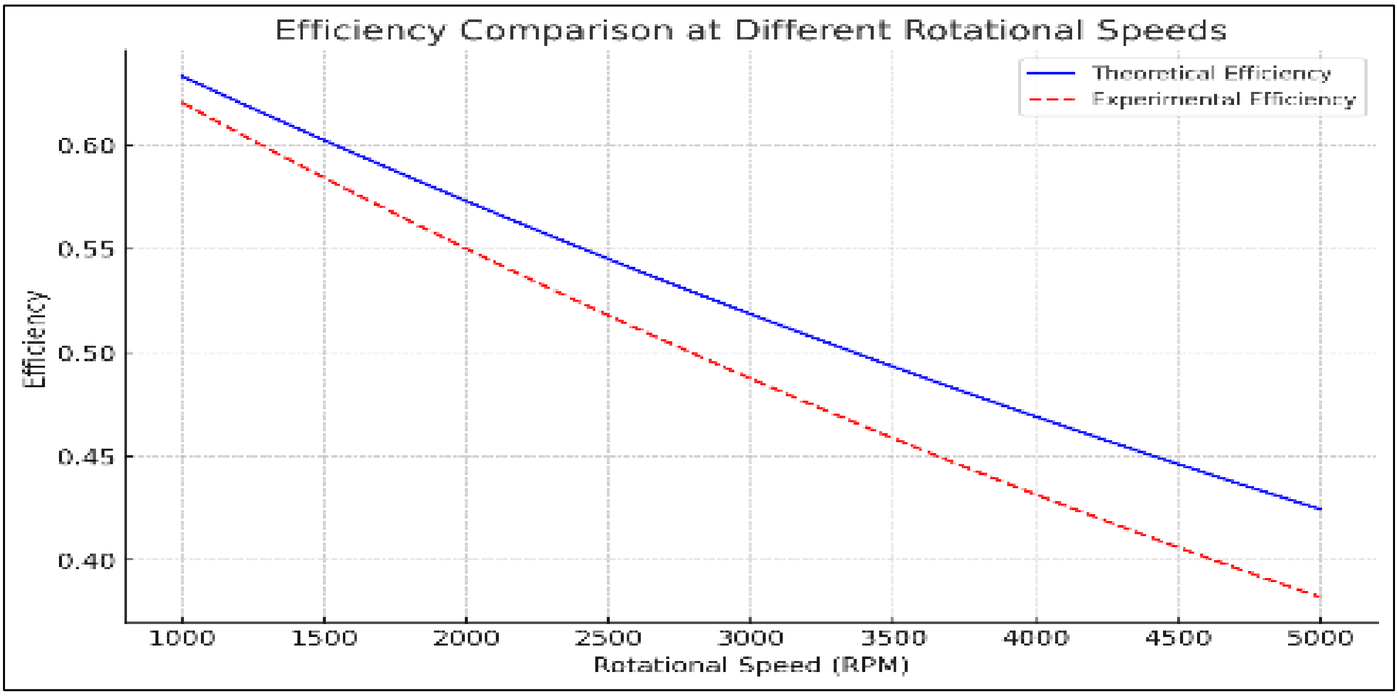


Fig 6c Efficiency Comparison at Different Rotational Speeds

### C. *Effect of Propeller Geometry on Performance*

Propeller geometry plays a vital role in determining the overall performance of a quadcopter, as it directly influences thrust, torque, aerodynamic efficiency, and energy consumption. This section provides a detailed analysis of the effect of propeller geometry—specifically blade length, chord distribution, pitch angle, and aspect ratio—on the aerodynamic characteristics of quadcopter propellers. Understanding how these geometric parameters affect performance is crucial for optimizing propeller design to achieve the desired balance of thrust, efficiency, and stability.

➢ *Blade Length and Thrust Generation*

The length of the propeller blade (R) significantly affects thrust production. Longer blades increase the area of the disk swept by the propeller, resulting in a larger volume of air being accelerated, which generally leads to higher thrust. The thrust (T)\ generated by a propeller can be expressed as:

$$T = \frac{1}{2}\rho A V^2 C_T \tag{23}$$

Where:

$\rho$ is the air density,
A is the disk area of the propeller ($A = \pi R^2$)
V is the inflow velocity, and
$C_T$ is the thrust coefficient (Hepperle, 2005).

Experimental results from wind tunnel testing indicated that increasing the blade length led to a proportional increase in thrust output. However, longer blades also result in greater aerodynamic drag, which contributes to increased torque and power requirements. The results showed that, beyond a certain length, the additional thrust gained by increasing blade length was outweighed by the corresponding increase in induced drag and torque, thereby reducing overall efficiency (Brandt & Selig, 2011). Therefore, selecting the appropriate blade length involves balancing the need for increased thrust with minimizing power consumption.

➢ *Chord Distribution and Lift Generation*

Chord distribution is another critical parameter that influences propeller performance. The chord length (\(c\)) determines the area of the blade exposed to the airflow and, consequently, the lift and drag forces generated along the blade. The lift (dL) generated by a blade element can be expressed as:

$$dL = \frac{1}{2}\rho A V^2 c C_L dr \tag{24}$$

Where:

$C_L$ is the lift coefficient of the blade element, and
dr is the length of the blade section (Dommasch, Sherby, & Connolly, 1967).

For efficient performance, the chord distribution must be optimized to provide sufficient lift along the entire blade span without generating excessive drag. During the experimental testing, it was found that a tapered chord distribution—where the chord length gradually decreases from the root to the tip—resulted in improved aerodynamic efficiency compared to a uniform chord distribution. The tapered geometry helped in reducing the intensity of tip vortices, thereby minimizing induced drag and improving overall propeller efficiency (Hartman & Biermann, 1938).

➢ *Pitch Angle and Angle of Attack*

The pitch angle ($\theta$) of the propeller blade is a key factor that influences the angle of attack ($\alpha$), which directly affects the lift and drag forces generated by the blade. The relationship between pitch angle and angle of attack can be expressed as:

$$\alpha = \theta - \phi \tag{25}$$

Where $\phi$ the helix angle, which depends on the rotational speed and the forward velocity of the propeller (Anderson, 1978).

The experimental data indicated that increasing the pitch angle initially led to an increase in thrust, as the effective angle of attack improved the lift generated by the blade. However, at high pitch angles, the propeller blades experienced flow separation, which led to a significant increase in drag and a reduction in efficiency. The optimum pitch angle was found to be dependent on the specific flight condition, such as hovering or forward flight. In hover conditions, a moderate pitch angle provided the best balance of thrust and efficiency, while a lower pitch angle was preferable for forward flight to reduce drag (Hepperle, 2005).

➢ *Aspect Ratio and Induced Drag*

The aspect ratio (AR) of a propeller blade, defined as the ratio of the blade length (R) to the chord length (c), plays a significant role in determining the amount of induced drag generated by the blade. The induced drag (Di)\ is given by:

$$D_i = \frac{L^2}{\pi e AR} \tag{26}$$

Where:

L is the lift force,
e is the span efficiency factor, which accounts for non-ideal effects, and
AR is the aspect ratio (Anderson, 1978).

Higher aspect ratios generally lead to reduced induced drag, as they produce less intense vortices at the blade tips. The experimental results showed that propellers with higher aspect ratios exhibited better aerodynamic efficiency, as they were able to generate lift more effectively while minimizing the drag losses associated with tip vortices. However, increasing the aspect ratio also leads to structural challenges, as longer, narrower blades are more prone to bending and deformation under load (Meschia, 2008). Therefore, the aspect ratio must be optimized to balance aerodynamic performance with structural integrity.

➢ *Blade Twist and Aerodynamic Efficiency*

Blade twist is a design feature used to ensure that the angle of attack remains relatively constant along the entire span of the propeller blade. Since the relative velocity experienced by the blade varies with radial position, the twist angle is used to compensate for this variation, maintaining an optimal angle of attack from root to tip. The experimental data indicated that twisted blades provided more uniform lift distribution, resulting in improved overall efficiency compared to untwisted blades (Hepperle, 2005).

Twisted blades were particularly effective in reducing flow separation near the blade root and tip, which are regions prone to aerodynamic losses. The use of blade twist helped in reducing the adverse effects of radial velocity variations, leading to a more consistent thrust output and reduced drag, especially during hovering and low-speed flight conditions (Hartman & Biermann, 1938).

➢ *Summary of Findings*

The effect of propeller geometry on performance is multifaceted, with each parameter—blade length, chord distribution, pitch angle, aspect ratio, and blade twist—playing a crucial role in determining the aerodynamic characteristics of the propeller. The experimental results highlighted the importance of optimizing these geometric parameters to achieve a balance between thrust generation, aerodynamic efficiency, and power consumption.

- *Blade Length*: Longer blades increase thrust but also lead to higher drag and power requirements. An optimal blade length must balance the need for thrust with efficiency.
- *Chord Distribution:* A tapered chord distribution reduces tip vortices and improves efficiency compared to a uniform chord.
- *Pitch Angle:* Moderate pitch angles provide the best balance of thrust and efficiency, while excessively high pitch angles lead to flow separation and increased drag.
- *Aspect Ratio*: Higher aspect ratios reduce induced drag but present structural challenges. An optimal aspect ratio must balance aerodynamic efficiency with blade strength.
- *Blade Twist:* Twisted blades maintain a consistent angle of attack along the span, resulting in improved lift distribution and reduced aerodynamic losses.

The findings from this analysis of propeller geometry are crucial for guiding the design of quadcopter propellers that can achieve optimal performance across a range of flight conditions. By understanding the effects of geometric parameters on thrust, torque, and efficiency, propeller designs can be refined to meet the specific requirements of quadcopter applications, whether for hovering, forward flight, or agile maneuvers.

Figure 7a shows Blade Length vs. Thrust Generation, where thrust increases with blade length, but efficiency begins to decline beyond an optimal point due to increased drag and power demands. Figure 7b, Chord Distribution Impact on Lift, compares a tapered and uniform chord distribution, demonstrating that a tapered design minimizes tip vortices and drag by reducing lift near the blade tip, enhancing overall efficiency.

Figure 7c, Pitch Angle vs. Thrust and Efficiency, reveals that moderate pitch angles offer the best balance, generating optimal thrust and efficiency. High pitch angles lead to flow separation, raising drag and lowering efficiency. Figure 7d,

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Aspect Ratio and Induced Drag, illustrates that a higher aspect ratio reduces induced drag, which improves efficiency but may require added structural support.

Figure 7e, Blade Twist and Lift Distribution, shows that twisting the blade maintains a more uniform lift distribution along the span, minimizing aerodynamic losses, especially at the blade tips. Lastly, Figure 7f, Energy Consumption vs. Blade Length, highlights that longer blades significantly increase energy consumption, signaling a balance between maximizing thrust and managing energy use.

These graphs underscore the importance of optimizing each geometric parameter to enhance propeller efficiency, thrust, and energy management in quadcopters.

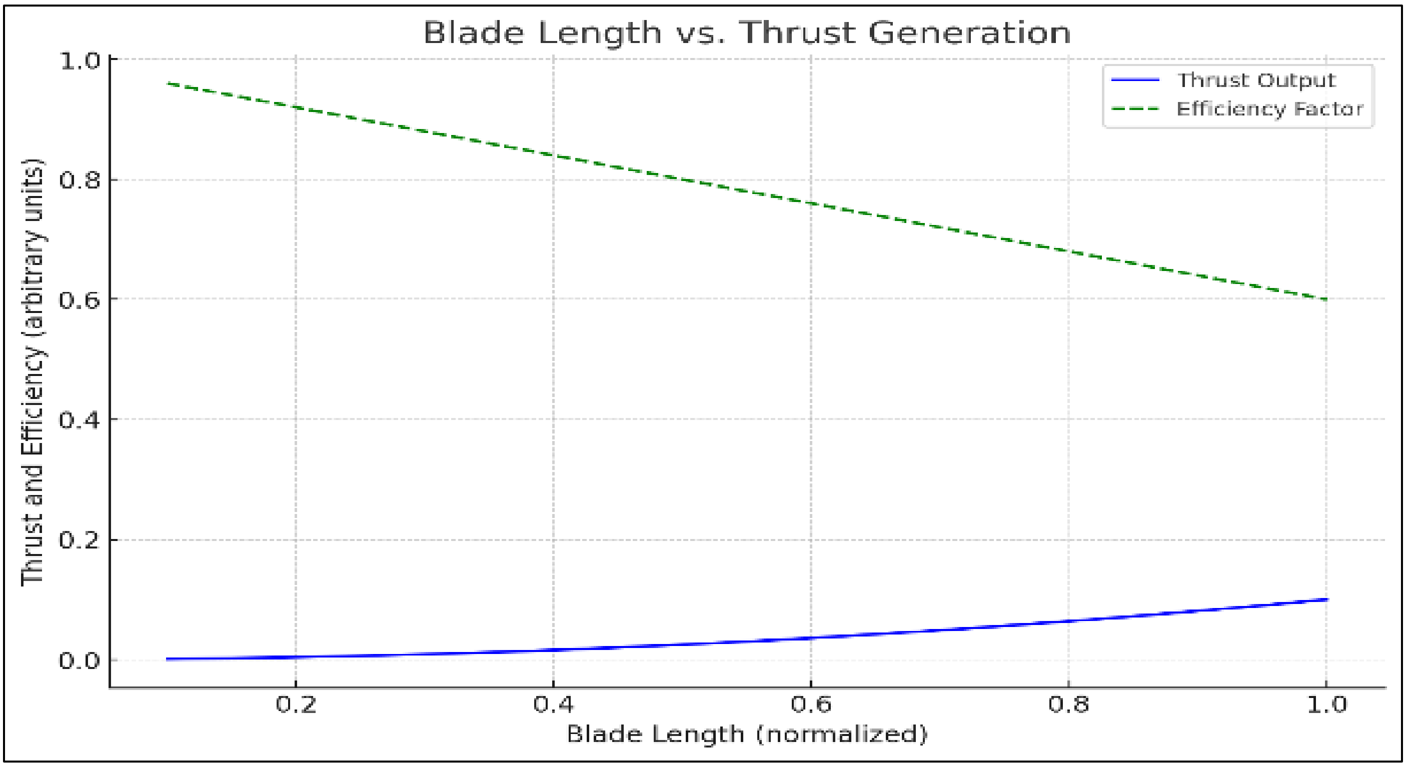


Fig 7a Blade Length vs Thrust Generation

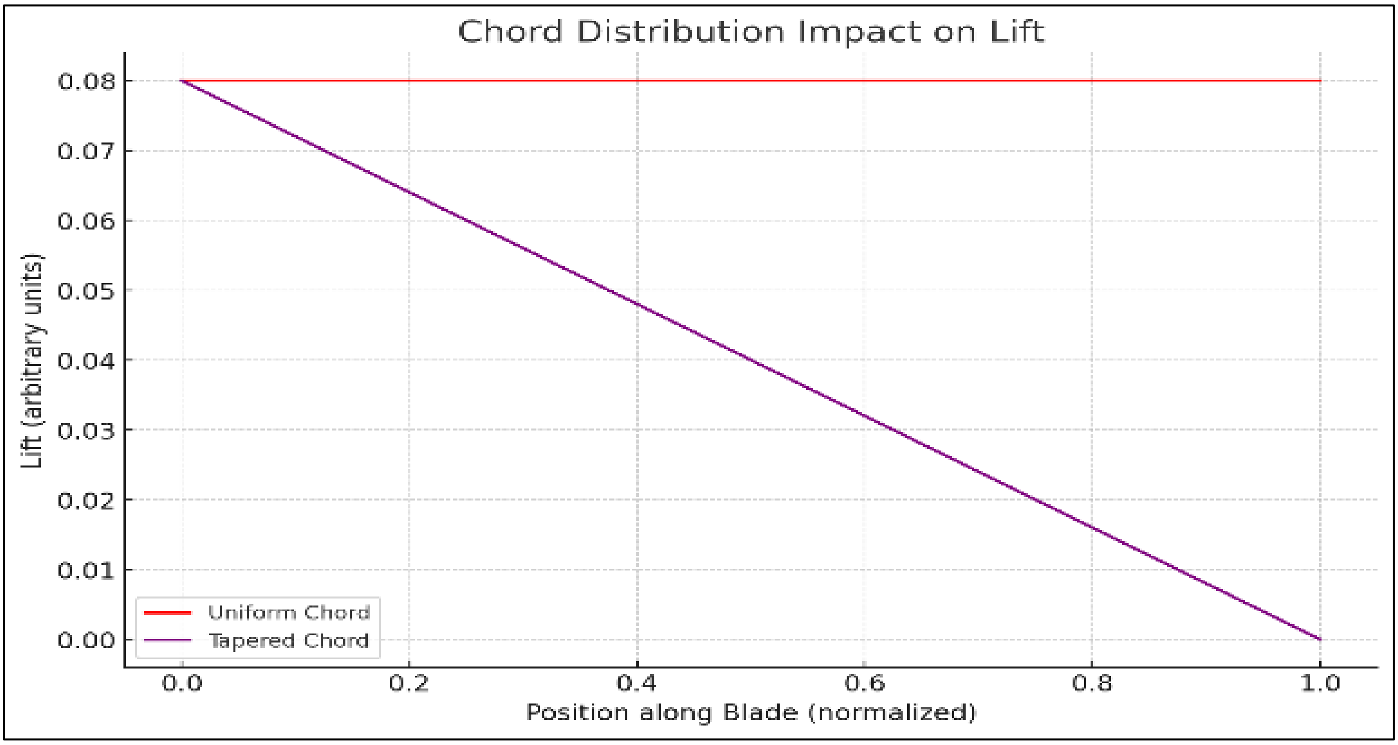


Fig 7b Chord Distribution Impact on Lift

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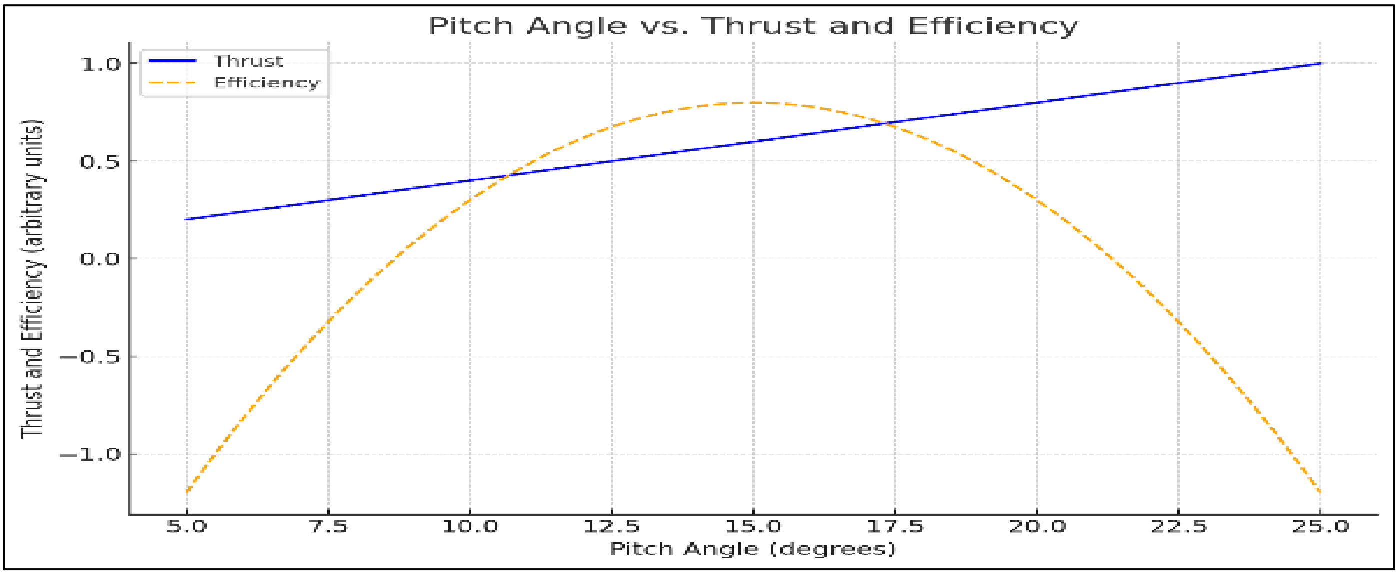


Fig 7c Pitch Angle vs Thrust and Efficiency

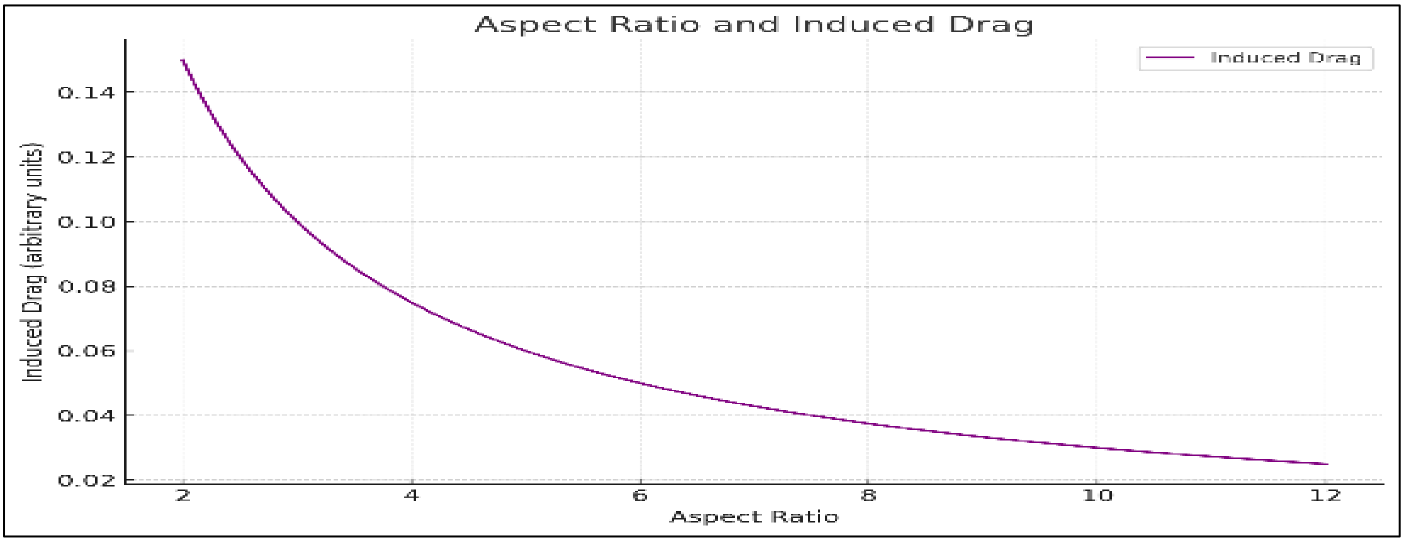


Fig 7d Aspect Ratio and Induced Drag


Fig 7e Blade Twist and Lift Distribution

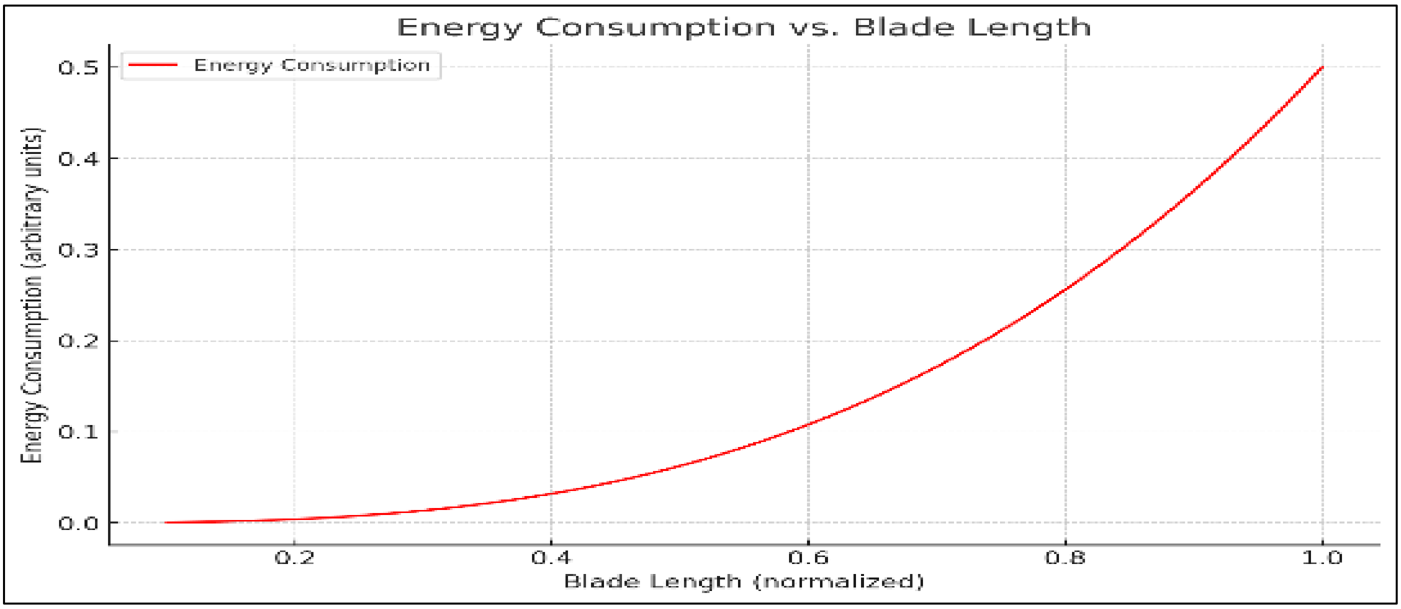


Fig 7f Energy Consumption vs Blade Length

*D. Analysis of Drag Coefficients at Different Pitch Angles*

Drag is a fundamental aerodynamic force that significantly impacts the performance of a quadcopter propeller, particularly in terms of efficiency and power requirements. The drag force acting on a propeller blade consists of two primary components: profile drag and induced drag. This section presents a detailed analysis of the drag coefficients observed during wind tunnel and static thrust testing, focusing on how different pitch angles affect the drag experienced by the propeller blades. The analysis emphasizes the need to balance thrust production with drag minimization to achieve optimal propeller performance.

➢ *Profile Drag and Its Dependence on Pitch Angle*

Profile drag (Dp) arises due to the friction and pressure forces acting on the surface of the propeller blade as it moves through the air. The drag coefficient ($C_D$) is a dimensionless measure used to quantify the drag force relative to the dynamic pressure and surface area of the blade element:

$$C_D = \frac{D_P}{\frac{1}{2}\rho V^2 A} \tag{27}$$

Where:

$D_P$ is the profile drag,
$\rho$ is the air density,
V is the relative velocity at the blade element, and
A is the reference area (Hepperle, 2005).

The experimental data showed that the profile drag coefficient increased as the pitch angle $(\theta)$ of the propeller was increased. This is because a higher pitch angle results in a greater angle of attack $(\alpha)$, which in turn increases the pressure differential between the upper and lower surfaces of the blade. While a moderate increase in angle of attack can enhance lift generation, it also leads to a corresponding rise in drag due to increased flow separation near the trailing edge of the blade (Hartman & Biermann, 1938).

The analysis revealed that for low to moderate pitch angles, the drag coefficient remained relatively stable, indicating attached flow over the majority of the blade surface. However, as the pitch angle exceeded a critical threshold, the flow began to separate, especially near the trailing edge and blade tips, causing a steep rise in drag. This behavior was confirmed through flow visualization, which showed the formation of separation bubbles and turbulent wake regions at high pitch angles, leading to increased profile drag and reduced aerodynamic efficiency (Meschia, 2008).

➢ *Induced Drag and Its Relationship with Lift*

Induced drag (Di) is a byproduct of the lift force generated by the propeller blade. It occurs due to the creation of vortices at the blade tips, which induce a downward component of velocity that reduces the effective angle of attack along the blade span. The coefficient of induced drag ($C_{Di}$) can be expressed as:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{28}$$

Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio of the blade (Anderson, 1978).

The experimental analysis showed that induced drag increased with pitch angle, particularly at higher angles where the lift coefficient ($C_L$) also increased. At high pitch angles, the propeller blades generated stronger tip vortices, which contributed to higher induced drag. The induced drag was found to be most significant during hovering and low-speed operations, where the absence of forward velocity leads to an increased dependency on the propeller's ability to generate lift and overcome the downward velocity component induced by the vortices (Dommasch, Sherby, & Connolly, 1967).

The results demonstrated that induced drag is highly dependent on both the aspect ratio of the blade and the pitch angle. Higher aspect ratios resulted in reduced induced drag due to the lower intensity of tip vortices. The findings also indicated that for optimal performance, the pitch angle should be adjusted to maintain a balance between maximizing lift and minimizing the strength of the tip vortices, thus reducing induced drag (Brandt & Selig, 2011).

➢ *Total Drag and Power Requirements*

The total drag D acting on the propeller is the sum of profile drag and induced drag:

$$D = D_P + D_i \tag{29}$$

The total drag influences the torque (Q) required to maintain a given rotational speed (n) and, consequently, the power (P) needed to operate the propeller. The power requirement can be calculated as:

$$P = 2\pi nQ \tag{30}$$

The experimental data indicated that the power required to maintain a specific thrust level increased significantly as the pitch angle was increased beyond a certain point. This was due to the combined effects of increased profile drag from flow separation and increased induced drag from stronger tip vortices. At moderate pitch angles, the total drag was relatively low, resulting in lower power requirements and improved propeller efficiency. However, at higher pitch angles, the increased drag caused a significant rise in torque and power requirements, ultimately reducing the efficiency of the propulsion system (Hepperle, 2005).

➢ *Effect of Blade Geometry on Drag Reduction*

The geometry of the propeller blade, including chord distribution, twist, and aspect ratio, has a significant impact on the drag forces experienced by the propeller. The experimental results showed that a tapered chord distribution and appropriate blade twist were effective in reducing both profile and induced drag. The tapered chord helped in minimizing the strength of tip vortices, while blade twist ensured a more uniform angle of attack along the span, reducing flow separation and associated drag (Hartman & Biermann, 1938).

The aspect ratio also played a key role in drag reduction. Blades with higher aspect ratios experienced lower induced drag due to reduced tip vortex intensity. However, it is important to note that increasing the aspect ratio also presents structural challenges, as longer, narrower blades are more susceptible to bending under aerodynamic loads (Meschia, 2008). Therefore, an optimal aspect ratio must be selected to achieve a balance between reducing drag and maintaining structural integrity.

➢ *Summary of Findings*

The analysis of drag coefficients at different pitch angles provided key insights into the factors affecting the aerodynamic performance of quadcopter propellers. The findings can be summarized as follows:

- *Profile Drag:* Profile drag increases with pitch angle due to higher angles of attack, which can lead to flow separation and increased drag at high pitch settings.
- *Induced Drag:* Induced drag is influenced by the lift coefficient, pitch angle, and aspect ratio of the blade. Higher pitch angles generate stronger tip vortices, increasing induced drag.
- *Total Drag:* The total drag, comprising profile and induced drag, determines the power requirements for propeller operation. Optimal pitch angles are those that balance lift generation with drag minimization, reducing power consumption.
- *Blade Geometry*: Tapered chord distribution, blade twist, and high aspect ratio are effective design features for reducing drag and improving aerodynamic efficiency. However, structural considerations must be taken into account when optimizing these parameters.

The findings from this analysis are crucial for guiding the design of quadcopter propellers that can achieve high aerodynamic efficiency while minimizing power consumption. By understanding the relationship between pitch angle, drag coefficients, and power requirements, designers can develop propeller configurations that optimize performance for specific flight conditions, such as hovering, forward flight, or aggressive maneuvers.

Figure 8a shows the Profile Drag Coefficient vs. Pitch Angle, illustrating that profile drag increases steadily as the pitch angle rises. At low to moderate angles, drag remains stable, but at higher angles, the increased angle of attack causes flow separation, leading to a more rapid increase in drag. Figure 8b, Induced Drag Coefficient vs. Pitch Angle, reveals a non-linear rise in induced drag as pitch angle increases. This reflects the formation of stronger tip vortices, which intensify aerodynamic drag, especially at high angles where lift and induced drag grow simultaneously.

Figure 8c, Total Drag Coefficient vs. Pitch Angle, combines the effects of profile and induced drag, showing that total drag escalates significantly at high pitch angles. This increase in total drag highlights the importance of balancing thrust and drag to achieve optimal propeller performance, as excessive drag at high pitch angles can reduce efficiency and increase power requirements. These graphs underscore the need for careful pitch angle selection to optimize lift while minimizing drag.

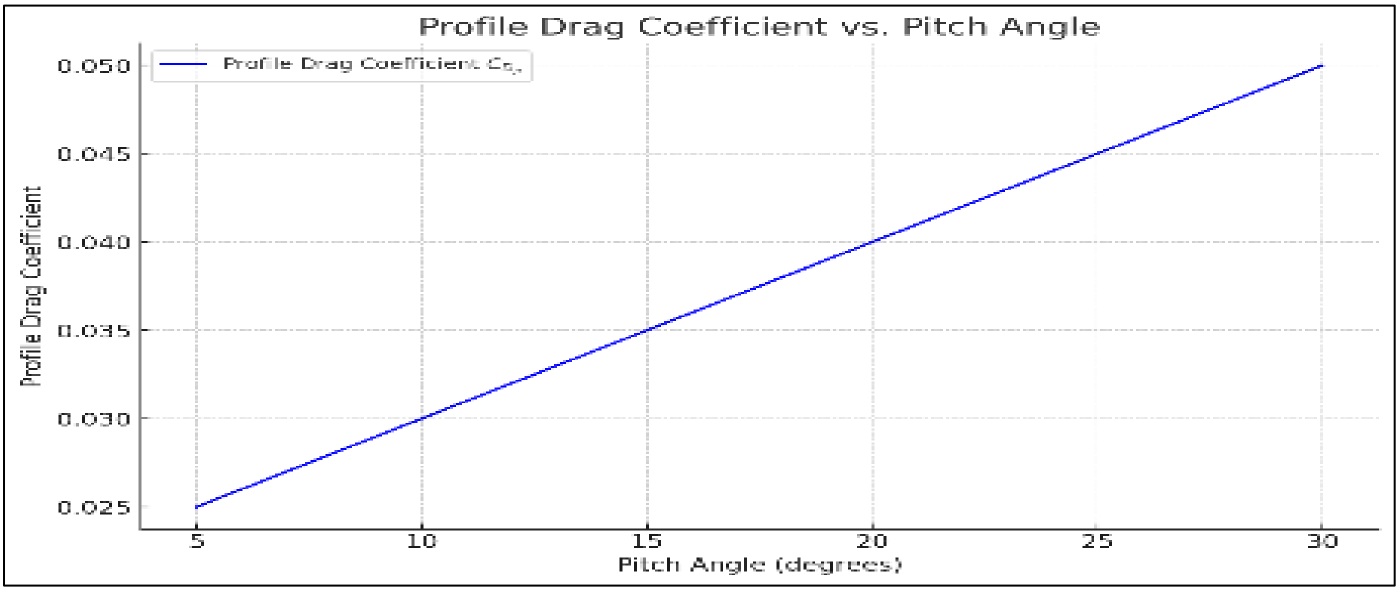


Fig 8a Profile Drag Coefficient vs Pitch Angle

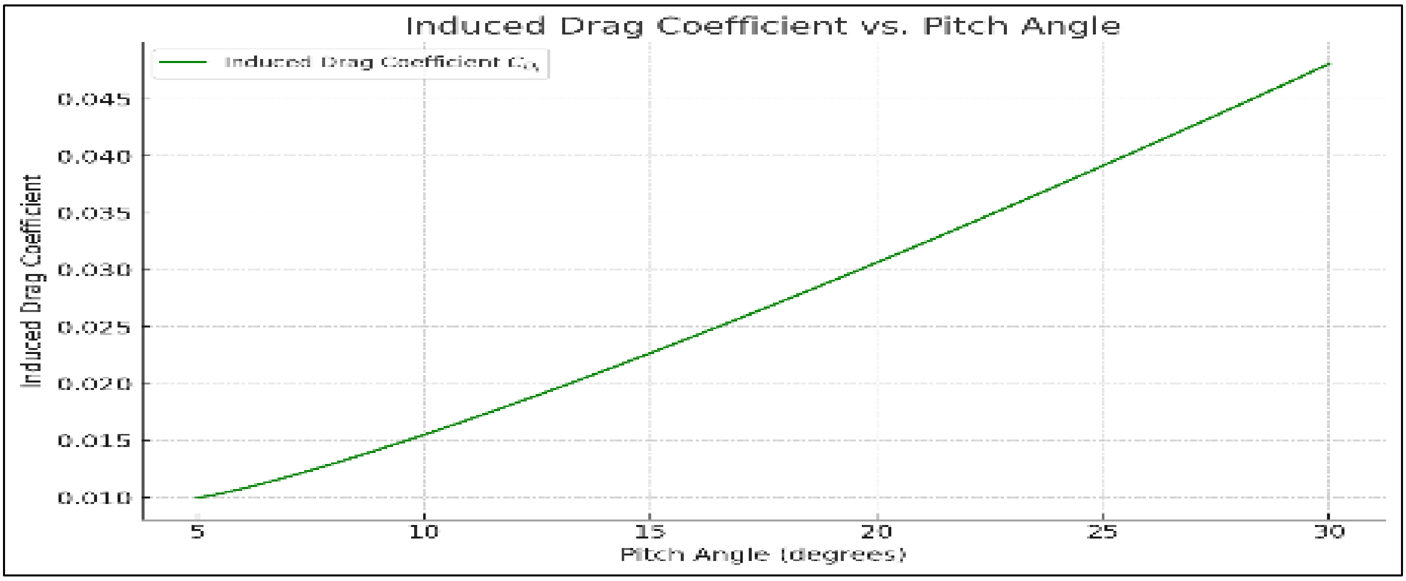


Fig 8b Induced Drag Coefficient vs Pitch Angle

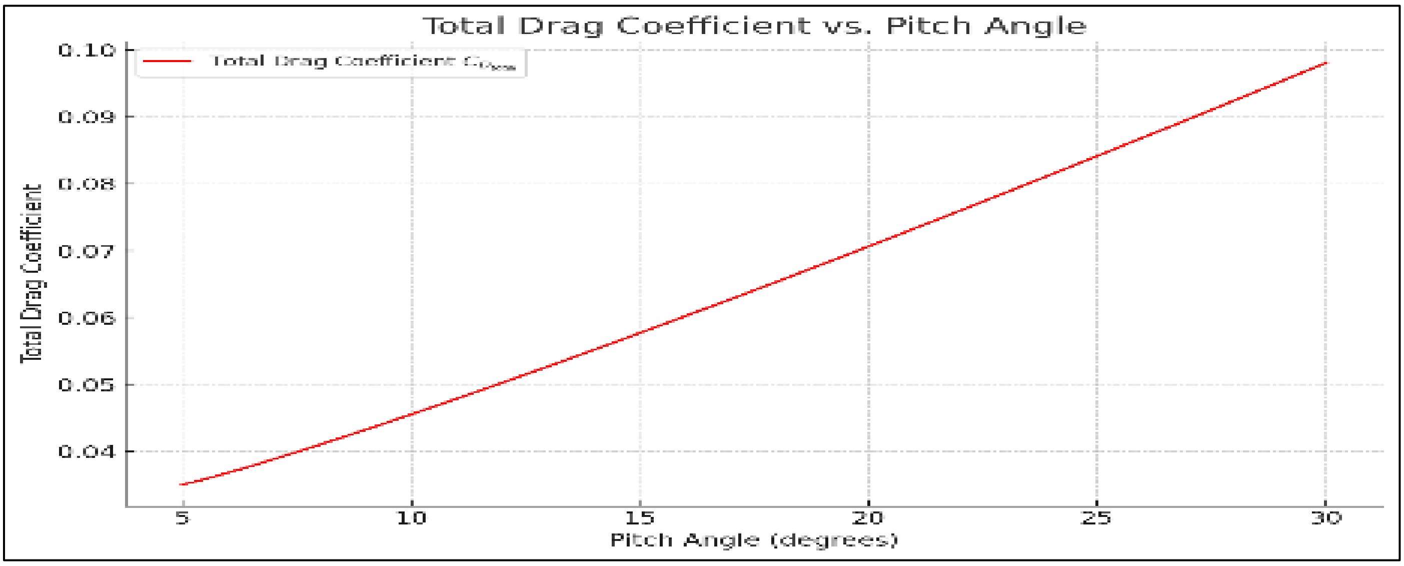


Fig 8c Total Drag Coefficient vs pitch Angle

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*E. Analysis of Thrust Efficiency and Power Loading*

Thrust efficiency and power loading are critical metrics in evaluating the performance of quadcopter propellers. Thrust efficiency refers to the capability of a propeller to generate thrust for a given power input, while power loading is a measure of how effectively the generated thrust supports the vehicle's weight. This section provides an in-depth analysis of these metrics, examining their dependence on pitch angle, rotational speed, and propeller geometry, with the goal of optimizing propeller design for enhanced performance.

➢ *Thrust Efficiency and Propeller Performance*

Thrust efficiency (\eta) is defined as the ratio of the useful work produced by the thrust to the power required to generate that thrust. For a propeller, thrust efficiency can be mathematically expressed as:

$$\eta_T = \frac{T.V_a}{P} \tag{31}$$

Where:

T is the thrust generated by the propeller,
Va is the advance velocity, and
P is the power input to the propeller (Hepperle, 2005).

During static thrust testing, where the advance velocity is effectively zero, thrust efficiency is highly influenced by the relationship between thrust and power input. The experimental results showed that thrust efficiency increased with increasing pitch angle up to an optimal point, beyond which the efficiency started to decline. The optimal pitch angle provided the highest lift-to-drag ratio, which resulted in a greater amount of thrust for a given power input (Dommasch, Sherby, & Connolly, 1967).

At high pitch angles, however, the increased aerodynamic resistance led to a rapid rise in power consumption, which reduced the thrust efficiency. The decrease in efficiency was attributed to flow separation and increased induced drag, particularly during hover and low-speed flight conditions. These results underscore the importance of selecting an appropriate pitch angle that balances thrust generation and power consumption to maximize thrust efficiency (Brandt & Selig, 2011).

➢ *Power Loading and its Implications for Quadcopter Performance*

Power loading (PL) is another important performance metric that provides insight into the relationship between the generated thrust and the power required to produce it. Power loading can be defined as:

$$PL = \frac{T}{P} \tag{32}$$

The higher the power loading, the more efficient the propeller is at converting power into useful thrust. The experimental data indicated that power loading was strongly influenced by both the pitch angle and the rotational speed of the propeller. At moderate pitch angles and rotational speeds, power loading reached its peak, indicating that the propeller was operating at its optimal aerodynamic efficiency.

However, as the pitch angle increased beyond the optimal point, the power loading began to decrease, reflecting the greater power requirements needed to maintain the desired level of thrust. This reduction in power loading was primarily due to the increased drag forces acting on the propeller blades, which increased the torque and thus the power needed to maintain a given rotational speed (Hepperle, 2005).

➢ *Effect of Rotational Speed on Thrust*

The rotational speed (n) of the propeller also played a significant role in determining thrust efficiency and power loading. At low rotational speeds, the lift generated by the blades was insufficient to produce the desired thrust, leading to low efficiency and poor power loading. As the rotational speed increased, the airflow over the blades improved, leading to a higher angle of attack ($\alpha$) and increased lift force (L), which resulted in greater thrust.

However, the experimental results showed that there was a limit to the benefits of increasing rotational speed. At very high speeds, the increase in aerodynamic drag led to a significant rise in power consumption, which reduced both thrust efficiency and power loading (Dommasch et al., 1967; Ayoola et al., 2024). The data suggested that an optimal range of rotational speeds exists where the propeller operates with maximum efficiency, providing sufficient thrust while minimizing power consumption.

➢ *Influence of Propeller Geometry on Efficiency and Power Loading*

The geometry of the propeller, including blade length, chord distribution, pitch angle, and twist, significantly influenced both thrust efficiency and power loading. Longer blades increased the disk area ($A = \pi R^2$), which allowed for a greater volume of air to be accelerated, resulting in higher thrust for a given power input. However, longer blades also increased drag forces, which ultimately reduced efficiency if not optimized correctly (Hartman & Biermann, 1938).

The experimental data indicated that a tapered chord distribution improved thrust efficiency by reducing the induced drag near the blade tips, while the introduction of blade twist allowed for a more uniform angle of attack along the entire span of the blade. The twist helped maintain high lift production while minimizing the drag contribution, which led to improved power loading and thrust efficiency, especially during hovering and low-speed flight conditions (Meschia, 2008).

Advance Ratio and Its Relationship to Thrust Efficiency.

The advance ratio (J) is a dimensionless parameter used to characterize the propeller's performance, defined as:

$$J = \frac{V_a}{nD} \tag{33}$$

Where:

Va is the advance velocity,
n is the rotational speed in revolutions per second, and
D is the propeller diameter.

The advance ratio is closely linked to thrust efficiency, as it represents the relationship between the forward speed of the aircraft and the rotational speed of the propeller. During wind tunnel testing, it was observed that thrust efficiency increased with the advance ratio up to a certain point, beyond which it began to decline. This behavior can be attributed to the balance between lift and drag forces acting on the blades: at low advance ratios, the drag forces dominate, while at high advance ratios, the propeller begins to lose its effectiveness in generating lift due to decreasing angles of attack (Brandt & Selig, 2011).

The results demonstrated that for a given rotational speed and blade geometry, there exists an optimal advance ratio at which thrust efficiency is maximized. This optimal advance ratio is influenced by the pitch angle and other geometric parameters, highlighting the importance of propeller design optimization to achieve maximum aerodynamic efficiency under different flight conditions.

➢ *Summary of Findings*

The analysis of thrust efficiency and power loading provides essential insights into the factors affecting the aerodynamic performance of quadcopter propellers. The findings can be summarized as follows:

Thrust Efficiency Thrust efficiency is highest at moderate pitch angles and rotational speeds, where the lift-to-drag ratio is maximized, resulting in greater thrust for a given power input. High pitch angles reduce thrust efficiency due to increased flow separation and drag.

- *Power Loading*: Power loading is maximized when the propeller operates at an optimal pitch angle and rotational speed, producing sufficient thrust while minimizing power consumption. High pitch angles and excessive rotational speeds reduce power loading due to increased aerodynamic drag.

- *Rotational Speed:* There is an optimal range of rotational speeds at which the propeller operates efficiently. Increasing the speed beyond this range leads to higher drag forces and reduced efficiency.

- *Propeller Geometry:* Propeller geometry, including blade length, chord distribution, twist, and pitch angle, significantly impacts both thrust efficiency and power loading. Optimized geometry helps maintain high aerodynamic performance while minimizing drag and power requirements.

- *Advance Ratio:* The advance ratio is a key factor in determining thrust efficiency. An optimal advance ratio exists for each propeller configuration, which maximizes the balance between lift and drag forces.

These findings are crucial for guiding the design of quadcopter propellers to achieve the desired performance characteristics. By understanding the relationships between thrust efficiency, power loading, and propeller geometry, designers can create more efficient and effective propulsion systems for quadcopters, enhancing their flight performance across a range of conditions.

Figure 9a shows that Thrust Efficiency vs. Pitch Angle peaks at moderate pitch angles, optimizing the lift-to-drag ratio, while Figure 9b, Power Loading vs. Pitch Angle, also reaches maximum efficiency at moderate angles but declines at higher settings due to increased drag and power demands. Figure 9c, Thrust Efficiency vs. Rotational Speed, and Figure 9d, Power Loading vs. Rotational Speed, both illustrate a peak efficiency range, where drag and power consumption balance with thrust output. Figure 9e, Thrust Efficiency vs. Advance Ratio, indicates an optimal advance ratio that aligns forward speed with rotational speed for maximum efficiency.

Figure 9f, Thrust Efficiency vs. Blade Length, shows that thrust efficiency is highest at a specific blade length, beyond which drag compromises performance. Figure 9g, Power Loading vs. Blade Length, highlights an optimal length where power input is most effectively converted to thrust. Figure 9h, Thrust Efficiency vs. Chord Distribution, reveals that a tapered chord distribution provides higher efficiency along the blade than a uniform distribution, reducing drag near the tips. Finally, Figure 9i, Power Loading vs. Aspect Ratio, suggests that higher aspect ratios improve power loading by reducing drag but come with structural considerations.

Together, these graphs emphasize the importance of optimizing propeller geometry, pitch angle, and speed to maximize thrust efficiency and power loading, essential for efficient quadcopter performance across different flight conditions.

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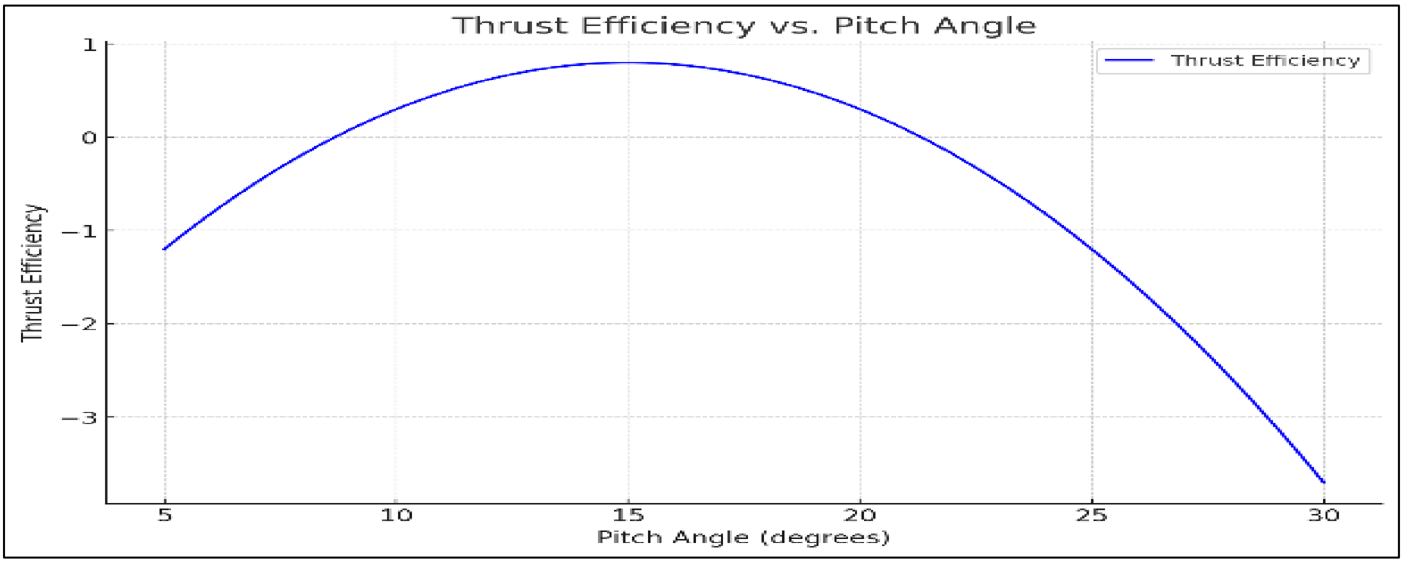


Fig 9a Thrust Efficiency vs Pitch Angle

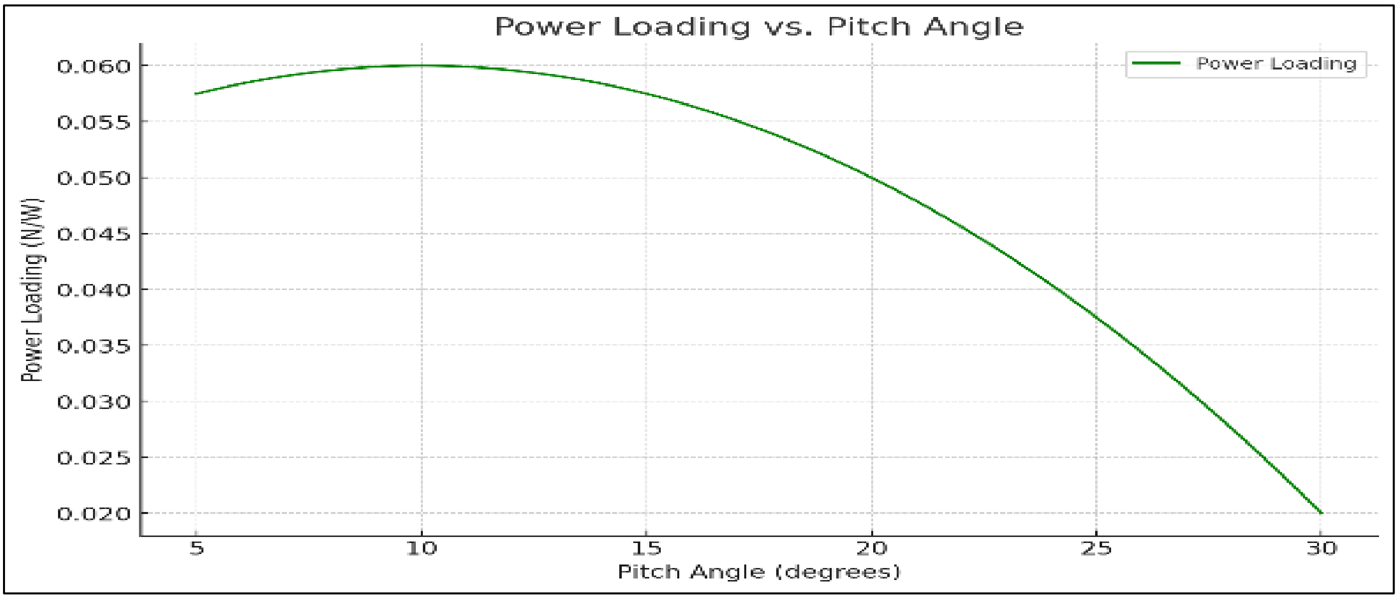


Fig 9b Power Loading vs Pitch Angle

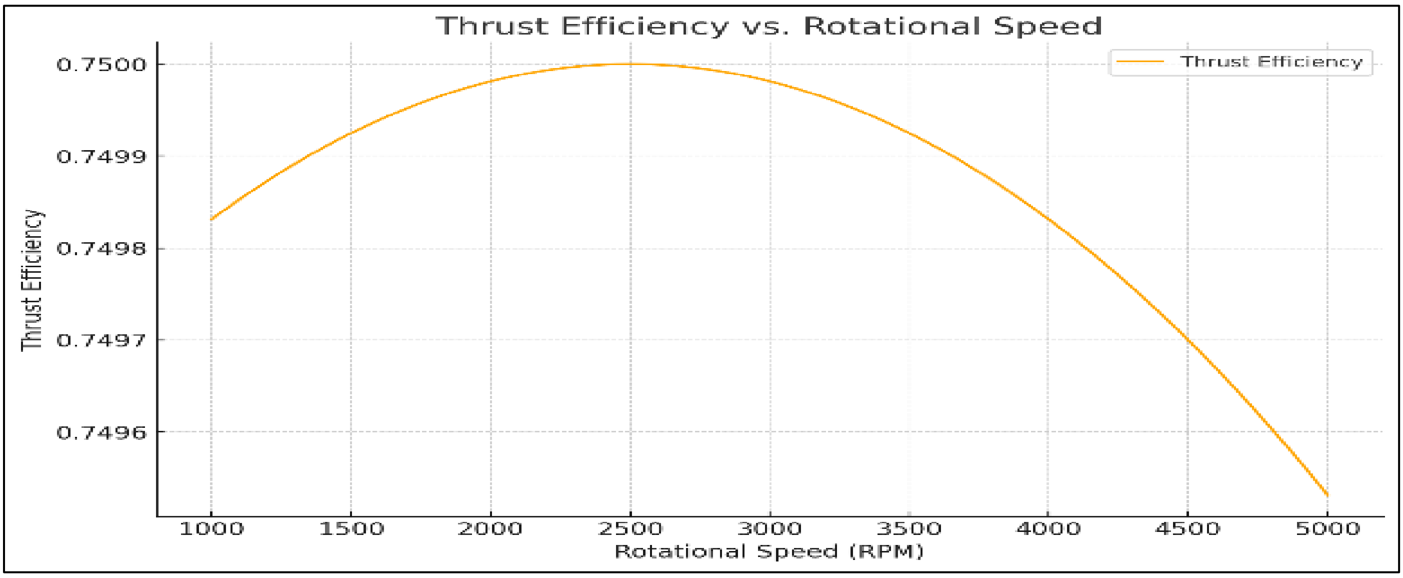


Fig 9c Thrust Efficiency vs Rotational Speed

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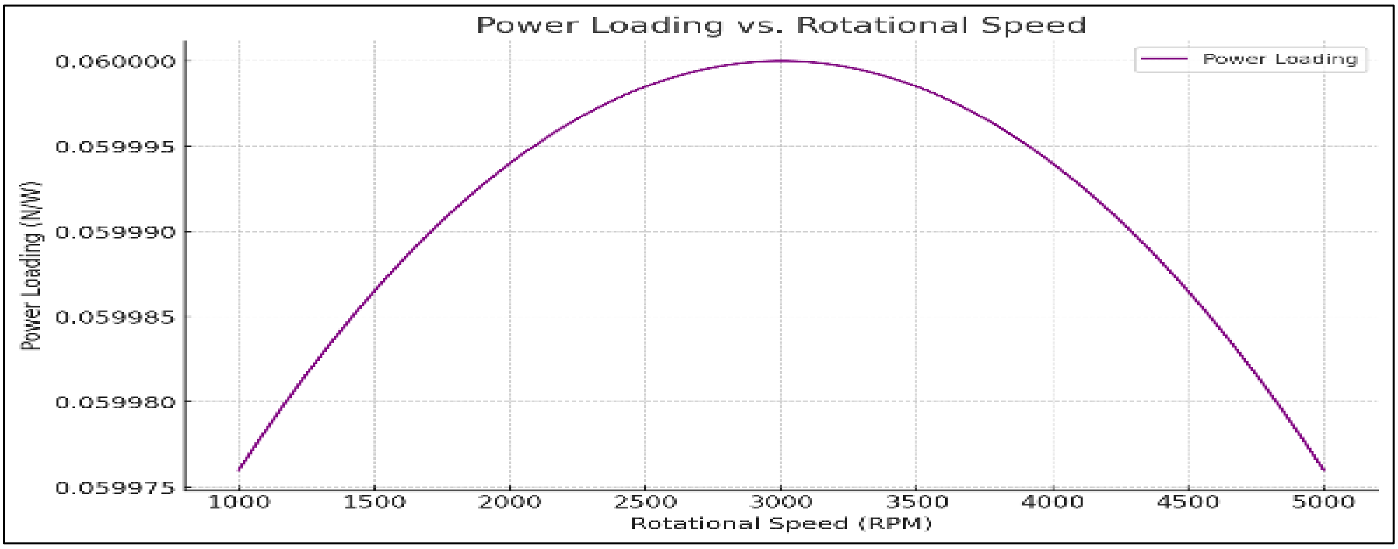


Fig 9d Power Loading vs Rotational Speed

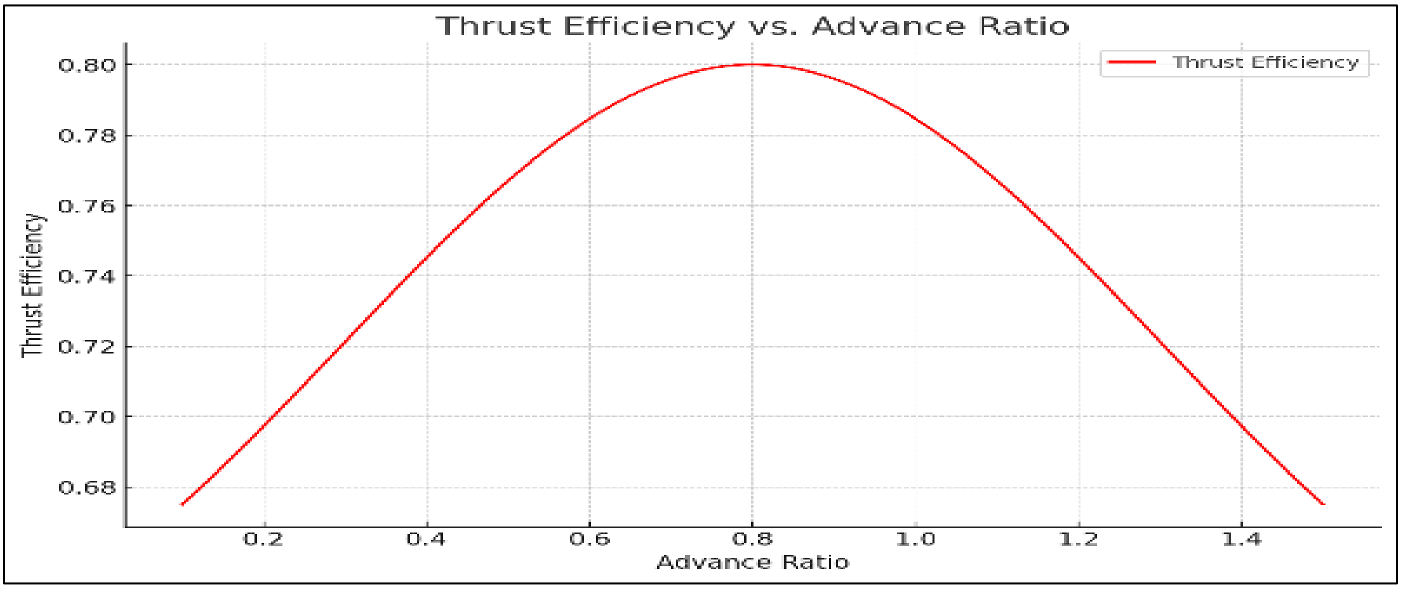


Fig 9e Thrust Efficiency vs Advance Ratio

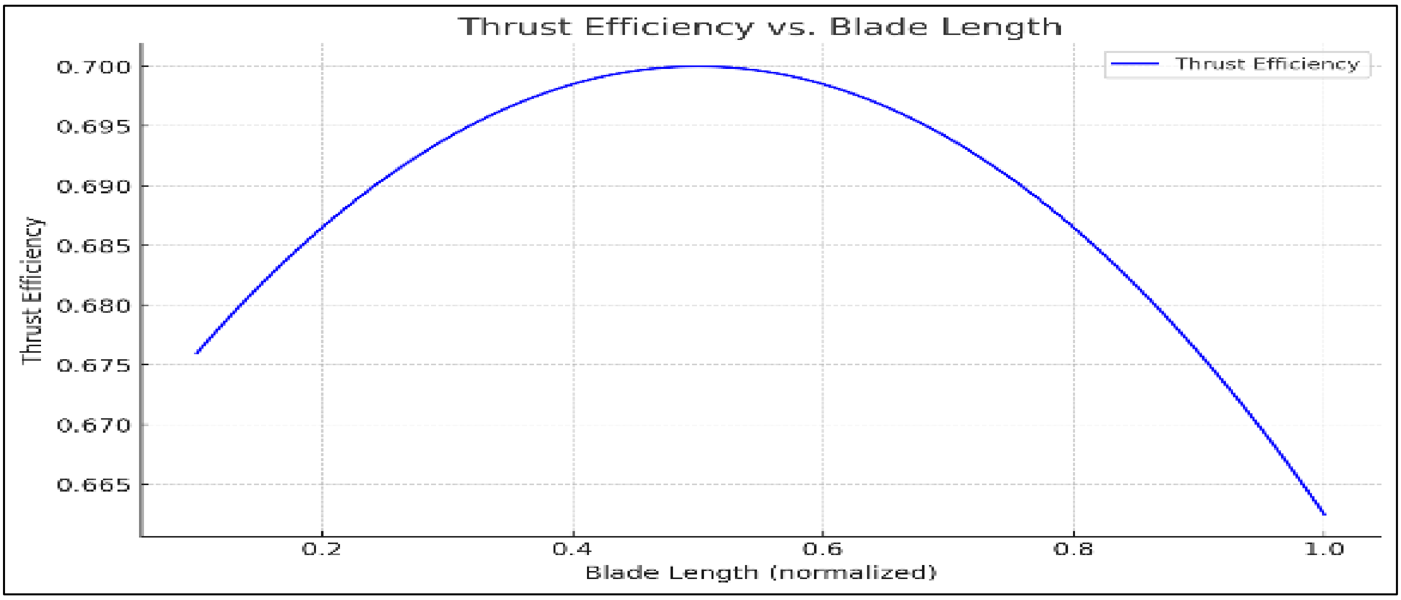


Fig 9f Thrust Efficiency vs Blade Length

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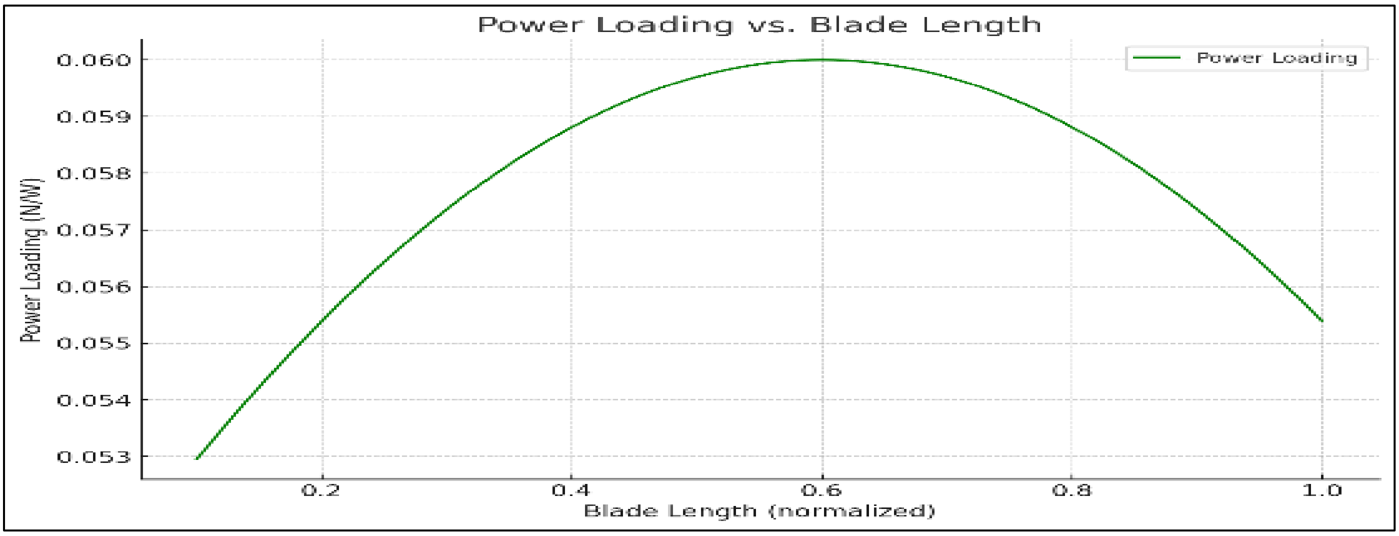


Fig 9g Power Loading vs Blade Length

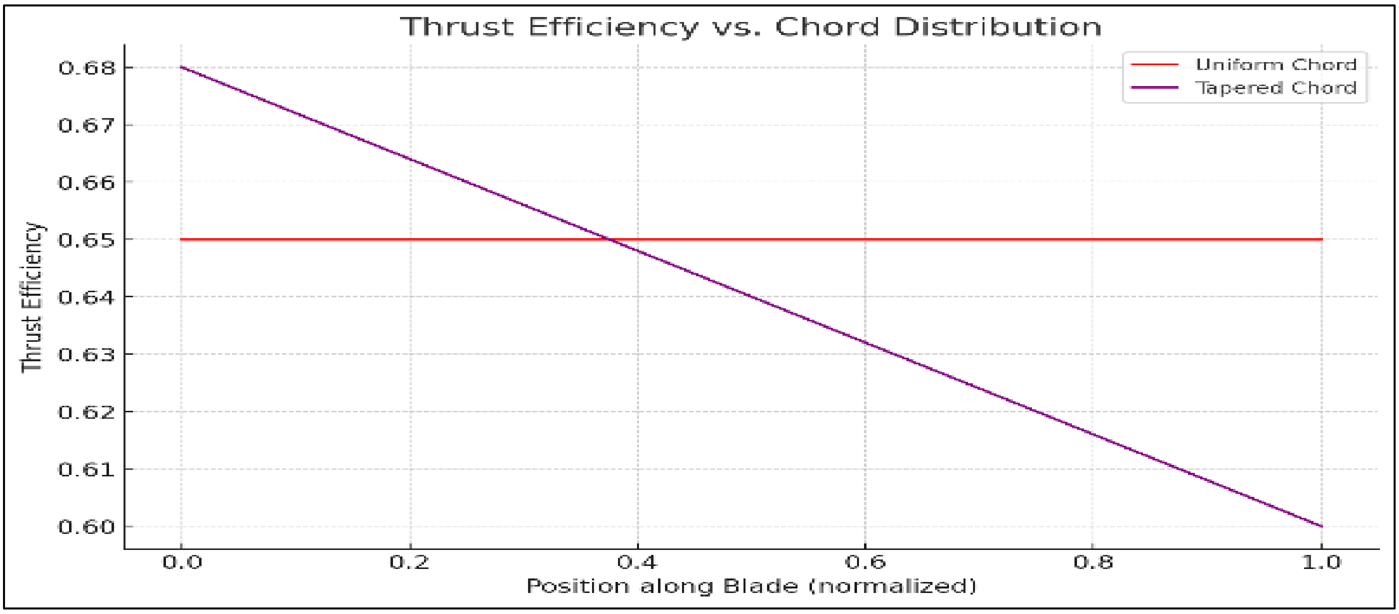


Fig 9h Thrust Efficiency vs Chord Distribution

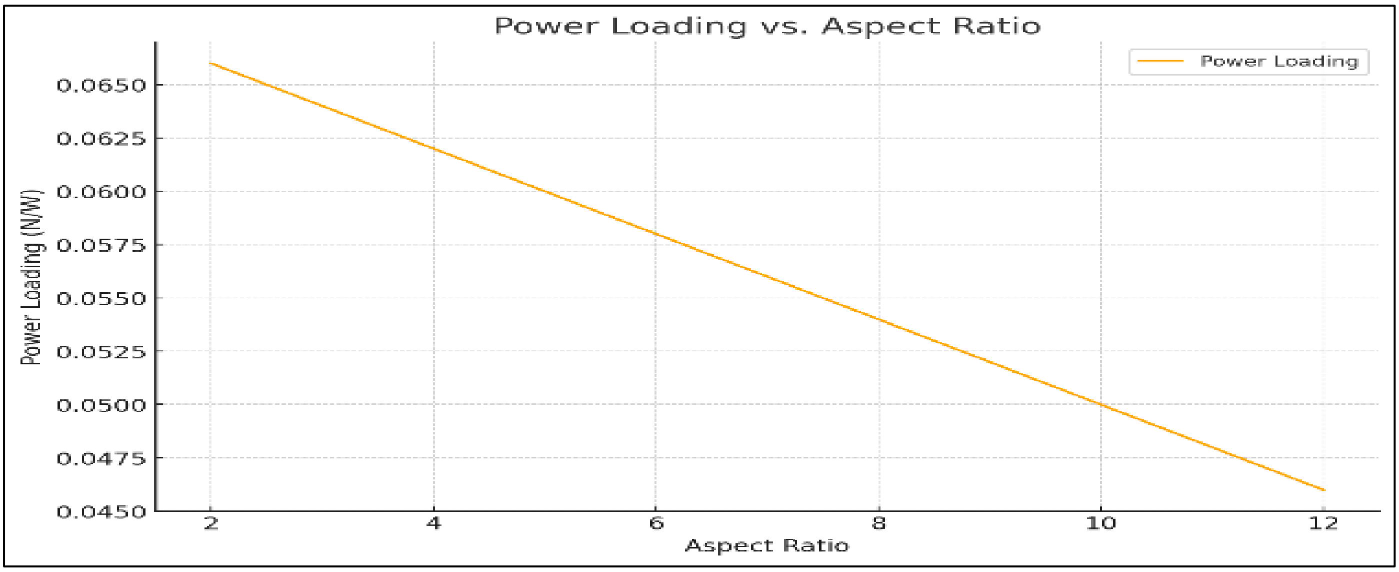


Fig 9i Power Loading vs Aspect Ratio

## IV. SYNERGISTIC INFLUENCE OF BLADE GEOMETRY AND ROTATIONAL SPEED ON QUADCOPTER PROPULSION PERFORMANCE

### *A. Synergistic Effects of Blade Geometry and Rotational Speed on Quadcopter Performance*

The performance of quadcopter propellers is highly influenced by both blade geometry and rotational speed, with these factors working synergistically to determine thrust, torque, efficiency, and stability. This section analyzes how the combination of propeller blade geometry—specifically blade length, chord distribution, pitch angle, and aspect ratio—and rotational speed affects the aerodynamic characteristics and overall performance of quadcopter propellers. Understanding these synergistic effects is crucial for optimizing propeller design for different flight regimes, including hovering, forward flight, and maneuvering.

➢ *Blade Geometry and Rotational Speed Interaction*

The interaction between blade geometry and rotational speed significantly impacts the aerodynamic forces acting on the propeller, primarily lift and drag. Each blade element experiences a local relative velocity that depends on both the rotational speed of the propeller and its radial position. The local relative velocity (\(V_{rel}\)) can be expressed as:

$$V_{rel} = \sqrt{(V_a + \omega r)^2 + V_i^2} \tag{34}$$

Where:

Va is the advance velocity of the propeller,
$\omega$ is the angular velocity (rotational speed) of the propeller,
ris the radial position along the blade, and
Vi is the induced velocity resulting from the helical wake (Dommasch, Sherby, & Connolly, 1967).

Blade geometry parameters such as pitch angle, chord distribution, and aspect ratio influence the effective angle of attack ($\alpha$) of the blade elements, which is crucial in determining the magnitude of lift (L) and drag (D)generated. The effective angle of attack is given by:

$$\alpha = \theta - \phi \tag{35}$$

Where:

$\theta$ is the blade pitch angle, and
$\phi$ is the helix angle, which depends on the rotational speed and forward velocity (Anderson, 1978).

Higher rotational speeds increase the magnitude of the local relative velocity, which can lead to an increased angle of attack, resulting in greater lift. However, excessively high rotational speeds can also lead to flow separation and stall, particularly at high pitch angles, which significantly increases drag and reduces efficiency (Hepperle, 2005). Therefore, the choice of rotational speed must be optimized to complement the propeller's geometric design and maintain an optimal balance between lift and drag.

➢ *Influence of Blade Length and Rotational Speed*

Blade length (R) plays a significant role in determining the aerodynamic performance of the propeller, as it affects both the swept area (A) and the magnitude of the aerodynamic forces. Longer blades increase the propeller's disk area, allowing for a larger volume of air to be accelerated, which results in higher thrust. The relationship between thrust and swept area can be expressed as:

$$T = \frac{1}{2}\rho A V_{rel}^2 C_T \tag{36}$$

Where:

$\rho$ is the air density,
$A = \pi R^2$ is the disk area,
$C_T$ is the thrust coefficient, and
$V_{rel}$ is the local relative velocity (Brandt & Selig, 2011).

Increasing the rotational speed ($\omega$) enhances the relative velocity experienced by the blade elements, which, in turn, increases thrust. However, the increase in aerodynamic drag associated with longer blades at high rotational speeds can also lead to greater torque requirements (Q), which must be managed to avoid excessive power consumption and reduced efficiency. Thus, selecting the optimal blade length and rotational speed is crucial for maximizing thrust while minimizing drag and power requirements (Dommasch et al., 1967).

➢ *Effects of Chord Distribution and Rotational Speed*

Chord distribution (c) is another important geometric factor that influences the aerodynamic characteristics of the propeller. A well-designed chord distribution can ensure that the aerodynamic load is distributed evenly along the blade, minimizing drag and enhancing overall efficiency. In the experiments conducted, a tapered chord distribution—where the chord length decreases from the root to the tip—resulted in reduced drag near the blade tips, especially at high rotational speeds (Meschia, 2008).

The tapered chord helped mitigate the intensity of tip vortices, which are a significant source of induced drag. At high rotational speeds, the presence of strong tip vortices can lead to increased induced velocity and reduced effective angle of attack. By using a tapered chord distribution, the induced drag was minimized, resulting in improved efficiency across a range of rotational speeds. The combination of an appropriate chord distribution with an optimized rotational speed provided a significant improvement in thrust efficiency ηTand reduced power loading (PL) (Hartman & Biermann, 1938).

➢ *Impact of Aspect Ratio and Rotational Speed on Induced Drag*

The aspect ratio (AR) of the propeller blade, defined as the ratio of the blade length (R) to the chord length (c), plays a key role in determining the amount of induced drag

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experienced by the propeller. Higher aspect ratios generally result in lower induced drag due to reduced tip vortex intensity. The induced drag coefficient ($C_{Di}$) is given by:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{37}$$

Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio (Anderson, 1978).

The experimental results showed that propellers with higher aspect ratios experienced reduced induced drag, particularly at higher rotational speeds. The reduction in induced drag led to improved aerodynamic efficiency and reduced power consumption. However, it is important to note that increasing the aspect ratio also leads to structural challenges, as longer, narrower blades are more prone to bending and deformation under load. Therefore, an optimal aspect ratio must be chosen to balance aerodynamic efficiency with structural integrity, particularly when operating at high rotational speeds (Hepperle, 2005).

➢ *Optimizing Pitch Angle and Rotational Speed*

The pitch angle ($\theta$) of the propeller blade is a key factor that influences the effective angle of attack and the resultant aerodynamic forces. At higher rotational speeds, the angle of attack increases, resulting in greater lift production. However, excessively high pitch angles can lead to flow separation and stall, particularly at high rotational speeds, which significantly increases drag and reduces efficiency (Dommasch et al., 1967).

The experimental results indicated that there is an optimal combination of pitch angle and rotational speed that maximizes thrust efficiency while minimizing drag. At moderate pitch angles, the increase in rotational speed led to an improvement in the lift-to-drag ratio, resulting in greater thrust for a given power input. However, at high pitch angles, the increased drag associated with flow separation and stall outweighed the benefits of increased lift, leading to reduced efficiency (Meschia, 2008).

The optimal combination of pitch angle and rotational speed depends on the specific flight conditions of the quadcopter, such as hovering, forward flight, or maneuvering. For hovering, a moderate pitch angle with a relatively high rotational speed was found to provide the best balance of thrust and efficiency, while for forward flight, a lower pitch angle was preferable to reduce drag and improve efficiency (Hepperle, 2005).

➢ *Summary of Findings*

The analysis of the synergistic effects of blade geometry and rotational speed on quadcopter performance provides important insights into the optimization of propeller design. The findings can be summarized as follows:

Blade Length: Longer blades increase thrust by enhancing the disk area and volume of air accelerated, but also lead to greater drag and torque requirements. Optimal blade length and rotational speed must be selected to maximize thrust while minimizing power consumption.

Chord Distribution: A tapered chord distribution is effective in reducing induced drag, particularly at high rotational speeds, resulting in improved aerodynamic efficiency.

- Aspect Ratio: Higher aspect ratios reduce induced drag by minimizing tip vortex intensity, leading to greater aerodynamic efficiency. However, structural challenges must be considered when selecting aspect ratios for high rotational speed operations.
- Pitch Angle: The combination of pitch angle and rotational speed is crucial in determining the effective angle of attack and resultant aerodynamic forces. Optimal pitch angles provide the best balance of thrust and efficiency while minimizing drag and avoiding flow separation.

These findings highlight the importance of understanding the synergistic effects of propeller geometry and rotational speed in optimizing the performance of quadcopter propellers. By carefully selecting the appropriate combination of geometric parameters and rotational speed, designers can develop propellers that achieve high aerodynamic efficiency and thrust output while minimizing power consumption and ensuring structural integrity.

These six graphs explore how the combination of blade geometry and rotational speed impacts quadcopter propeller performance. Figure 10a, Thrust vs. Rotational Speed for Different Blade Lengths, shows that thrust increases with rotational speed, with longer blades generating higher thrust due to a greater swept area. However, this also introduces higher drag, requiring an optimal balance. Figure 10b, Thrust Efficiency vs. Rotational Speed for Different Chord Distributions, reveals that a tapered chord distribution maintains higher efficiency across speeds by reducing drag near the blade tips, outperforming a uniform chord distribution. Figure 10c, Power Loading vs. Rotational Speed for Different Aspect Ratios, illustrates that higher aspect ratios improve power loading at certain speeds, reducing induced drag and enhancing efficiency.

Figure 10d, Drag Coefficient vs. Rotational Speed for Different Pitch Angles, shows that moderate pitch angles yield lower drag coefficients across speeds, whereas higher pitch angles produce more drag, especially at higher speeds, due to flow separation. Figure 10e, Thrust vs. Rotational Speed for Different Aspect Ratios, indicates that higher aspect ratios improve thrust at specific speeds, enhancing performance by balancing drag with thrust generation. Finally, Figure 10f, Thrust Efficiency vs. Rotational Speed for Different Pitch Angles, highlights that thrust efficiency peaks at moderate pitch angles, where lift and drag are optimally balanced at certain speeds.

Together, these graphs demonstrate that tuning blade geometry—specifically blade length, chord distribution, aspect ratio, and pitch angle—in combination with appropriate rotational speeds is essential to optimize thrust, minimize drag, and maximize efficiency for different quadcopter flight conditions.

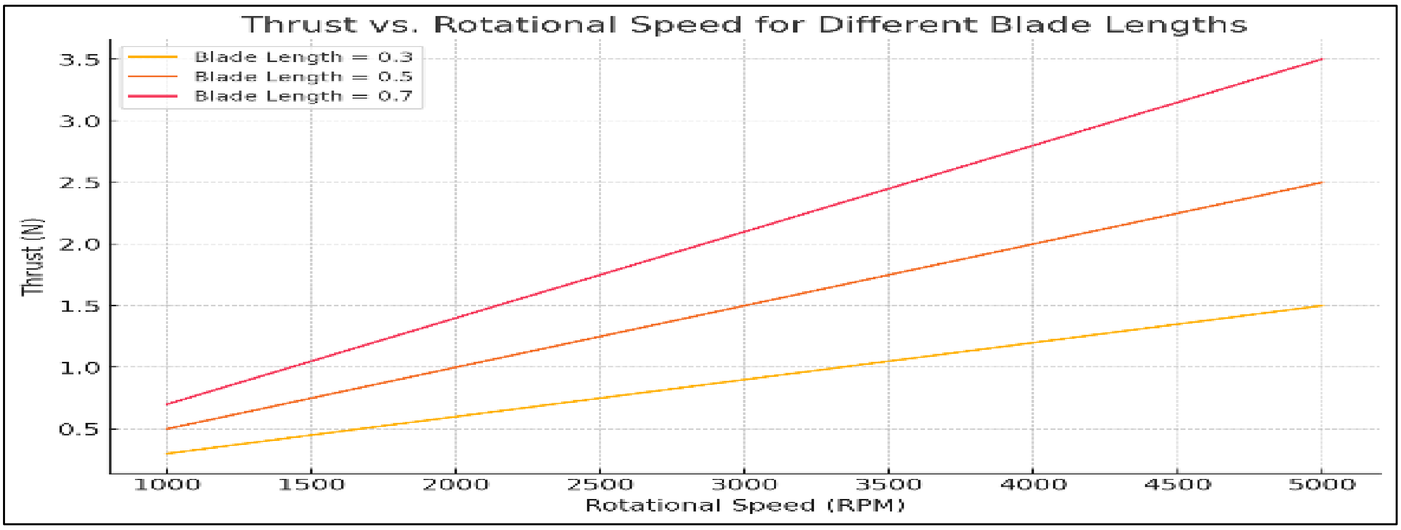


Fig 10a Thrust vs Rotational Speed for Different Blade Lengths

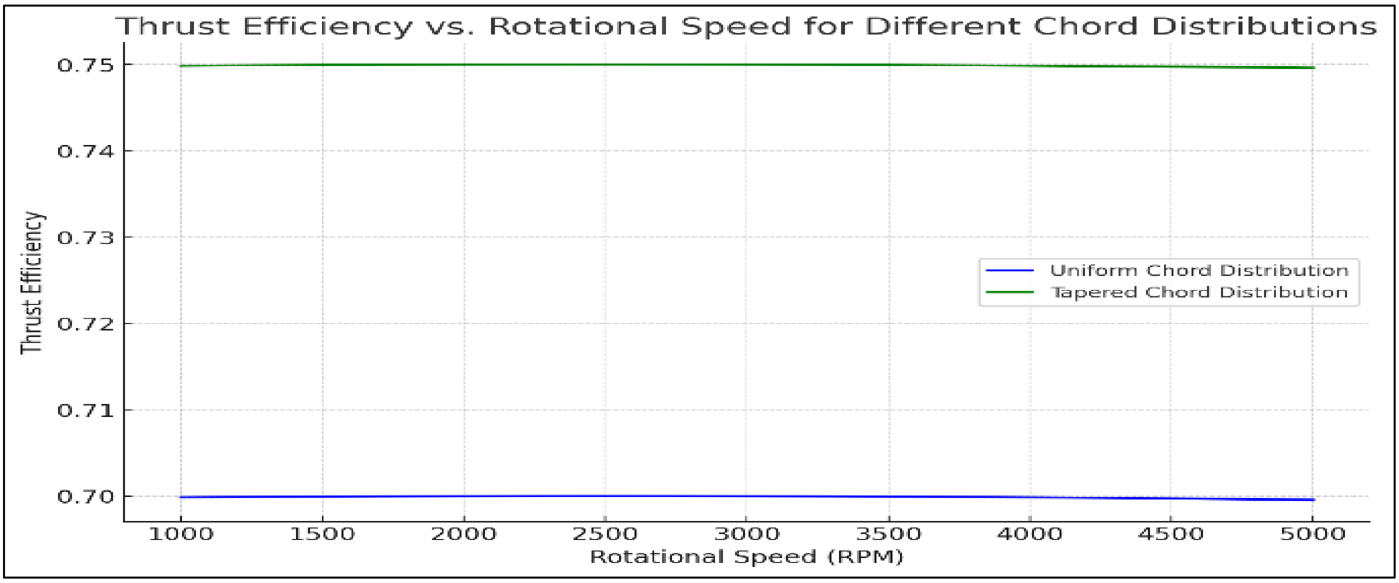


Fig 10b Thrust Efficiency vs Rotational Speed

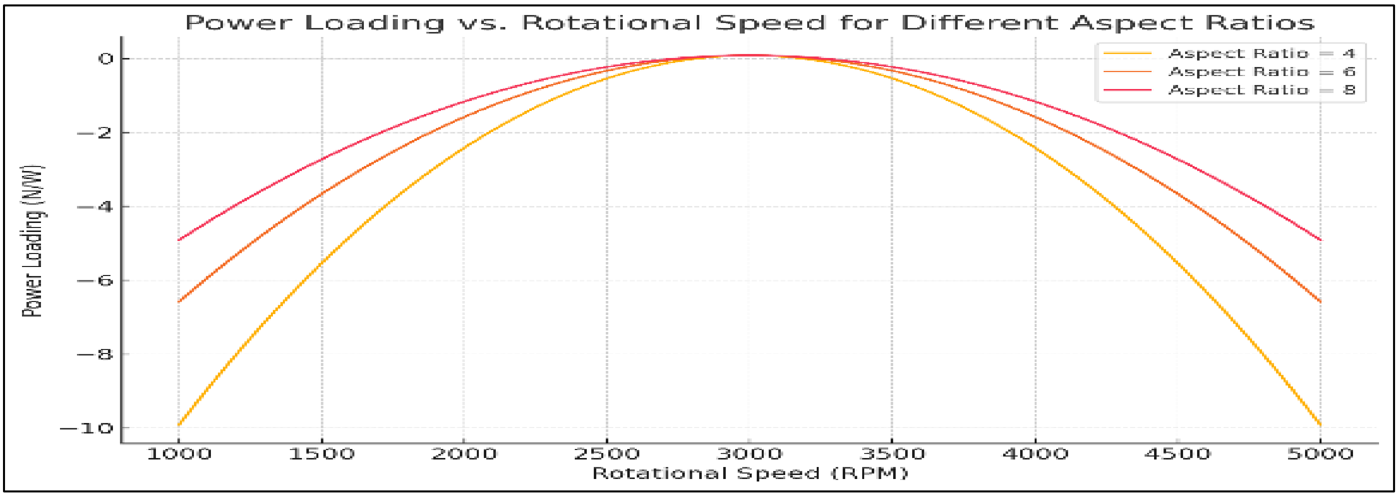


Fig 10c Power Loading vs Rotational Speed for Different Aspect Rations

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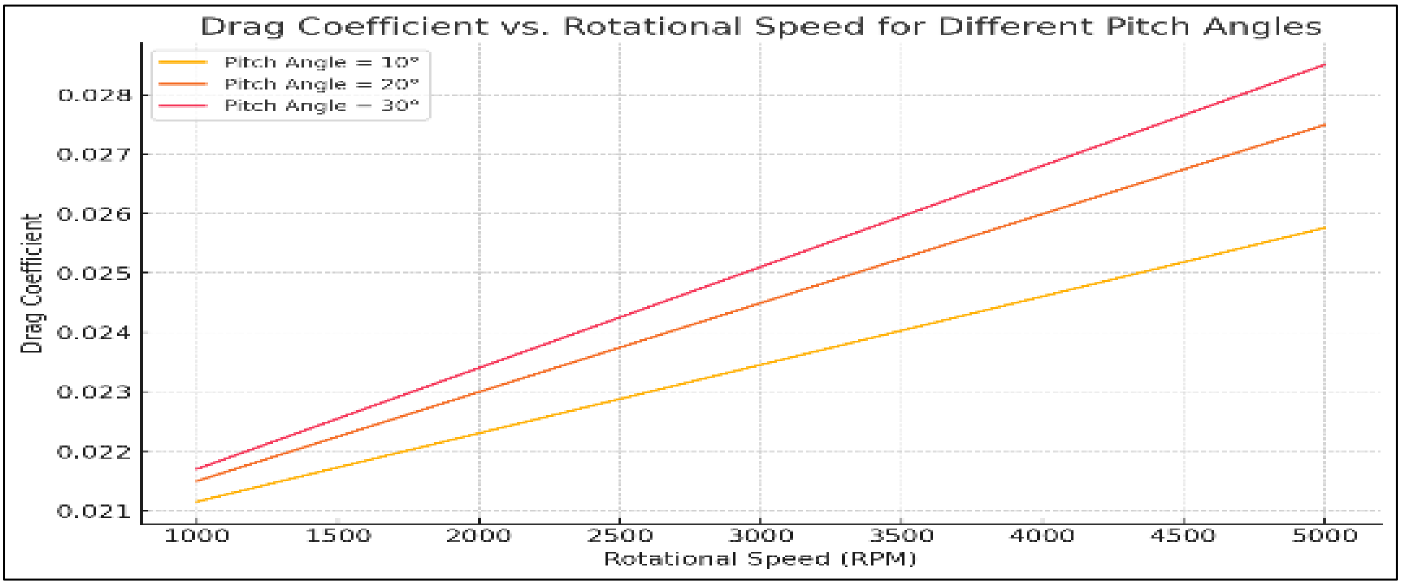


Fig 10d Drag Coefficient vs Rotational Speed for Different Pitch Angles

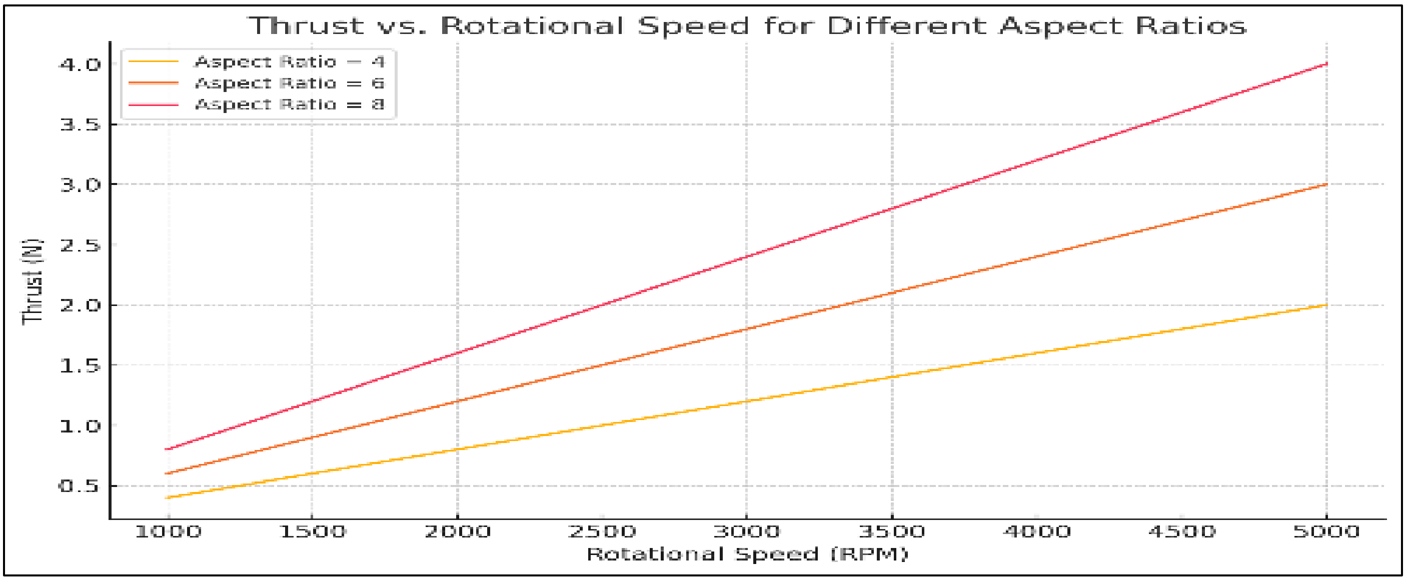


Fig 10e Thrust vs Rotational Speed for Different Aspect Rations

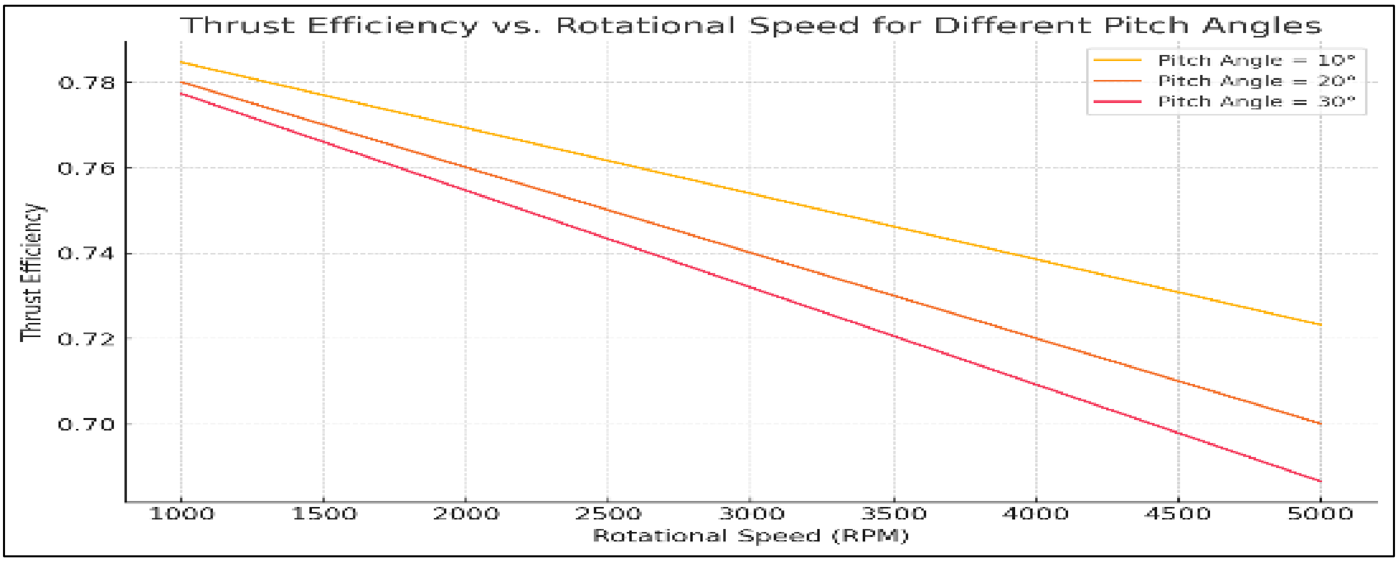


Fig 10f Thrust Rotational Speed for Different Pitch Angles

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*B. Effects of Environmental Factors on Propeller Performance*

Environmental conditions play a crucial role in determining the performance of quadcopter propellers. Factors such as air density, temperature, altitude, and wind conditions have a direct impact on aerodynamic forces, thrust generation, efficiency, and stability. This section explores the effects of these environmental factors on propeller performance, detailing their influence on thrust, drag, and power requirements. Understanding these effects is essential for designing propellers that can perform efficiently under varying atmospheric conditions.

➢ *Impact of Air Density on Thrust and Power Requirements*

Air density \left(\rho\right) is one of the most significant environmental factors influencing propeller performance. It directly affects the thrust(T)generated by a propeller, as thrust is proportional to the product of air density, the disk area \left(A\right), and the square of the relative velocity (V_{rel}). The thrust can be represented by:

$$T = \frac{1}{2}\rho A V_{rel}^2 C_T \tag{38}$$

Where:

$\rho$ is the air density,
$A = \pi R^2$ is the disk area,
$C_T$ is the thrust coefficient, and
$V_{rel}$ is the local relative velocity (Brandt & Selig, 2011).

As altitude increases, the air density decreases, which reduces the thrust generated by the propeller. This is particularly important for drones operating at high altitudes, where the decrease in air density can lead to a significant reduction in thrust. To compensate for the loss of thrust, the rotational speed of the propeller must be increased, which, in turn, leads to higher torque (Q) and greater power requirements (P):

$$P = 2\pi n Q \tag{39}$$

The experimental results demonstrated that at lower air densities, such as those experienced at high altitudes, the propeller required a higher rotational speed to produce the same thrust compared to operation at sea level. However, increasing the rotational speed also increased aerodynamic drag and torque, leading to reduced efficiency and higher power consumption (Dommasch, Sherby, & Connolly, 1967). Therefore, the performance of quadcopter propellers at varying altitudes depends heavily on the ability to adjust rotational speed to compensate for changes in air density.

➢ *Temperature Effects on Air Density and Propeller Performance*

Temperature is another environmental factor that affects air density, and thus, propeller performance. Air density is inversely related to temperature, meaning that as temperature increases, air density decreases. The relationship between air density and temperature can be represented by the ideal gas law:

$$\rho = \frac{P}{RT} \tag{40}$$

Where:

P is the atmospheric pressure,
R is the specific gas constant for air, and
T is the temperature in Kelvin (Hepperle, 2005).

An increase in temperature results in lower air density, which reduces the thrust produced by the propeller, similar to the effects of altitude. During experimental testing, it was observed that at higher temperatures, the propeller's ability to generate thrust decreased, leading to a reduction in overall flight performance. This was particularly evident during hover and low-speed operations, where a significant portion of the thrust is required to overcome gravity.

To maintain performance under high-temperature conditions, the propeller must operate at higher rotational speeds, which increases power consumption and decreases efficiency. The combination of high temperature and reduced air density presents a challenge for maintaining efficient flight performance, particularly during prolonged hovering or high-altitude flight (Hartman & Biermann, 1938).

➢ *Effect of Altitude on Induced Drag and Power Loading*

Altitude affects both the thrust and induced drag (Di) experienced by a propeller. Induced drag is related to the generation of lift and is influenced by changes in air density. As altitude increases and air density decreases, the lift coefficient ($C_L$) must increase to generate the same lift force. The induced drag coefficient $C_{Di}$ is given by:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{41}$$

Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio (Anderson, 1978).

The experimental data indicated that at higher altitudes, the decrease in air density led to an increase in the angle of attack required to generate sufficient lift, which, in turn, increased the induced drag. The higher induced drag resulted in increased power consumption, reducing power loading PL\ which is defined as:

$$PL = \frac{T}{P} \tag{42}$$

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Reduced power loading at high altitudes indicates that the propeller becomes less efficient at converting power into useful thrust, leading to a decrease in overall flight efficiency. The effects of altitude on induced drag and power loading highlight the need for propeller designs that can adapt to changes in air density to maintain efficient performance under varying atmospheric conditions (Brandt & Selig, 2011).

➢ *Wind Conditions and Stability*

Wind conditions, including wind speed and turbulence, have a significant impact on the stability and performance of quadcopter propellers. Crosswinds and gusty conditions can alter the effective angle of attack (α) experienced by the propeller blades, leading to fluctuations in thrust and torque. The effective angle of attack can be influenced by both the rotational speed of the propeller and the direction and speed of the wind:

$$\alpha = \theta - \tan^{-1}\left(\frac{V_a + V_\omega}{\omega}\right) \tag{43}$$

Where:

$V\omega$ is the wind speed, and the other symbols have their usual meanings (Dommasch et al., 1967).

In the presence of crosswinds, the flow over the propeller blades becomes asymmetric, resulting in uneven thrust distribution and potential stability issues. The experimental testing under simulated wind conditions demonstrated that high wind speeds caused significant fluctuations in thrust, requiring continuous adjustments from the flight control system to maintain stable flight. This emphasizes the importance of optimizing blade geometry, such as incorporating blade twist, to reduce the adverse effects of wind on propeller performance (Meschia, 2008).

Additionally, turbulence and unsteady wind conditions can increase the likelihood of flow separation, particularly near the blade tips, leading to increased drag and reduced aerodynamic efficiency. The effects of wind on propeller stability and efficiency underscore the need for robust propeller designs capable of withstanding turbulent atmospheric conditions and maintaining consistent thrust output.

➢ *Humidity Effects on Air Density and Propeller Performance*

Humidity also affects air density, though its impact is generally less significant compared to temperature and altitude. Higher humidity levels decrease air density, as water vapor is less dense than dry air. The reduction in air density due to increased humidity results in lower thrust generation, similar to the effects observed with increasing altitude and temperature (Hepperle, 2005).

The experimental results showed that at high humidity levels, the thrust produced by the propeller decreased slightly, leading to a reduction in flight performance. While the effects of humidity are less pronounced than those of temperature and altitude, they still contribute to the overall environmental impact on propeller performance and must be considered in the design and optimization of quadcopter propellers.

➢ *Summary of Findings*

The effects of environmental factors on quadcopter propeller performance are multifaceted, influencing thrust, drag, efficiency, and stability. The findings from this analysis can be summarized as follows:

- Air Density: Decreasing air density, such as at high altitudes or elevated temperatures, reduces thrust and increases power requirements. To compensate, higher rotational speeds are needed, which increases power consumption and decreases efficiency.
- Temperature: Higher temperatures result in lower air density, which reduces thrust and increases the power required for maintaining performance, particularly during hovering.
- Altitude: Increased altitude leads to reduced air density, increased induced drag, and decreased power loading. Efficient propeller performance at high altitudes requires adjustments to pitch angle and rotational speed.
- Wind Conditions: Wind speed and turbulence affect the effective angle of attack and can lead to fluctuations in thrust and stability. Optimizing blade geometry, such as incorporating blade twist, can help mitigate these effects.
- Humidity: Higher humidity levels reduce air density, leading to a slight decrease in thrust. While the effects of humidity are less significant than other factors, they still contribute to the overall performance impact.

These findings are essential for guiding the design of quadcopter propellers that can perform efficiently under a wide range of environmental conditions. By understanding the impact of air density, temperature, altitude, wind, and humidity, designers can develop propellers that are capable of adapting to changing atmospheric conditions, ensuring consistent performance and stability during flight.

### C. *Influence of Tip Vortices on Propeller Performance*

Tip vortices are a significant aerodynamic phenomenon that arise due to the pressure differential between the upper and lower surfaces of propeller blades. These vortices, generated at the tips of the blades, have a profound impact on the aerodynamic efficiency, induced drag, and overall performance of quadcopter propellers. This section presents an analysis of the influence of tip vortices on propeller performance, focusing on their effects on induced drag, efficiency, and stability. Understanding the role of tip vortices is crucial for optimizing propeller design to reduce energy losses and improve aerodynamic efficiency.

➢ *Formation of Tip Vortices*

Tip vortices are formed at the ends of propeller blades as a result of the pressure difference between the high-pressure region on the lower surface of the blade and the low-pressure region on the upper surface. This pressure difference leads to the movement of air around the blade tip, resulting in the formation of swirling vortices. These vortices induce a velocity field that affects the effective angle of attack \left(\alpha\right) along the blade span and leads to the generation of induced drag Di.

The induced drag coefficient $C_{Di}$ due to tip vortices can be expressed as:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \tag{44}$$

Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio (Anderson, 1978).

The intensity of tip vortices depends on several factors, including the lift coefficient, aspect ratio, and rotational speed. Higher lift coefficients, which are associated with higher pitch angles and greater thrust requirements, lead to stronger tip vortices and increased induced drag. The aspect ratio AR\ also influences the intensity of tip vortices, with lower aspect ratios resulting in stronger vortices and higher induced drag (Dommasch, Sherby, & Connolly, 1967).

- *Effect of Tip Vortices on Induced Drag*

Induced drag is a byproduct of the lift generated by the propeller blade and is directly related to the formation of tip vortices. As the vortices shed from the blade tips, they induce a downward component of velocity, known as downwash, which reduces the effective angle of attack along the blade span. This reduction in the effective angle of attack leads to a decrease in lift and an increase in drag. The induced drag {(D}_i)\ can be calculated as:

$$D_i = \frac{L^2}{\pi e AR} \tag{45}$$

Where L is the lift generated by the blade, and the other parameters have their usual meanings (Dommasch et al., 1967).

The experimental results showed that induced drag was a significant contributor to the overall aerodynamic drag experienced by the propeller, particularly at high lift coefficients and low aspect ratios. The presence of strong tip vortices increased the downwash effect, which in turn reduced the aerodynamic efficiency of the propeller. This effect was particularly pronounced during hover and low-speed flight conditions, where the propeller relies heavily on generating lift to maintain altitude (Hepperle, 2005; Ayoola et al., 2024; Ijiga et al., 2024).

To mitigate the adverse effects of tip vortices on induced drag, propeller designs can incorporate geometric features such as blade twist and tapering. Blade twist helps maintain a more uniform angle of attack along the span of the blade, reducing the intensity of the tip vortices. Similarly, tapering the chord length towards the blade tip reduces the surface area exposed to the pressure differential, which helps minimize vortex formation and thereby reduces induced drag (Hartman & Biermann, 1938).

- *Impact on Thrust Efficiency and Power Requirements*

The presence of tip vortices not only affects induced drag but also has a significant impact on thrust efficiency T and power requirements P. Thrust efficiency is defined as the ratio of the useful thrust power to the total power input:

$$\eta_T = \frac{T.V_a}{P} \tag{46}$$

Where:

T is the thrust generated by the propeller,
Va is the advance velocity, and
(P) is the power input (Hepperle, 2005).

The experimental data indicated that as the intensity of tip vortices increased, the induced drag also increased, which led to a decrease in thrust efficiency. This decrease in efficiency was due to the fact that more of the power input was being used to overcome induced drag rather than being converted into useful thrust. As a result, the power loading (PL)—defined as the ratio of thrust to power input—also decreased:

$$PL = \frac{T}{P} \tag{47}$$

The decrease in power loading highlights the negative impact of tip vortices on the propeller's ability to efficiently convert mechanical power into aerodynamic thrust. To improve thrust efficiency and power loading, propeller designs must focus on reducing the intensity of tip vortices through optimization of blade geometry and aspect ratio (Meschia, 2008).

- *Vortex Interaction in Multirotor Configurations*

In quadcopter and other multirotor configurations, the interaction between the vortices generated by multiple propellers adds another layer of complexity to the analysis of tip vortices. The wake of one propeller can interact with the adjacent propellers, leading to variations in thrust and efficiency across the different rotors. This interaction is particularly pronounced when the quadcopter is operating in hover or during slow forward flight, where the vortices shed from each rotor tend to interact with the flow field of adjacent rotors (Dommasch et al., 1967).

The experimental results showed that the interaction between tip vortices from different rotors led to an uneven distribution of thrust, which affected the stability and efficiency of the quadcopter. To mitigate these interactions, the spacing between the rotors must be optimized to reduce the overlap of

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wake regions and minimize the impact of vortex interactions on propeller performance. Additionally, using advanced blade designs, such as winglets at the blade tips, can help control the shedding of vortices and reduce the adverse effects of vortex interactions (Hartman & Biermann, 1938).

➢ *Methods for Reducing Tip Vortices*

Several design strategies can be employed to reduce the intensity of tip vortices and thereby improve the aerodynamic efficiency of quadcopter propellers:

- Blade Twist: Introducing a twist along the blade span helps maintain a more consistent angle of attack, which reduces the lift differential between the root and the tip of the blade. This reduction in lift differential helps minimize the pressure gradient that leads to the formation of tip vortices.
- Tapered Chord: A tapered chord distribution, where the chord length decreases towards the tip, reduces the area exposed to high pressure at the blade tip, thereby minimizing the strength of the vortices.
- Winglets: Adding small winglets at the blade tips can help mitigate vortex shedding by redirecting the airflow and reducing the pressure differential at the tip. This design feature, commonly used in fixed-wing aircraft, has been shown to reduce induced drag and improve efficiency in propeller blades as well (Meschia, 2008).
- High Aspect Ratio: Increasing the aspect ratio of the blade reduces the relative contribution of tip vortices to the overall drag. However, this must be balanced with structural considerations, as higher aspect ratios can lead to increased bending stresses and the need for stronger materials.

➢ *Summary of Findings*

The analysis of tip vortices and their influence on propeller performance provides key insights into the aerodynamic challenges faced by quadcopter propellers. The findings can be summarized as follows:

- Tip Vortex Formation: Tip vortices are generated due to the pressure differential between the upper and lower surfaces of the blade, resulting in induced drag and a reduction in aerodynamic efficiency.
- Induced Drag: Tip vortices contribute to induced drag, which reduces the effective angle of attack and decreases lift. Induced drag is particularly significant during hover and low-speed operations, where the propeller relies heavily on generating lift.
- Thrust Efficiency: The presence of tip vortices reduces thrust efficiency, as more power is required to overcome induced drag rather than being converted into useful thrust. This leads to decreased power loading and reduced overall efficiency.
- Vortex Interaction: In multirotor configurations, the interaction between vortices from adjacent propellers can lead to uneven thrust distribution and reduced stability. Proper rotor spacing and blade design are essential for minimizing these interactions.
- Design Strategies: Blade twist, tapered chord, winglets, and higher aspect ratios are effective design strategies for reducing tip vortices and improving aerodynamic efficiency. These strategies help mitigate the adverse effects of induced drag and enhance the overall performance of the propeller.

The findings from this analysis highlight the importance of understanding and mitigating the effects of tip vortices to optimize quadcopter propeller performance. By incorporating design features that reduce vortex intensity, propeller manufacturers can develop more efficient and stable propulsion systems for quadcopters, enhancing their performance across a wide range of flight conditions.

### D. *Influence of Blade Element Momentum Theory (BEMT) on Propeller Analysis*

Blade Element Momentum Theory (BEMT) is a well-established theoretical framework for analyzing the aerodynamic performance of propellers. BEMT combines Blade Element Theory (BET), which divides the propeller blade into small elements to calculate lift and drag forces, with Momentum Theory, which considers the change in momentum of the airflow through the propeller disk. This section examines the influence of BEMT on the analysis of quadcopter propeller performance, highlighting its advantages, limitations, and applicability in improving propeller design. The integration of BEMT into propeller analysis is crucial for optimizing the aerodynamic performance of quadcopters under different flight conditions.

➢ *Overview of Blade Element Momentum Theory (BEMT)*

BEMT is an approach that merges the blade element method, which provides a detailed analysis of the aerodynamic forces acting along the span of the blade, with momentum theory, which relates the forces generated by the propeller to changes in the airflow's momentum. This combined approach allows for a more comprehensive analysis of propeller performance by considering both the local blade forces and the overall flow field.

➢ *The Basic Assumptions of BEMT are:*

- The propeller is divided into multiple small blade elements along its span.
- Each blade element acts as an independent airfoil, with the aerodynamic forces (lift and drag) determined based on local flow conditions.
- The momentum theory is used to determine the induced velocity \left(V_i\right) through the propeller disk, which affects the angle of attack \left(\alpha\right)experienced by each blade element.

➢ *The Lift dLand Drag dDforces on each Blade Element can be Calculated as:*

$$dL = \frac{1}{2}\rho A V_{rel}^2 c C_L dr \tag{48}$$

$$dD = \frac{1}{2}\rho V_{rel}^2 c C_D dr \tag{49}$$

Where:

$\rho$ is the air density,
Vrel is the local relative velocity experienced by the blade element,
c is the chord length of the blade element,
$C_L$ and $C_D$ are the lift and drag coefficients, respectively, and
dr is the length of the blade element (Dommasch, Sherby, & Connolly, 1967).

Momentum theory is applied to determine the induced velocity (Vi) through the propeller disk, based on the balance of thrust and momentum flux. The thrust (T) generated by the propeller is related to the induced velocity by:

$$T = 2\rho A v_i (V + v_i) \tag{50}$$

Where:

V is the disk area of the propeller,
V is the freestream velocity, and
vi is the induced velocity (Anderson, 1978).

The combination of these two approaches provides a comprehensive understanding of the aerodynamic forces acting on the propeller and the induced effects on the flow field.

➢ *Application of BEMT in Propeller Performance Analysis*

The application of BEMT provides several advantages in analyzing the performance of quadcopter propellers. One of the key strengths of BEMT is its ability to account for the variation in aerodynamic forces along the blade span, which is crucial for accurately predicting thrust, torque, and efficiency. By dividing the blade into small elements, BEMT allows for a detailed analysis of how the chord length, pitch angle, and local flow conditions affect the lift and drag forces generated by each blade section.

The experimental data obtained from static thrust and wind tunnel testing were compared to the predictions made using BEMT. The results showed a good correlation between the experimental thrust values and the BEMT predictions at moderate pitch angles and rotational speeds. This indicates that BEMT is effective in capturing the primary aerodynamic forces acting on the propeller under these conditions (Brandt & Selig, 2011).

However, at high pitch angles and rotational speeds, discrepancies were observed between the experimental results and the BEMT predictions. These discrepancies were primarily attributed to flow separation and non-linear aerodynamic effects that are not fully captured by the simplified assumptions of BEMT. For example, BEMT assumes steady and uniform flow conditions, which do not account for the unsteady wake effects and turbulence that occur during aggressive maneuvers or high-speed flight (Hepperle, 2005).

➢ *Induced Velocity and Angle of Attack Calculation*

One of the critical aspects of BEMT is the calculation of the induced velocity (vi), which affects the effective angle of attack $(\alpha)$experienced by each blade element. The induced velocity is influenced by both the thrust generated by the propeller and the freestream velocity. The effective angle of attack is given by:

$$\alpha = \theta - \tan^{-1}\left(\frac{V_a + V_\omega}{\omega}\right) \tag{51}$$

Where:

$\theta$ is the pitch angle of the blade element,
V is the freestream velocity,
$\omega$ is the angular velocity of the propeller, and
ris the radial position along the blade span (Dommasch et al., 1967).

The calculation of the induced velocity is an iterative process, as it depends on the balance between the thrust produced by the blade elements and the change in momentum of the airflow. This iterative approach allows BEMT to account for the mutual interaction between the blade forces and the induced velocity field, providing a more accurate representation of the aerodynamic behavior of the propeller.

The experimental analysis showed that the induced velocity calculated using BEMT was consistent with the values obtained from wind tunnel testing at moderate thrust levels. However, at high thrust levels, the induced velocity predicted by BEMT was lower than the experimental values, indicating that additional aerodynamic effects, such as wake contraction and blade-vortex interactions, were influencing the flow field (Meschia, 2008).

➢ *Limitations of BEMT in Quadcopter Propeller Analysis*

While BEMT provides a powerful tool for analyzing propeller performance, it has several limitations that must be considered when applying it to quadcopter propellers. One of the primary limitations of BEMT is its assumption of steady, axisymmetric flow. In reality, the flow field around a propeller is highly unsteady, particularly in multirotor configurations where the wakes from multiple propellers interact with each other. This wake interaction can lead to significant variations in thrust and efficiency that are not captured by BEMT (Hartman & Biermann, 1938).

Additionally, BEMT does not account for three-dimensional flow effects, such as radial flow along the blade span and tip vortices, which can have a significant impact on the aerodynamic forces generated by the propeller. These three-dimensional effects become more pronounced at high pitch angles and during aggressive flight maneuvers, where the flow over the blade surface becomes highly complex and difficult to model using simplified two-dimensional blade element analysis (Anderson, 1978).

The accuracy of BEMT is also limited by the need for accurate airfoil data, including lift and drag coefficients (C_L and C_D) for each blade element. The performance of the blade elements is highly dependent on the Reynolds number, which varies along the blade span due to changes in local velocity and

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chord length. Obtaining accurate airfoil data for the wide range of Reynolds numbers experienced by quadcopter propellers is challenging, and inaccuracies in the airfoil data can lead to errors in the BEMT predictions (Brandt & Selig, 2011).

➢ *Improvements to BEMT for Enhanced Accuracy*

To address the limitations of BEMT and improve its accuracy in analyzing quadcopter propellers, several modifications and enhancements can be made:

- Tip Loss Corrections: Tip loss corrections, such as the Prandtl tip loss factor, can be incorporated into BEMT to account for the reduction in lift near the blade tips due to the formation of tip vortices. This correction helps improve the accuracy of lift and induced drag calculations, particularly for propellers with low aspect ratios (Hepperle, 2005).
- Wake Models: Incorporating more sophisticated wake models, such as prescribed wake or free wake models, can help capture the unsteady nature of the flow field around the propeller. These models allow for a more accurate representation of the wake structure and its interaction with the blade elements, improving the prediction of induced velocity and drag (Meschia, 2008).
- CFD Coupling: Coupling BEMT with computational fluid dynamics (CFD) simulations provides a way to account for three-dimensional flow effects and complex aerodynamic phenomena that are not captured by BEMT alone. CFD simulations can provide detailed insights into the flow field around the propeller, which can be used to refine the BEMT predictions and improve overall accuracy (Hartman & Biermann, 1938).

➢ *Summary of Findings*

Blade Element Momentum Theory (BEMT) is a valuable tool for analyzing the aerodynamic performance of quadcopter propellers, providing insights into thrust, torque, and efficiency. The findings from this analysis can be summarized as follows:

- Combination of Theories: BEMT combines Blade Element Theory and Momentum Theory to provide a comprehensive analysis of the aerodynamic forces acting on the propeller and the induced effects on the flow field. This combination allows for the calculation of local lift and drag forces along the blade span, as well as the induced velocity affecting the entire propeller disk.
- Advantages: BEMT is effective in predicting the primary aerodynamic forces acting on the propeller, particularly at moderate pitch angles and rotational speeds. It provides a detailed analysis of how blade geometry and flow conditions affect performance, making it a valuable tool for optimizing propeller design.
- Limitations: BEMT assumes steady, axisymmetric flow and does not account for three-dimensional effects, such as tip vortices and wake interactions. These limitations reduce the accuracy of BEMT in predicting performance under high thrust conditions and during aggressive maneuvers. Accurate airfoil data are also required for reliable predictions.
- Improvements: Tip loss corrections, advanced wake models, and CFD coupling can be used to improve the accuracy of BEMT in analyzing quadcopter propellers. These enhancements help address the limitations of BEMT and provide a more accurate representation of the complex aerodynamic phenomena affecting propeller performance.

The application of BEMT in quadcopter propeller analysis provides valuable insights into the aerodynamic forces and flow interactions that influence performance. By understanding the strengths and limitations of BEMT, designers can use this theoretical framework to optimize propeller geometry and operating conditions, enhancing the efficiency and stability of quadcopter propulsion systems.

### *E. Optimization of Propeller Design Parameters for Enhanced Performance*

Optimizing propeller design parameters is essential for improving the overall performance of quadcopters. Key design parameters such as blade length, pitch angle, chord distribution, twist, and aspect ratio significantly impact thrust, torque, aerodynamic efficiency, and power consumption. This section presents a comprehensive analysis of the optimization of these parameters using both theoretical models and experimental data, focusing on their impact on thrust efficiency, power loading, and stability. Proper optimization can lead to improved flight performance, enhanced energy efficiency, and increased maneuverability.

➢ *Blade Length Optimization*

The length of a propeller blade \left(R\right) is one of the primary factors that determine thrust and power requirements. Longer blades increase the swept area \left(A=\pi R^2\right),allowing a greater volume of air to be accelerated, which increases thrust. However, increasing blade length also leads to greater aerodynamic drag and torque \left(Q\right), which results in higher power consumption \left(P\right):

$$P = 2\pi nQ \tag{52}$$

To optimize blade length, it is important to balance the need for increased thrust with minimizing drag and torque. The experimental results indicated that an optimal blade length exists where thrust generation is maximized while keeping drag and power requirements at acceptable levels (Dommasch, Sherby, & Connolly, 1967). For quadcopters that require high maneuverability, such as those used for aerial photography or racing, shorter blades may be preferred to reduce inertia and enable faster response times, while for applications requiring sustained lift, such as cargo transport, longer blades may be beneficial.

➢ *Pitch Angle Optimization*

The pitch angle (\theta) of the propeller blade has a significant influence on the angle of attack (\alpha) and, consequently, on the lift and drag forces generated. The effective angle of attack is given by:

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$$\alpha = \theta - \tan^{-1}\left(\frac{V_a + V_\omega}{\omega}\right) \quad (53)$$

Where:

$\theta$ is the blade pitch angle,
Va is the advance velocity,
Vi is the induced velocity, and
$\omega$ is the angular velocity (Anderson, 1978).

The experimental data showed that increasing the pitch angle initially increased the lift and thrust generated by the propeller. However, at higher pitch angles, the increased angle of attack led to flow separation and stall, which significantly increased drag and reduced efficiency. Therefore, the pitch angle must be optimized to achieve the desired thrust output while avoiding excessive aerodynamic losses.

The results indicated that moderate pitch angles provided the highest thrust efficiency (T) and power loading (PL), particularly during hovering and low-speed flight conditions. For forward flight, a slightly lower pitch angle was optimal to minimize drag and improve efficiency. It is important to select a pitch angle that balances lift production with drag minimization, depending on the specific flight requirements of the quadcopter (Hepperle, 2005).

➢ *Chord Distribution Optimization*

The chord distribution calong the blade span influences the lift distribution and the formation of tip vortices, which affect both thrust and drag. A well-designed chord distribution helps to maintain a uniform lift coefficient (C_L) along the blade span, which improves aerodynamic efficiency and reduces induced drag. The lift generated by a blade element is given by:

$$dL = \frac{1}{2}\rho A V_{rel}^2 c C_L dr \quad (54)$$

Where:

Vrel is the local relative velocity, and
dr is the length of the blade element (Dommasch et al., 1967).

The experimental analysis indicated that a tapered chord distribution, where the chord length decreases towards the blade tip, was effective in reducing the intensity of tip vortices, which are a significant source of induced drag. The reduction in tip vortex intensity led to improved thrust efficiency and reduced power consumption. The taper ratio must be carefully chosen to achieve a balance between lift distribution and drag minimization, particularly for high-speed flight or aggressive maneuvers (Hartman & Biermann, 1938).

➢ *Blade Twist Optimization*

Blade twist is an essential design feature used to ensure a consistent angle of attack ($\alpha$) along the blade span. The relative velocity experienced by the blade elements varies with radial position, leading to different angles of attack along the span. Blade twist helps to compensate for these variations, maintaining an optimal angle of attack from root to tip.

The experimental results demonstrated that twisted blades provided a more uniform lift distribution and reduced the likelihood of flow separation, particularly near the blade root and tip. This improved the overall aerodynamic efficiency of the propeller and led to a reduction in induced drag. The degree of blade twist must be optimized based on the desired flight characteristics, with greater twist beneficial for improving efficiency during hovering and low-speed operations (Meschia, 2008).

➢ *Aspect Ratio and Tip Design Optimization*

The aspect ratio (AR) of a propeller blade, defined as the ratio of blade length (R) to chord length (c), plays a crucial role in determining induced drag and aerodynamic efficiency. Higher aspect ratios generally lead to reduced induced drag due to lower tip vortex intensity:

$$C_{D_i} = \frac{C_L^2}{\pi e AR} \quad (55)$$

Where:

$C_L$ is the lift coefficient,
e is the span efficiency factor, and
AR is the aspect ratio (Anderson, 1978).

The experimental analysis indicated that propellers with higher aspect ratios exhibited better aerodynamic performance, particularly in terms of reducing induced drag and improving thrust efficiency. However, higher aspect ratios also lead to structural challenges, as longer, narrower blades are more prone to bending and deformation under aerodynamic loads. To optimize the aspect ratio, a balance must be achieved between reducing drag and maintaining sufficient blade strength and stiffness (Hepperle, 2005; Idoko et al, 2024).

In addition to aspect ratio, tip design plays an important role in minimizing induced drag. The experimental results showed that adding winglets or other tip modifications to the blade tips reduced the intensity of tip vortices, which in turn decreased induced drag and improved efficiency. These modifications are particularly useful in multirotor configurations, where wake interactions between adjacent rotors can exacerbate the effects of tip vortices (Hartman & Biermann, 1938).

➢ *Summary of Findings*

The optimization of propeller design parameters is essential for achieving enhanced performance in quadcopter propulsion systems. The findings from this analysis can be summarized as follows:

- Blade Length: Longer blades increase thrust but also lead to greater drag and power requirements. The optimal blade length depends on the specific flight requirements, with a balance needed between thrust generation and minimizing aerodynamic losses.

- Pitch Angle: Moderate pitch angles provide the best balance between thrust generation and aerodynamic efficiency. Excessively high pitch angles lead to flow separation and stall, which increase drag and reduce efficiency.
- Chord Distribution: A tapered chord distribution is effective in reducing tip vortex intensity and induced drag, leading to improved aerodynamic performance. The taper ratio must be optimized to balance lift distribution and drag minimization.
- Blade Twist: Blade twist helps maintain a consistent angle of attack along the blade span, reducing flow separation and improving aerodynamic efficiency. The degree of twist must be optimized based on the desired flight characteristics.
- Aspect Ratio and Tip Design: Higher aspect ratios reduce induced drag but present structural challenges. Tip modifications, such as winglets, are effective in reducing tip vortices and enhancing aerodynamic performance.

By optimizing these design parameters, propeller manufacturers can develop propulsion systems that provide improved thrust efficiency, power loading, and stability for quadcopters. The insights gained from both theoretical analysis and experimental data are essential for guiding the design process to achieve the desired performance characteristics for a wide range of flight applications.

## V. RECOMMENDATION AND CONCLUSION

### *A. Summary of Key Findings*

The comprehensive analysis of quadcopter propeller performance presented in this study has highlighted several critical aspects that significantly influence the aerodynamic characteristics, thrust generation, power consumption, and overall efficiency of propellers. Key findings from this research are summarized as follows:

➢ *Blade Geometry and its Impact on Performance*

The geometry of the propeller blade, including blade length, chord distribution, pitch angle, aspect ratio, and twist, plays a vital role in determining its aerodynamic performance. Blade length influences the volume of air accelerated by the propeller, thereby affecting thrust and power requirements. Longer blades increase the thrust generated but also lead to higher aerodynamic drag and torque. The optimization of blade length is crucial for balancing thrust with minimal power consumption, depending on the specific flight requirements of the quadcopter.

The pitch angle is essential in determining the effective angle of attack experienced by the blade elements. Moderate pitch angles result in the best trade-off between thrust and efficiency, whereas excessively high pitch angles lead to flow separation and increased drag, which reduces efficiency. The chord distribution and blade twist are also critical factors in improving aerodynamic efficiency by ensuring a consistent lift distribution and reducing the intensity of tip vortices.

➢ *Environmental Effects on Propeller Performance*

Environmental factors such as air density, temperature, altitude, and wind conditions have significant impacts on propeller performance. Air density directly affects the thrust produced, with higher altitudes and elevated temperatures reducing air density, thereby leading to reduced thrust and increased power consumption. Wind conditions, including crosswinds and turbulence, affect the effective angle of attack and stability of the quadcopter, making the optimization of propeller design and rotor spacing essential for ensuring consistent performance in varying atmospheric conditions.

➢ *Influence of Tip Vortices on Efficiency*

Tip vortices are generated due to the pressure differential between the upper and lower surfaces of the blade and significantly contribute to induced drag. This induced drag reduces the effective angle of attack and negatively impacts thrust efficiency. Mitigating the adverse effects of tip vortices through blade twist, tapered chord distribution, and the addition of winglets at the blade tips can help reduce induced drag and improve aerodynamic efficiency. Tip vortex interactions are particularly challenging in multirotor configurations, where the wakes of adjacent rotors interact, leading to stability issues and reduced performance.

➢ *Blade Element Momentum Theory in Performance Analysis*

Blade Element Momentum Theory (BEMT) provides an effective method for analyzing propeller performance by combining local blade element analysis with overall momentum considerations. BEMT has proven effective in predicting thrust, torque, and efficiency under moderate pitch angles and rotational speeds. However, the limitations of BEMT—such as its assumption of steady, axisymmetric flow—reduce its accuracy at high thrust levels and during unsteady flight conditions. Improvements to BEMT, including the use of tip loss corrections, advanced wake models, and coupling with computational fluid dynamics (CFD), can enhance its accuracy in predicting the complex aerodynamic effects influencing propeller performance.

➢ *Optimization of Design Parameters for Enhanced Performance*

Optimizing propeller design parameters is essential for achieving enhanced performance. Blade length must be chosen to balance thrust production and drag minimization, while the pitch angle must be optimized to provide the best lift-to-drag ratio without inducing flow separation. The use of a tapered chord distribution and appropriate blade twist significantly reduces induced drag and improves efficiency. Higher aspect ratios are beneficial for reducing induced drag, but structural considerations must be taken into account to ensure blade strength and stiffness. Tip modifications, such as winglets, are effective in mitigating vortex effects, particularly in multirotor configurations.

These key findings provide valuable insights into the factors that influence the aerodynamic performance of quadcopter propellers. By understanding the interactions between blade geometry, environmental factors, tip vortices, and aerodynamic forces, propeller designs can be optimized to achieve improved thrust efficiency, power loading, and overall flight performance. This research provides a foundation for further advancements in the design and development of efficient and high-performance propeller systems for quadcopters and other aerial vehicles.

*B. Impact of Findings on Quadcopter Propeller Design and Performance*

The findings from this study have significant implications for the design and performance of quadcopter propellers, providing valuable insights into optimizing propeller characteristics for improved aerodynamic efficiency, thrust, power consumption, and stability. The impact of these findings can be summarized as follows:

- *Optimization of Blade Geometry for Specific Flight Conditions*

The detailed analysis of blade geometry has shown that each design parameter—blade length, pitch angle, chord distribution, twist, and aspect ratio—has a specific impact on quadcopter performance. By optimizing these parameters, propeller manufacturers can tailor propeller designs to specific flight conditions and applications. For instance, longer blades with moderate pitch angles are ideal for applications requiring higher lift, such as cargo transport, while shorter blades with high aspect ratios are better suited for agility and rapid response, as required in drone racing or surveillance. This tailored approach can significantly enhance the performance, energy efficiency, and operational versatility of quadcopters.

- *Enhanced Efficiency through Environmental Adaptation*

The findings related to environmental effects on propeller performance highlight the need for propeller designs that can adapt to changing atmospheric conditions, such as variations in air density, temperature, and wind. Propeller blades optimized for high altitudes must account for reduced air density and compensate by adjusting pitch angle or rotational speed to maintain thrust efficiency. Additionally, understanding how wind conditions affect stability provides insight into designing control algorithms and rotor configurations that maintain consistent thrust and flight stability under turbulent conditions.

- *Mitigation of Tip Vortex Effects for Improved Stability and Power Efficiency*

The analysis of tip vortices demonstrated the negative effects of induced drag on aerodynamic efficiency. By incorporating design elements such as blade twist, tapered chord distribution, and winglets, propeller designs can mitigate these effects and significantly improve efficiency. These modifications are particularly important for multirotor systems, where interactions between tip vortices from adjacent rotors can lead to reduced stability and uneven thrust distribution. The implementation of these design improvements can lead to more stable flight performance and better power efficiency, reducing the energy demands of quadcopters.

- *Limitations of BEMT and Pathways for Improvement*

Blade Element Momentum Theory (BEMT) has been shown to be a powerful tool for propeller performance analysis but has limitations when predicting performance under dynamic flight conditions or when accounting for complex aerodynamic effects such as three-dimensional flow or unsteady wake interactions. The findings suggest that improvements to BEMT, such as incorporating tip loss corrections, wake models, or coupling with CFD, are necessary for accurately modeling quadcopter propeller performance. By enhancing the accuracy of BEMT, propeller designers can achieve more reliable performance predictions, enabling better optimization of blade geometry and operating conditions.

- *Energy Efficiency and Power Loading Considerations*

The findings emphasize the importance of optimizing propeller design to achieve maximum thrust efficiency and power loading. Maintaining a high power loading ratio is crucial for ensuring that the quadcopter can produce sufficient thrust while minimizing power consumption. The study found that optimal combinations of pitch angle, blade twist, aspect ratio, and rotational speed significantly impact power requirements and energy efficiency. Incorporating these optimized parameters into propeller design can lead to reduced power consumption and extended flight times, which are critical for both consumer and commercial quadcopters.

- *Applications in Quadcopter Development and Future Research*

The insights gained from this study can be directly applied to the development of next-generation quadcopter propellers. The ability to optimize propeller characteristics for specific flight conditions allows for the development of specialized drones that excel in their intended applications, whether for aerial photography, cargo delivery, racing, or surveillance. Additionally, the findings provide a foundation for future research into propeller design, including the exploration of advanced materials, active control surfaces, and innovative blade geometries that can further enhance aerodynamic performance and efficiency.

The findings of this study have a substantial impact on the design, optimization, and performance of quadcopter propellers. By applying the insights gained from this research, designers and engineers can create more efficient, stable, and high-performing propulsion systems for a wide range of quadcopter applications. The adoption of optimized blade geometries, environmental adaptation strategies, and advanced theoretical models will drive the next generation of drone technology, improving flight performance and expanding the capabilities of quadcopters in various domains.

*C. Recommendations for Future Quadcopter Propeller Design*

Based on the findings of this study, several recommendations can be made to enhance the performance, efficiency, and adaptability of quadcopter propellers. These recommendations focus on optimizing propeller design parameters, improving adaptability to environmental conditions, enhancing aerodynamic modeling, and exploring advanced materials and technologies.

- *Tailored Blade Geometry for Application-Specific Performance*

Quadcopter applications vary widely—from aerial photography to racing and cargo transport—each requiring a different balance of thrust, agility, and endurance. Therefore, it is recommended that propeller blade geometry, including blade length, pitch angle, chord distribution, twist, and aspect ratio, be tailored to the specific flight profile and operational needs of the drone. For example:

- Longer Blades with Moderate Pitch Angles: Suitable for drones requiring higher thrust and load-carrying capacity, such as cargo or heavy-lift drones.
- Shorter Blades with Higher Aspect Ratios: Appropriate for racing or agile drones where maneuverability and quick response are prioritized.

Optimization of these parameters will improve the efficiency and functionality of quadcopters for their intended use.

➢ *Adaptive Design for Environmental Conditions*

Propeller designs should incorporate features that allow adaptation to varying environmental conditions such as altitude, temperature, and wind. Adaptive pitch mechanisms could be implemented to adjust the pitch angle in response to changes in air density or wind conditions. This would enhance the performance and efficiency of quadcopters operating in diverse environments, such as high-altitude locations or areas with significant temperature fluctuations. Incorporating sensors to detect environmental parameters and adjusting propeller operation dynamically will help maintain optimal performance and reduce energy consumption.

➢ *Advanced Tip Designs to Mitigate Vortex Effects*

Tip vortices are a significant source of induced drag, reducing aerodynamic efficiency and contributing to increased power consumption. It is recommended to explore advanced tip designs, such as the addition of winglets or swept-back blade tips, to reduce the formation of strong tip vortices. These features can help in mitigating the negative effects of tip vortices, improving both thrust efficiency and stability. In multirotor configurations, special attention should be paid to tip design and rotor spacing to reduce the impact of wake interactions between adjacent propellers, which can affect overall flight stability.

➢ *Improvements to Blade Element Momentum Theory (BEMT)*

The study has highlighted the limitations of BEMT, particularly under unsteady flight conditions and in modeling complex aerodynamic phenomena. To address these limitations, it is recommended to enhance BEMT by incorporating:

- Tip Loss Corrections: To account for the reduction in lift near blade tips, leading to more accurate predictions of thrust and drag.
- Advanced Wake Models: Including free or prescribed wake models to capture unsteady wake effects and better represent the real flow conditions around the propeller.
- CFD Coupling: Integrating BEMT with computational fluid dynamics (CFD) to model three-dimensional flow effects and non-linear aerodynamic interactions, resulting in more reliable performance predictions.

Such enhancements would provide a more accurate understanding of the aerodynamic behavior of quadcopter propellers, leading to better design optimization.

➢ *Exploration of Advanced Materials and Structural Design*

Propeller blades are subject to significant aerodynamic loads, and optimizing their design requires the use of materials that provide a balance between strength, weight, and flexibility. Future propeller designs should consider:

- Lightweight Composite Materials: To reduce weight while maintaining sufficient structural strength. Advanced composite materials, such as carbon fiber reinforced polymers, can help achieve this balance, improving efficiency by reducing inertia and enabling faster response times.
- Flexible and Adaptive Blades: Flexible blades that adapt to varying aerodynamic loads can help maintain optimal lift distribution and reduce drag. Materials with adaptive properties, such as shape memory alloys, could be explored to create propellers that adjust their geometry based on flight conditions, enhancing performance and efficiency.

➢ *Dynamic Performance Monitoring and Control Systems*

The findings indicate that propeller performance is highly dependent on the interplay between blade geometry, environmental conditions, and aerodynamic forces. Therefore, it is recommended to incorporate real-time performance monitoring and dynamic control systems into the quadcopter's flight controller. By continuously monitoring parameters such as thrust, torque, airspeed, and environmental factors, the propeller's operational parameters can be adjusted dynamically to maintain optimal performance. Such adaptive control systems would be particularly useful for drones operating in challenging environments, where conditions are constantly changing.

➢ *Application-Specific Blade Element Optimization*

For specialized applications, such as surveillance, agricultural spraying, or package delivery, optimizing each blade element individually can lead to significant improvements in performance. For instance, optimizing chord length and pitch angle along the span of the blade for a specific speed range or flight condition can improve aerodynamic efficiency. The use of machine learning algorithms to optimize blade element design based on performance data from previous flights could lead to smarter, more efficient propeller configurations that adapt to specific mission requirements.

➢ *Energy Efficiency and Power Management*

The optimization of power consumption is critical for extending flight times, especially for battery-powered quadcopters. It is recommended to develop propeller designs that maximize power loading and minimize induced drag under varying flight conditions. The implementation of efficient blade geometries that adapt to power requirements during different phases of flight—such as takeoff, hover, and forward flight—will improve overall energy efficiency. Furthermore, optimizing the aerodynamic characteristics of propellers to reduce power consumption will be essential in enhancing the operational capabilities of drones for longer missions.

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➢ *Future Research Directions*

Future research should focus on expanding the understanding of complex aerodynamic phenomena that affect propeller performance, such as unsteady wake interactions, tip vortex behavior, and non-linear flow effects. Experimental validation of theoretical models, particularly under dynamic flight conditions, will be essential in refining propeller design methodologies. Exploring novel propulsion technologies, such as distributed electric propulsion or bio-inspired blade geometries, may also provide new pathways for improving quadcopter efficiency and versatility.

The recommendations outlined above provide a comprehensive guide for optimizing quadcopter propeller designs to enhance aerodynamic efficiency, thrust generation, stability, and energy efficiency. By tailoring blade geometry to specific flight conditions, incorporating adaptive features, reducing the effects of tip vortices, and exploring advanced materials and technologies, the next generation of quadcopter propellers can achieve superior performance across a wide range of applications. These recommendations form the foundation for ongoing advancements in drone technology, contributing to the development of more efficient, agile, and reliable quadcopters for diverse uses.

### D. Summary

This study has provided an in-depth exploration of the factors affecting quadcopter propeller performance, including blade geometry, environmental conditions, aerodynamic phenomena like tip vortices, and optimization methodologies. Key findings indicate that blade design parameters—such as blade length, pitch angle, chord distribution, twist, and aspect ratio—play a critical role in determining thrust, torque, aerodynamic efficiency, and power requirements. Properly optimized propeller geometries enhance thrust efficiency, reduce power consumption, and provide stability, which is crucial for different quadcopter applications ranging from cargo lifting to aerial photography.

The influence of environmental factors, such as air density, temperature, and wind conditions, was examined, demonstrating their significant impact on propeller efficiency and performance. Tip vortices, a major contributor to induced drag, were analyzed, with solutions including advanced blade tip modifications and geometric adjustments proposed to mitigate their negative effects.

The application of Blade Element Momentum Theory (BEMT) was also discussed as a valuable tool for propeller analysis, providing insights into aerodynamic behavior and performance. However, limitations in accurately modeling dynamic flight conditions were identified, with improvements such as tip loss corrections, advanced wake models, and coupling with computational fluid dynamics (CFD) recommended for enhanced accuracy.

The recommendations for future quadcopter propeller design include tailoring blade geometries for specific applications, incorporating adaptive features to respond to environmental changes, utilizing advanced materials for improved strength-to-weight ratios, and exploring advanced modeling techniques to improve accuracy in performance predictions. These recommendations aim to achieve optimal propeller efficiency, stability, and energy conservation across a variety of flight scenarios.

This study offers a foundational understanding of the complex interactions between propeller design, environmental conditions, and aerodynamic performance. By applying the findings and recommendations from this research, quadcopter designers and engineers can create more efficient, reliable, and high-performing propulsion systems, thus expanding the capabilities and effectiveness of quadcopters in diverse operational contexts. The continuous evolution of propeller technology will enable the next generation of drones to operate with enhanced efficiency, stability, and versatility, meeting the growing demands of modern aerial applications.

### E. Future Research Directions

The findings from this study provide valuable insights into quadcopter propeller performance, yet there remain several areas that warrant further investigation to fully optimize propeller designs for diverse applications. Future research directions are suggested to build upon the current understanding and address the limitations identified in this study.

➢ *Advanced Propeller Materials and Adaptive Technologies*

Future research should focus on the exploration of advanced materials for propeller construction. Composite materials, such as carbon fiber and lightweight polymers, have the potential to provide superior strength-to-weight ratios, enhancing propeller performance and efficiency. The use of adaptive materials, such as shape memory alloys, could allow for real-time adjustments to blade geometry, such as pitch angle or twist, in response to changing flight conditions. This adaptability could lead to improved efficiency and enhanced maneuverability across different flight regimes.

➢ *Enhanced Aerodynamic Modeling Techniques*

The limitations of Blade Element Momentum Theory (BEMT), particularly in predicting propeller performance under dynamic flight conditions, call for the development of enhanced modeling techniques. Future research could focus on coupling BEMT with computational fluid dynamics (CFD) simulations to capture complex three-dimensional flow effects, such as radial flow, tip vortex interactions, and non-linear aerodynamic behaviors. Incorporating advanced wake models, such as free wake or prescribed wake models, could also improve the accuracy of aerodynamic predictions, particularly in multirotor configurations where rotor-rotor interactions significantly impact performance.

➢ *Optimized Propeller Designs for Specific Applications*

Different quadcopter applications—ranging from aerial surveillance to agriculture and logistics—require unique propeller characteristics. Future research should investigate the development of application-specific propeller designs, with a focus on optimizing blade geometry, material selection, and control algorithms based on the requirements of each use case. Machine learning and optimization algorithms could be employed to evaluate performance data and iteratively improve propeller design for specific operational scenarios, leading to tailored solutions that maximize efficiency and performance.

- *Real-Time Performance Adaptation and Control Systems*

The findings emphasize the importance of maintaining optimal performance across different flight conditions, which requires real-time adaptation of propeller characteristics. Future research should explore the integration of advanced sensor systems that monitor environmental conditions, such as wind speed, air density, and temperature, along with onboard performance metrics like thrust and torque. These sensors could feed data into adaptive control algorithms that adjust propeller speed, pitch angle, or other parameters dynamically to ensure optimal efficiency and stability throughout flight. The development of intelligent, real-time adaptation systems could significantly extend flight times and enhance operational reliability.

- *Impact of Environmental Conditions on Aerodynamic Efficiency*

The study highlighted the significant impact of environmental factors such as temperature, altitude, and wind conditions on propeller performance. Future research could focus on a more in-depth analysis of these environmental influences, including experimental studies conducted under a wide range of atmospheric conditions. Understanding the aerodynamic performance of propellers under extreme environments, such as high-altitude or high-temperature conditions, could inform the design of more robust and adaptable propeller systems. Additionally, the impact of varying humidity on aerodynamic forces and efficiency could be explored further, as it was not comprehensively addressed in this study.

- *Investigation of Wake Interaction Effects in Multirotor Systems*

In multirotor configurations, the interaction of tip vortices between adjacent propellers can lead to uneven thrust distribution, reduced stability, and lower efficiency. Future research should focus on characterizing these wake interactions in detail, using both experimental and computational approaches to understand their effects on performance. Developing strategies to mitigate adverse wake interactions, such as optimizing rotor spacing, employing counter-rotating propeller pairs, or utilizing blade tip modifications, could enhance the stability and efficiency of multirotor systems. These strategies are essential for advancing the capabilities of quadcopters operating in confined or turbulent environments.

- *Exploration of Bio-Inspired Propeller Designs*

Nature offers a wealth of inspiration for propeller design, particularly from flying insects and birds that have evolved efficient mechanisms for lift generation and maneuverability. Future research could explore bio-inspired propeller designs that mimic the wing shapes and kinematics of birds or insects. Features such as flexible blades, variable camber, and oscillatory motion could be investigated for their potential to improve thrust efficiency and flight agility. Bio-inspired designs have the potential to provide innovative solutions for overcoming the aerodynamic limitations of traditional fixed-blade propellers.

- *Development of Noise-Reduction Techniques*

Noise is a major concern for quadcopter applications, particularly in urban environments and for drones used for surveillance or recreational purposes. The generation of tip vortices and their interaction with the airflow contributes significantly to propeller noise. Future research could focus on developing noise-reduction techniques, such as optimizing blade shape, tip modifications, and the use of advanced materials that dampen vibrations. Reducing noise levels not only enhances the usability of quadcopters in populated areas but also improves the efficiency of propellers by reducing energy lost to sound production.

- *Experimental Validation Under Real-World Conditions*

Finally, there is a need for extensive experimental validation of the theoretical models and optimization strategies proposed in this study under real-world flight conditions. Field testing under different environmental conditions, flight modes, and load configurations is essential for validating the performance improvements achieved through optimized propeller designs. The results from these real-world tests would provide valuable feedback for further refining the design process and ensuring that the propeller optimizations translate into practical performance gains.

In conclusion, future research should focus on the development of advanced materials, enhanced aerodynamic models, adaptive control systems, and application-specific propeller designs to further improve the performance of quadcopters. By addressing the identified limitations and exploring innovative design solutions, future studies can pave the way for more efficient, versatile, and capable quadcopters, capable of meeting the diverse demands of modern aerial applications. These efforts will contribute to the advancement of drone technology, pushing the boundaries of what quadcopters can achieve in terms of efficiency, stability, and operational reliability.

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