# DESIGN AND ANALYSIS OF PROPELLER WITH THE WINGLETS FOR IMPROVED UAV PERFORMANCE

*A PROJECT REPORT*

*submitted to*

**SRM INSTITUTE OF SCIENCE & TECHNOLOGY**

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# SRM INSTITUTE OF SCIENCE TECHNOLOGY

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This is to certify that the Seminar report entitled submitted by Certified that this project report titled "DESIGN AND ANALYSIS OF PROPELLER WITH WINGLET FOR ENHANCED UAV PERFORMANCE " is the bona-fide work of **MOHAMED NAVAZ FAHIR, LALIT KISHORE , KRISHA KOTIAN** who carried out the project work under my supervision. Certified further, that to the best of my knowledge the work reported herein does not form any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

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# ABSTRACT

**Keywords:** UAV Propeller, Winglet, NACA 4412, Thrust Optimization, Induced Drag, 3D Printing, Experimental Analysis

This study focuses on the aerodynamic enhancement of a 7-inch UAV propeller by integrating winglet geometries at the blade tips. The primary aim is to reduce induced drag and improve thrust efficiency through the use of three different winglet configurations—vertical winglet, wingtip fence, and backswept winglet—modeled using NACA 4412 airfoil. The propellers were designed in CATIA V5, fabricated using ABS via FDM 3D printing, and tested experimentally using a custom thrust measurement setup.

Results showed that the vertical winglet configuration delivered the highest thrust improvement, with notable performance gains across increasing RPM values. The wingtip fence showed moderate improvement, while the backswept winglet provided the least thrust benefit. The study concludes that proper winglet integration at the tip can enhance UAV propeller efficiency, offering a cost-effective modification to improve endurance and overall performance.

# ACKNOWLEDGEMENT

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of UAV Propulsion and Propeller Aerodynamics

Unmanned Aerial Vehicles (UAVs) have become indispensable in fields such as surveillance, agriculture, delivery, environmental monitoring, and defense. Their performance, endurance, and efficiency are strongly influenced by the propulsion system, with the propeller playing a critical role in generating thrust and maintaining stability. For small to medium-sized UAVs, fixed-pitch, electric motor-driven propellers are commonly used due to their simplicity and reliability.

Propeller aerodynamics is primarily governed by lift and drag forces acting along the rotating blades. Unlike stationary wings, propeller blades experience varying angles of attack and relative velocities from root to tip. The resulting aerodynamic performance is a function of blade geometry including airfoil profile, pitch, twist, and chord distribution. However, one of the primary sources of aerodynamic inefficiency in propellers is the formation of tip vortices, which contribute to induced drag and energy losses.

## 1.2 Motivation for Winglet Integration in UAV Propellers

Winglets have been widely used in fixed-wing aircraft to reduce induced drag and improve aerodynamic efficiency. These small, upward or outward extensions at the wingtips mitigate the strength of trailing vortices by redirecting airflow and reducing pressure differentials. Translating this concept to UAV propellers, winglets have the potential to suppress vortex formation at blade tips, resulting in lower energy loss and improved thrust efficiency.

This project aims to explore the aerodynamic advantages of propeller winglets through a performance analysis, providing insight into how such modifications can enhance the functionality of UAV propulsion systems.

## 1.3 Problem Statement

One of the persistent challenges in propeller-driven UAVs is the formation of tip vortices spiral-shaped flows generated by pressure differences between the upper and lower surfaces of the rotating blades. These vortices contribute significantly to induced drag, which reduces overall thrust and propulsive efficiency. In the case of small UAVs where power availability and endurance are limited, minimizing such losses becomes essential. The problem addressed in this study is how to reduce tip vortex formation through geometric modifications, specifically by integrating winglets at the blade tips to achieve enhanced aerodynamic performance without significant structural complexity or additional weight.

## 1.4 Applications in UAVs

Propeller winglet designs are particularly beneficial in small and medium-sized UAVs where efficiency, endurance, and stability are critical. These applications include aerial surveillance, mapping, agricultural monitoring, and delivery drones. By reducing induced drag and enhancing thrust output, winglet-integrated propellers can extend flight time, improve maneuverability, and reduce energy consumption, making them well-suited for missions requiring high aerodynamic efficiency and longer range.

## 1.5 Advantages and Disadvantages

The main advantages of integrating winglets into UAV propellers include improved thrust generation, reduced tip vortices, and increased aerodynamic efficiency. These benefits can lead to quieter operation, better fuel or battery usage, and smoother performance in windy or turbulent conditions. However, there are also disadvantages, such as increased design complexity, additional fabrication steps, and potential structural concerns due to added components at the propeller tip. Additionally, improper winglet design may lead to adverse flow effects or imbalances, potentially reducing the overall effectiveness if not optimized carefully.

# CHAPTER 2

# LITERATURE SURVEY

## 2.1 INTRODUCTION

A significant amount of research has been conducted on propeller aerodynamics, airfoil selection, tip modifications, and winglet integration for UAVs and other aerial vehicles. This literature survey summarizes eight key studies that provide a foundation for the current work on optimizing UAV propeller performance through winglet modifications.

## 2.2 BACKROUND

This study investigates various geometric modifications to UAV propellers such as ducted blades, twisted profiles, and sinusoidal leading edges under low Reynolds number conditions. The researchers used CFD simulations to evaluate lift, stall behavior, and thrust. Their results showed that sinusoidal leading edges improved lift by approximately 7% and delayed stall. While this study did not consider winglets, it demonstrates how small changes at the blade tip can lead to meaningful aerodynamic improvements, providing relevant insight for tip modification strategies. (Singh et al., 2020)

The authors compared the aerodynamic performance of three airfoils NACA 0012, S809, and NACA 4412 by conducting CFD simulations to analyze flow characteristics, tip vortex formation, and pressure distribution. Among the tested profiles, NACA 4412 displayed superior lift and pressure recovery, especially in low-speed UAV applications. This finding supports the use of NACA 4412 in propeller designs where aerodynamic efficiency and low-speed stability are essential, making it a suitable choice for winglet integration. (Ahmed & Raza, 2021)

This research evaluated a mathematically designed UAV propeller using the Eppler E63 airfoil and compared its thrust performance with APC Slow Flyer and NACA 4412 propellers. The study employed CFD simulations and observed that the Eppler E63 airfoil offered better thrust output at lower RPMs due to its high-lift geometry. However, the current project opts for NACA 4412 owing to its greater structural suitability for winglet modifications, despite the E63's efficiency advantage. (Mishra & Kulkarni, 2022)

This study performed a parametric optimization of novel winglet designs including multi-tip, twisted, bird-type, and wingtip fence configurations using the NASA Common Research Model. Employing CFD simulations and Taguchi methods, the researchers identified that design factors like cant angle and taper ratio significantly influence aerodynamic performance. The multi-tip and bird-type winglets showed up to 18% improvement in lift-to-drag ratio. While focused on aircraft wings, the insights are applicable to optimizing UAV propeller winglets. (Kumar & Thomas, 2021)

This CFD-based study analyzed how various winglet shapes including simple, blended, and wingtip fence types affect secondary flow and vortex formation on UAV wings with an Eppler 562 airfoil. Among the tested configurations, wingtip fences were most effective at reducing tip vortices and enhancing upper surface pressure retention. These findings support the integration of wingtip fences in propeller design for improved aerodynamic stability and reduced induced drag. (Chen & Zhao, 2020)

This research investigated how blade tip modifications such as swept-back tips, leading-edge tubercles, and serrated trailing edges affect both aerodynamic efficiency and noise levels in Urban Air Mobility (UAM) vehicles. The results showed up to 8 dB noise reduction with minimal impact on thrust performance. The aerodynamic advantages of swept and serrated tips validate the inclusion of swept-back winglets in this study's test configurations, reinforcing the idea that tip geometry significantly affects propeller behavior. (Lopez & Nakamura, 2021)

This study explored the use of Gurney flaps and vortex generators on the Eppler 423 airfoil to enhance lift and flow attachment. The results indicated that small Gurney flaps increased lift by improving effective camber, while vortex generators delayed stall by controlling boundary layer separation. Although the research was airfoil-focused, it parallels the objective of this study by showing how minor aerodynamic add-ons can significantly improve performance, supporting the rationale for using winglets in propeller applications. (Patel & Banerjee, 2019)

The authors conducted a comparative CFD analysis of propellers designed with Eppler E63, APC Slow Flyer, and NACA 4412 airfoils under different temperature conditions. While the E63 outperformed others in thrust at low RPMs, NACA 4412 was preferred in this project due to its ease of structural modification and suitability for integrating winglets. The study's methodology featuring twist and chord optimization provides a relevant framework for the experimental approach used in the current research. (Ravi & Jadhav, 2023)

## 2.3 RESEARCH GAP

Across the reviewed studies, extensive CFD-based investigations have been conducted on airfoil performance**,** blade geometry**,** and winglet optimization, often with a focus on fixed-wing aircraft **or** noise reduction**.** However, there is a lack **o**f experimental, RPM-based evaluation of winglet configurations specifically applied to small UAV propellers**.** Most of the existing literature also relies heavily on numerical simulation methods (CFD)**,** with limited real-world testing.

This project addresses this gap by experimentally analyzing the influence of winglet shapes vertical, swept-back, and wingtip fence on thrust output across an RPM range of 4000-7000 using NACA 4412 airfoil-based propellers**.** By excluding CFD and focusing on practical testing, this study provides novel insights into how physical modifications at the blade tip can lead to measurable performance gains in UAV propulsion.

# CHAPTER 3

# OBJECTIVE AND SCOPE

## 3.1 Objectives of the Study

The primary goal of this study is to evaluate the aerodynamic benefits of integrating winglets into UAV propeller designs, with a focus on enhancing thrust performance and reducing energy losses due to tip vortices. This will be achieved through experimental thrust testing across a range of rotational speeds (RPMs), comparing standard propellers with winglet-equipped variants. The specific objectives are:

### 3.1.1 To study the aerodynamic performance of UAV propellers through thrust measurements

This involves evaluating how thrust varies with RPM for a baseline (no winglet) propeller. Measurements will be taken using a calibrated thrust test stand to establish reference performance data under controlled conditions.

### 3.1.2 To design and fabricate UAV propellers with integrated winglets

Various winglet configurations such as vertical winglets, blended winglets, and wingtip fences will be integrated into the tip geometry of the baseline propeller. These designs will be modeled using CAD software and manufactured using appropriate prototyping methods (e.g., 3D printing).

### 3.1.3 To perform comparative thrust testing of winglet-integrated propellers

Each winglet-equipped propeller will be tested at multiple RPM levels to measure thrust output and evaluate how tip modifications influence performance. This comparison will help quantify the potential aerodynamic benefits of winglet designs in real-world conditions.

### 3.1.4 To determine the most effective winglet configuration for performance enhancement

Based on the experimental thrust data, the winglet design that yields the highest improvement in thrust generation especially at critical RPM ranges will be identified as the optimum configuration. The outcome will help guide future propeller development for UAV applications.

## 3.2 Scope and Limitations

### 3.2.1 Scope

This project focuses on the design, fabrication, and experimental evaluation of UAV propellers integrated with various winglet configurations to enhance aerodynamic performance. The main area of analysis is thrust measurement across a range of RPMs (4000–7000), using a physical test setup. Key aspects within the scope include:

- Designing propeller geometries with and without winglets (vertical and wingtip fence designs)
- Fabricating these propellers using 3D printing or other rapid prototyping methods
- Conducting thrust tests at RPMs between 4000 and 7000 to measure performance differences
- Comparing the thrust output of different designs to identify the most effective winglet configuration
- Evaluating how tip modifications influence propeller efficiency and potential improvements for UAV applications

### 1.5.2 Limitations

- The analysis is limited to thrust measurement only; no force balance testing or drag/lift component separation is conducted.
- The RPM range for testing is restricted to 4000–7000, typical of small UAV propulsion systems.
- Only a specific propeller design and airfoil (e.g., NACA 4412) is used to ensure design consistency.
- Structural analysis (e.g., material stress, fatigue) and CFD simulations are not included in this study.

# CHAPTER 4
# METHODOLOGY

## 4.1 Design Objective

The primary objective of the propeller design in this study is to enhance the aerodynamic performance of small UAVs by integrating winglets that mitigate tip vortex losses. By refining blade geometry and incorporating effective twist distribution, the design aims to improve thrust efficiency within a practical RPM range. The NACA 4412 airfoil is selected for its favorable low-speed lift characteristics. All parameters are tailored to balance performance, manufacturability, and compatibility with experimental thrust testing.

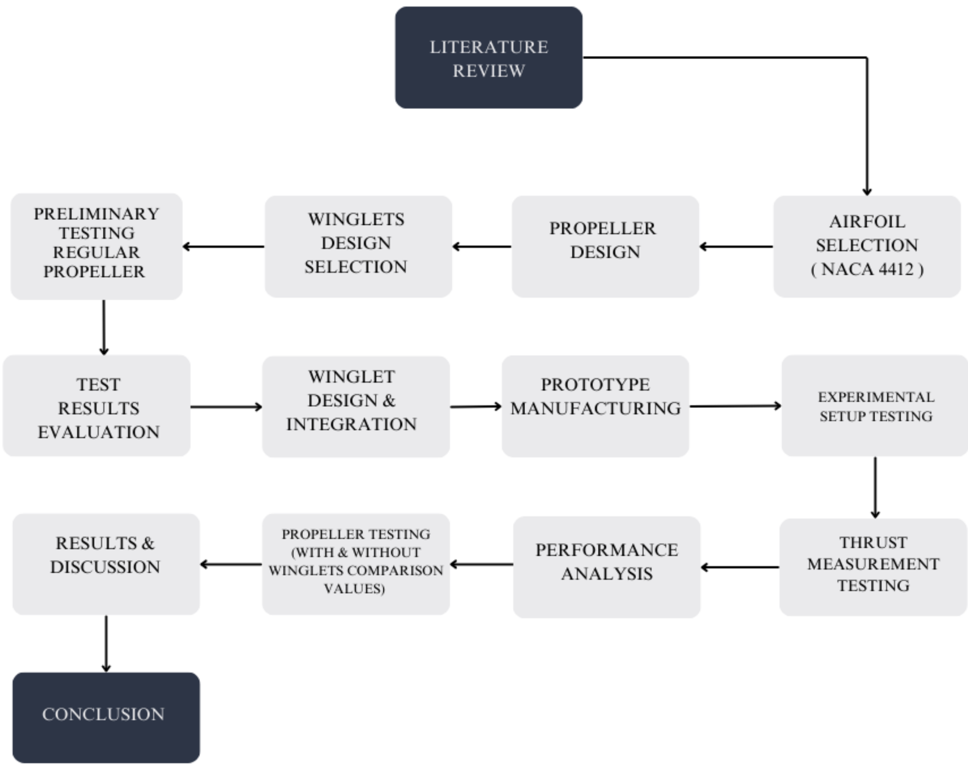


**Fig 4.1. Methodology flow chart**

### 4.2 Propeller Design

For this study, the propeller was designed using the NACA 4412 airfoil, which is well-suited for low-speed UAV applications due to its high lift characteristics and stable aerodynamic behavior. The selected airfoil allows for effective performance under the RPM range considered (4000–7000 RPM) and provides a robust platform for integrating various winglet configurations.

The geometric parameters of the propeller were carefully chosen to reflect realistic UAV-scale dimensions while maintaining aerodynamic efficiency. The key specifications are:

**Table 4.1. Design Parameters and Values**

| Design Parameters | Values |
|---|---|
| Airfoil Profile | NACA 4412 |
| Diameter | 7 inches |
| Pitch | 4.5 inches |
| Root Chord | 16 mm |
| Tip Chord | 7 mm |

To ensure smooth and efficient airflow along the blade, a twist distribution was implemented along the span of the propeller:

**Table 4.2. Twist Distribution and Angles**

| Twist Distribution | Angle (°) |
|---|---|
| Root Twist | 12° |
| Mid-span Twist | 7° |
| Tip Twist | 4° |

### 4.2.1 Model creation

After selecting the airfoil profile and geometric parameters, the propeller was modeled using CATIA V5, a robust CAD software widely used in aerospace component design. The process began with importing the NACA 4412 airfoil coordinates, which were then scaled and aligned according to the root, mid-span, and tip chord dimensions. Using CATIA's wireframe and surface design module, individual airfoil sections were positioned at defined radial stations and rotated according to the specified twist angles (12°, 7°, and 4°). The lofting feature was then applied to generate a smooth aerodynamic blade surface across the span. Finally, winglet designs—including vertical, blended, and wingtip fence types—were integrated at the blade tips with accurate dimensional constraints, ensuring proper curvature and orientation.\

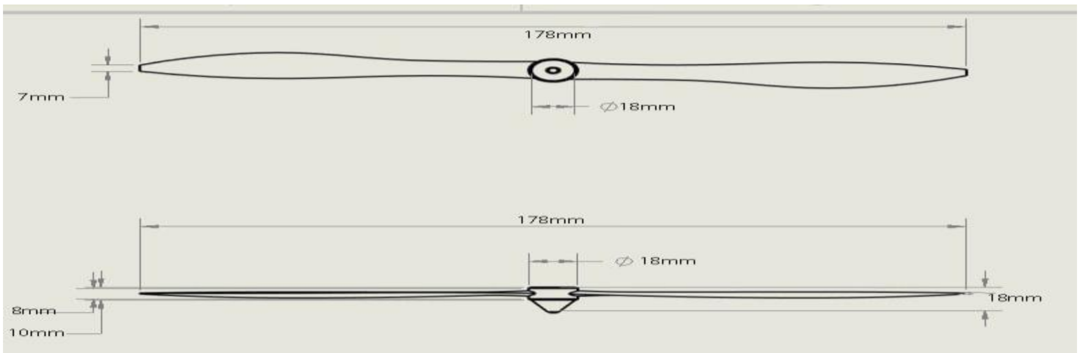


**Fig 4.2. 2D Schematic of Propeller NACA 4412**

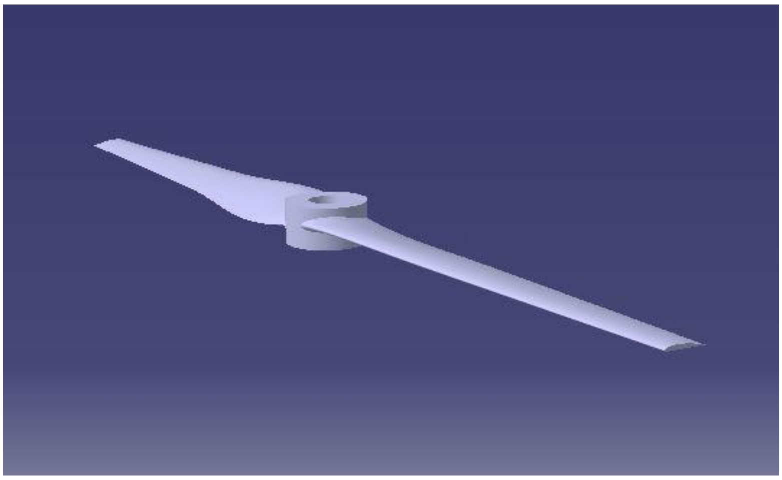

**Fig 4.3. 3D Model of Propeller NACA 4412**

### 4.3 Winglet Configurations and Integration Procedure

To analyze the effect of wingtip modifications on propeller performance, three different winglet configurations were selected and modeled using CATIA V5. Each configuration was designed to minimize tip vortices and enhance aerodynamic efficiency, especially in the low Reynolds number regime typical of small UAVs. The winglets were integrated onto the previously designed NACA 4412-based propeller blades**.**

**a. Vertical Winglet**

A simple upward-facing extension from the blade tip.

- Height: 10–15% of propeller radius (approximately 9–13 mm)
- Sweep Angle**:** 5–15° backward
- Taper Ratio**:** 0.6–0.8
- Purpose: Helps reduce spanwise flow and tip vortex intensity.

**b. Wingtip Fence**

Symmetrical vertical plates attached to the upper and lower blade surfaces at the tip.

- Height: 5–10% of propeller radius (approximately 5–9 mm)
- Purpose: Restricts spanwise pressure differential, limiting tip vortex generation and improving thrust stability.

**c. Backward Swept Winglet (Blended Type)**

A smoothly curved extension swept backward from the blade tip.

- Height: 8–12% of propeller radius (approximately 8–11 mm)
- Sweep Angle: 10–45°
- Curvature: Gradual blending into the blade surface
- Purpose: Optimizes tip airflow, reduces induced drag, and contributes to smoother thrust distribution.

#### 4.3.1 Integration in CATIA V5:

- Each winglet was designed as a separate surface body, using sketches and spline curves to define the outer profile.

- Winglets were then attached to the blade tips using the "Join" and "Blend Surface" tools in the Generative Shape Design module.
- The winglet surfaces were adjusted for smooth transitions with the blade using fillet and **s**weep operations to ensure aerodynamic continuity.
- Dimensional constraints for sweep angle, taper ratio, and height were precisely set using parameter control for repeatability across design iterations.
- The final propeller with each winglet type was saved as separate models for further analysis and fabrication.

### 4.4 CAD designs of winglets and parameters

The winglet design was carried out using CATIA V5, where three configurations vertical, wingtip fence, and backward swept were modeled and integrated at the blade tip of the UAV propeller.

#### 4.4.1 Vertical winglet and parameters

**Table 4.3. vertical winglet parameters**

| PARAMETER | VALUE |
|---|---|
| Height | 9 mm |
| Sweep Angle | 15° backward |
| Taper Ratio | 0.4375 |

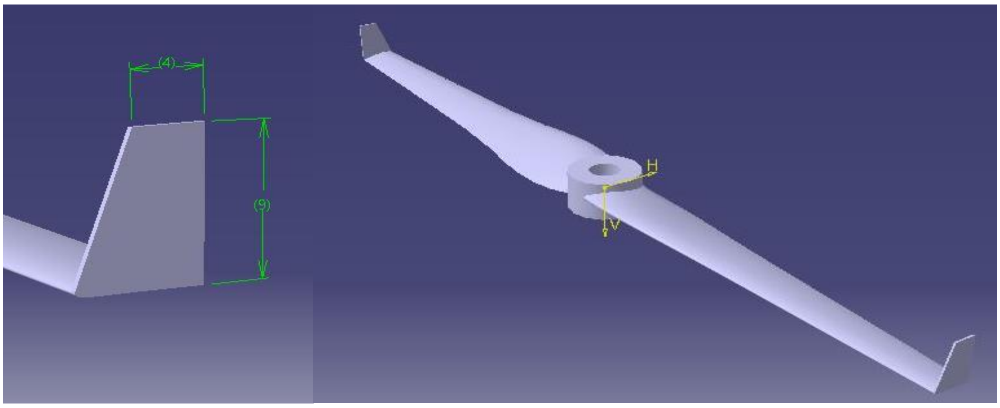


**Fig 4.4. CAD of propeller with vertical winglet**

### 4.4.2 Wingtip Fence and parameters

**Table 4.4. Wingtip fence parameters**

| PARAMETER | VALUE |
|---|---|
| Height | 9 mm |
| Tip height | 3 mm |
| Placement | On both sides of wingtip |

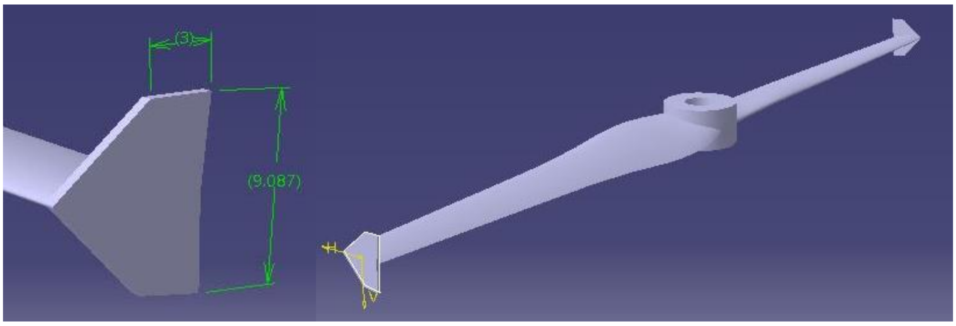


**Fig 4.5. CAD of propeller with Wingtip fence**

### 4.4.3 Backward Swept winglet and parameters

**Table 4.5. Backward Swept  parameters**

| PARAMETER | VALUE |
|---|---|
| Height | 9.1 mm |
| Sweep Angle | 45° backward |
| Placement | On both sides of tip |

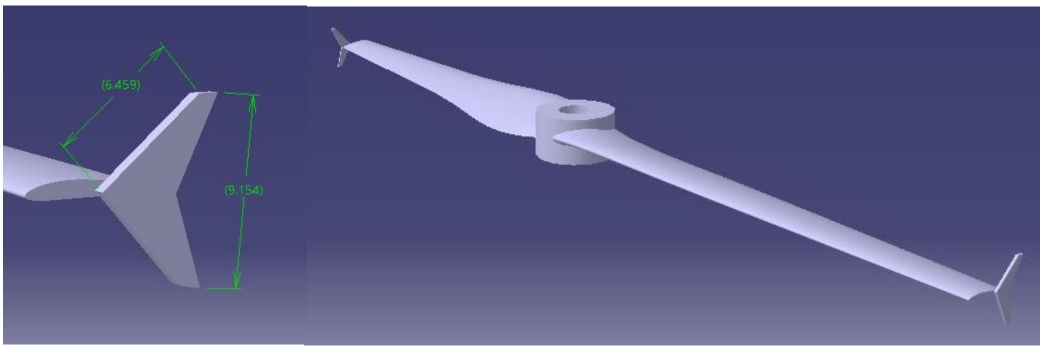


**Figure 4.6. CAD of propeller with Backward swept winglet**

### 4.5 Fabrication and 3D Printing of Propellers with Winglets

After completing the CAD modeling of the propeller and integrated winglet designs in CATIA V5, the finalized geometries were exported in STL format and prepared for additive manufacturing. The fabrication process employed 3D printing technology using ABS (Acrylonitrile Butadiene Styrene) filament, selected for its favorable mechanical and thermal properties suited for aerodynamic testing.

ABS was chosen due to the following advantages:

- Lightweight yet durable, providing sufficient strength without increasing overall mass
- Good layer adhesion, resulting in improved surface finish and dimensional accuracy
- High resistance to impact and deformation during operational loading conditions
- Easily machinable, allowing for smooth post-processing
- Cost-effective, making it ideal for rapid prototyping and multiple design iterations

To ensure structural stability, especially at high RPMs and under aerodynamic loading, the following printing parameters were used:

**Table 4.6. Printing parameters**

| Printing Parameter | Value |
|---|---|
| Nozzle Size | 0.2 mm |
| Infill Density | 100% (solid infill) |
| Layer Height | Optimized for fine detailing |
| Print Orientation | Aligned to minimize overhangs |

### 4.5.1 Fabricated Propellers

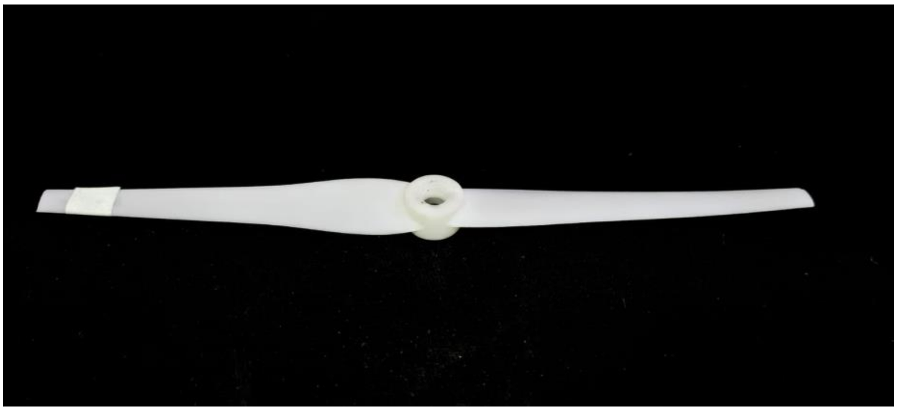

**Fig 4.7. Propeller without winglet**

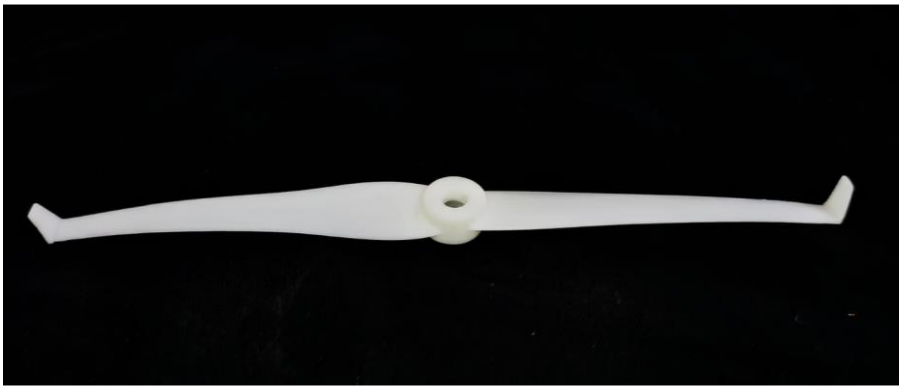

**Fig 4.8. Propeller with vertical winglet**

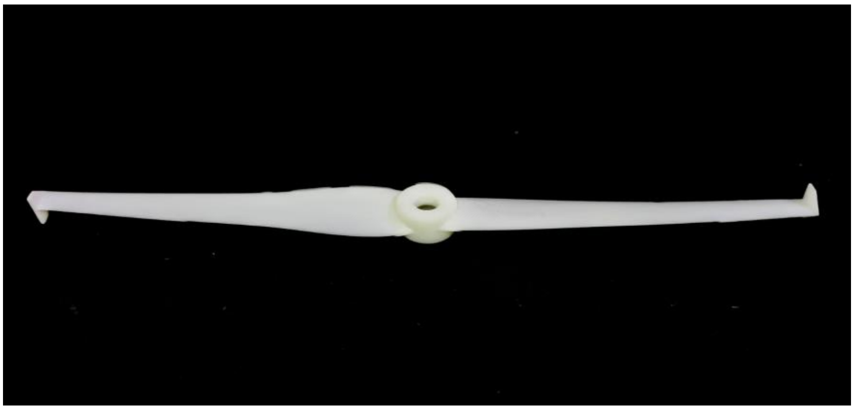

**Fig 4.9. Propeller with wingtip fence**

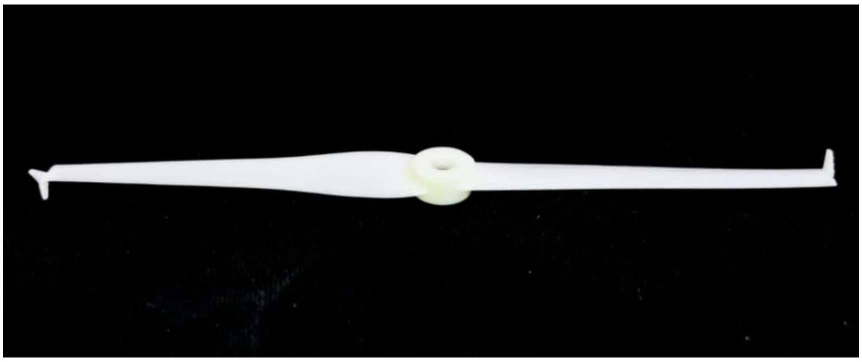

**Fig 4.10. Propeller with Backward swept**

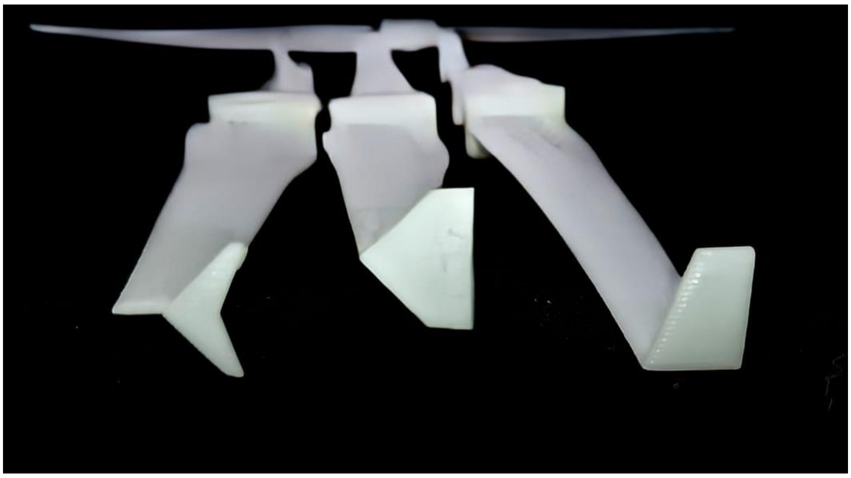

**Fig 4.11. Side view of Propeller with winglets**

### 4.6 Analysis Approach

The analysis was based solely on thrust measurement through RPM testing, conducted under two conditions: without flow (static environment) and with flow (open-air environment outside a wind tunnel). In both cases, the same experimental setup was used, consisting of a test rig fitted with a load cell to capture thrust at RPM intervals ranging from 4000 to 7000.

Three different winglet configurations vertical, wingtip fence, and backward swept were tested and compared against a baseline propeller without winglets. Thrust values were recorded for each configuration across the RPM range under both testing conditions.

To evaluate and compare performance, the results were plotted using:

- Thrust vs RPM graph for all configuration
- Percentage thrust increment vs RPM graphs

This approach allowed clear identification of the most effective winglet design by analyzing improvements in thrust output. The graphs revealed which configuration consistently enhanced thrust performance and at which RPM levels the gains were most significant.

# CHAPTER 5

# EXPERIMENTAL SETUP

## 5.1. Thrust measurement setup without freestream flow

In the static thrust testing configuration, the propeller was securely mounted on a wooden base aligned vertically above a digital weighing scale to measure generated thrust. The propeller was driven by a 1400 KV brushless DC motor, which was connected to an Electronic Speed Controller (ESC). The ESC was powered by an 11.1V (3S) LiPo battery, providing sufficient voltage and current for stable high-speed operation.

A manual servo tester was used to regulate the throttle input to the ESC, allowing for precise control of the motor's RPM. Thrust was recorded by observing the change in force on the digital scale, and a handheld laser digital tachometer was employed to measure the propeller’s rotational speed (RPM). Tests were conducted at intervals between 4000 and 7000 RPM for each winglet configuration and the baseline propeller without winglets.

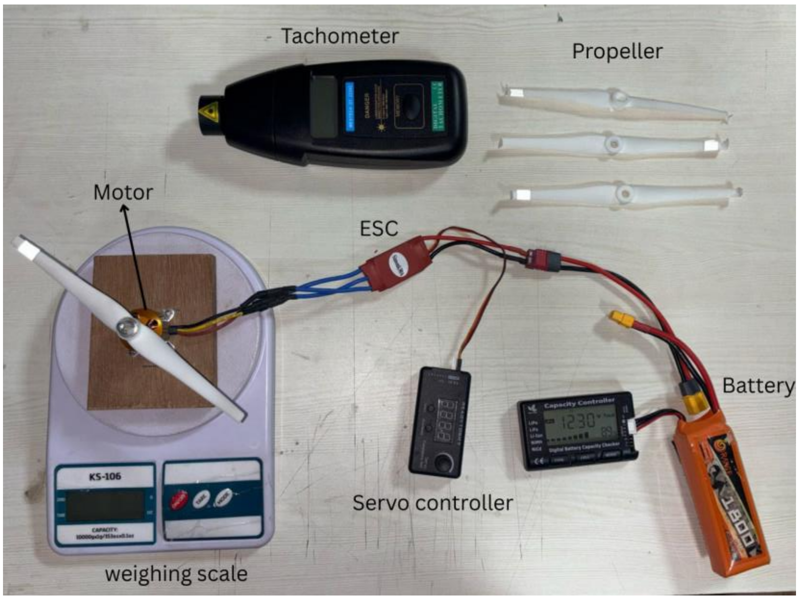


**Fig 5.1. Thrust measurement setup without freestream flow**

### 5.2. . Thrust measurement setup with freestream flow

In the flow test setup, the same motor-propeller assembly with a 1400 KV motor and 11.1V LiPo battery was used. However, the entire rig was positioned in the test section of an open-circuit wind tunnel, where a controlled freestream airflow of 20 m/s was introduced to simulate forward flight conditions.

The thrust measurement method remained unchanged, relying on the downward force measured by the digital scale. RPM control and measurement were also handled using the same servo tester and digital tachometer. This setup allowed for a comparative analysis of aerodynamic performance under actual flow conditions, helping determine the impact of each winglet design on thrust enhancement.


**Fig 5.2. Thrust measurement setup with freestream flow**

# CHAPTER 6

# RESULTS AND DISCUSSION

After completing the experimental tests, the analysis was performed using the collected thrust data under two conditions: without freestream flow and with freestream flow at a tunnel velocity of 20 m/s. The baseline thrust values from the standard propeller (without winglets) were compared with those from the winglet-equipped configurations vertical, wingtip fence, and Backward swept designs. Graphs of thrust versus RPM revealed performance trends, while percentage increment versus RPM plots helped quantify the improvements.

## 6.1 Thrust measurements and Performance Comparison of No Freestream Flow

### 6.1.1 Propeller without winglet

**Table 6.1 Thrust vs RPM for No Winglet Propeller**

| RPM | Thrust (N) |
|---|---|
| 4000 | 0.0686 |
| 5000 | 0.1275 |
| 6000 | 0.1765 |

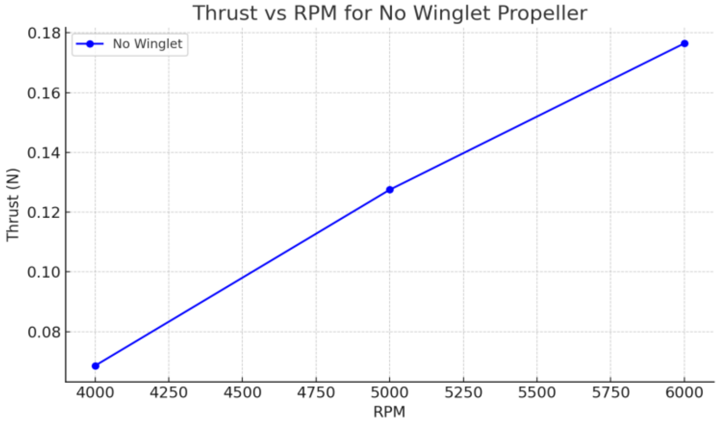


**Fig 6.1. Graph of Thrust vs RPM for no winglet propeller**

The graph illustrates a linear increase in thrust with RPM for the propeller without a winglet. As the RPM rises from 4000 to 6000, the thrust output significantly improves, showing the expected aerodynamic behavior. This configuration, without any winglet, serves as the baseline for performance comparison with other winglet-integrated propellers. Any improvement in thrust beyond this curve would indicate the effectiveness of the winglet designs.

### 6.1.2 Propeller with vertical winglet

**Table 6.2 Thrust vs RPM for Vertical winglet**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.1176798 | 71% |
| 5000 | 0.1569064 | 23% |
| 6000 | 0.23536 | 33% |

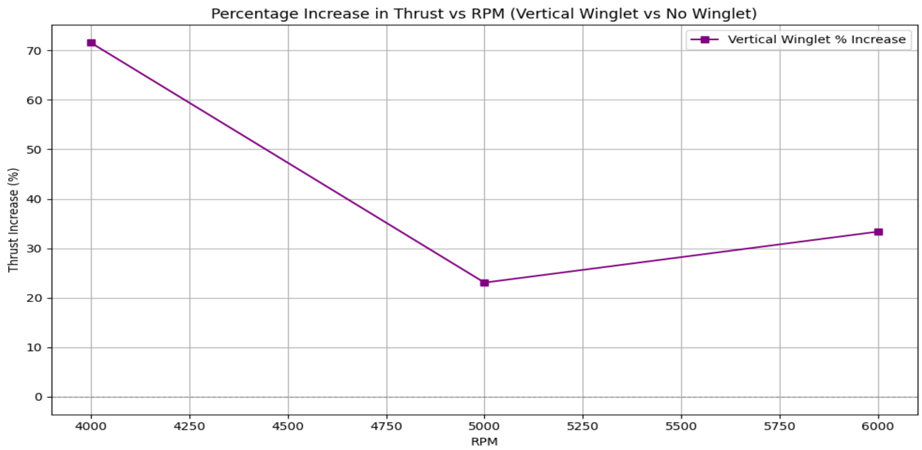


**Fig 6.2. Graph of Thrust increment% vs RPM for vertical winglet**

The increase in thrust when compared to the baseline configuration with no winglet. At 4000 RPM, the increase is especially significant at 71 percent, which indicates that the vertical winglet is highly effective at lower speeds by minimizing the formation of wingtip vortices and thereby conserving the propeller's thrust output. As the RPM increases, the percentage improvement declines to 23 percent at 5000 RPM but rises slightly again to 33 percent at 6000 RPM, suggesting that the aerodynamic benefits of vertical winglets remain notable even at higher speeds.

### 6.1.3 Propeller with wingtip fence

**Table 6.3 Thrust vs RPM for Wingtip fence**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.0980665 | 43% |
| 5000 | 0.1471 | 15% |
| 6000 | 0.196132 | 11% |

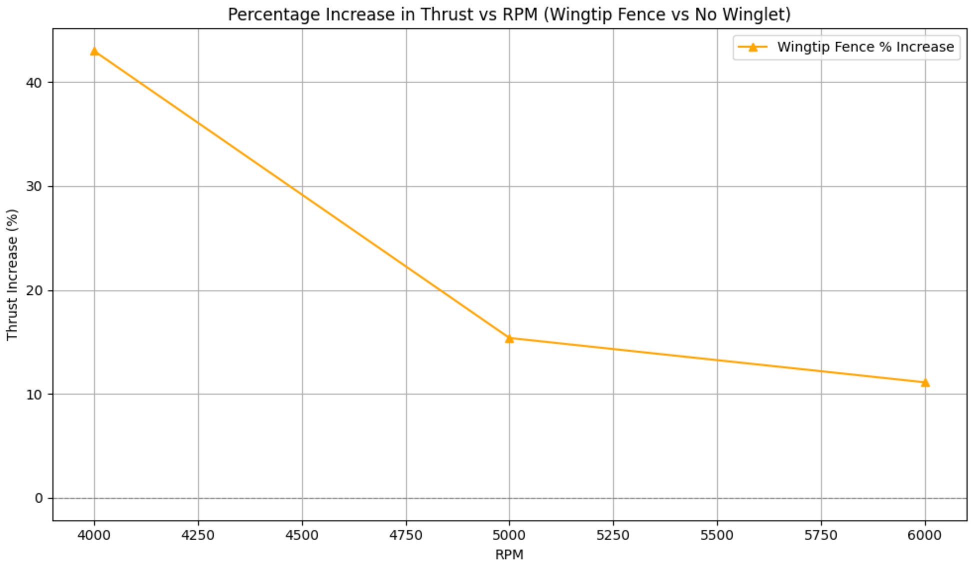


**Fig 6.3. Graph of Thrust increment% vs RPM for Wingtip fence**

In contrast, the wingtip fence provides moderate gains in thrust. The maximum thrust difference occurs at 4000 RPM, with a 43 percent increase over the no-winglet case. However, the benefit diminishes to 15 percent at 5000 RPM and further drops to 11 percent at 6000 RPM. This pattern suggests that while wingtip fences are helpful in reducing drag and improving thrust at lower RPMs, their effect becomes less pronounced as propeller speed increases.

### 6.1.4 Propeller with Backward swept

**Table 6.4 Thrust vs RPM for Backward swept**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.0784532 | 14% |
| 5000 | 0.1372931 | 8% |
| 6000 | 0.18632635 | 6% |

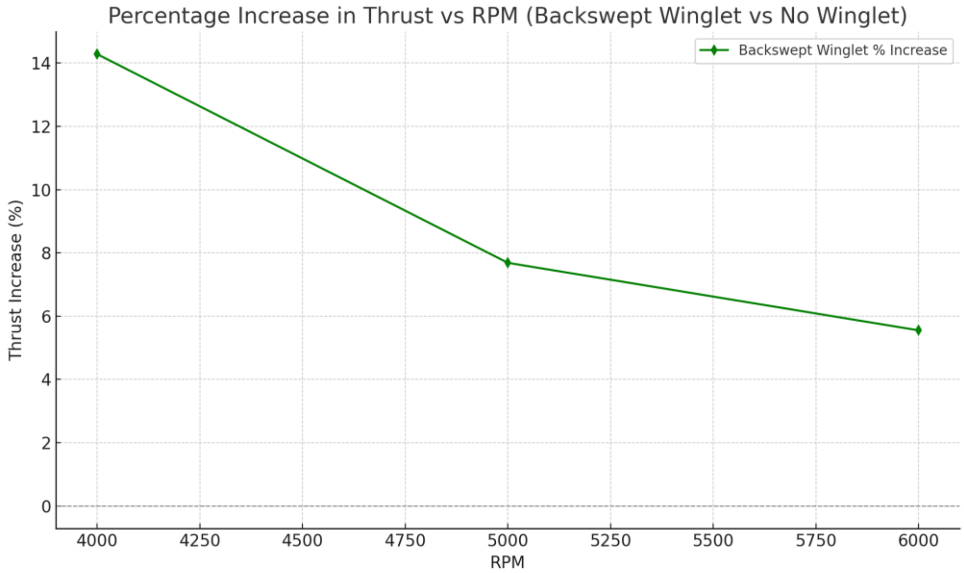


**Fig 6.4. Graph of Thrust increment% vs RPM for Backward swept**

The backswept winglet shows the least improvement among all configurations. It offers only a 14 percent increase at 4000 RPM, decreasing steadily to 8 percent at 5000 RPM and just 6 percent at 6000 RPM. This indicates that the aerodynamic design of the backswept winglet may not be as efficient in redirecting airflow to enhance thrust, especially at higher rotational speeds. Overall, its contribution to thrust efficiency appears to be minimal.

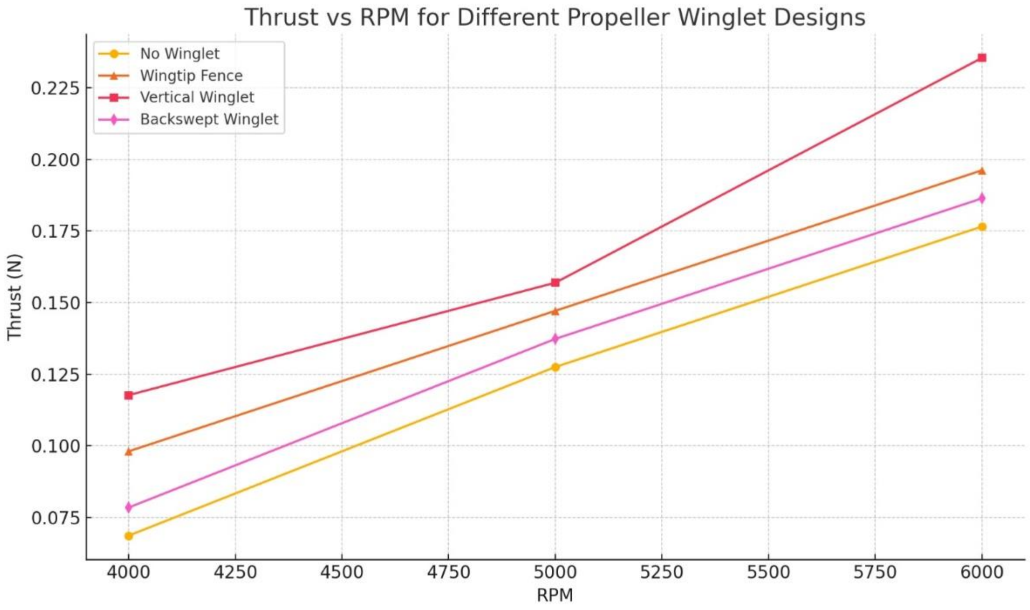


**Fig 6.5. Graph of Thrust vs RPM for Different propeller winglet designs**

This graph shows the relationship between RPM and thrust for different propeller winglet designs. It is evident that all configurations produce more thrust as RPM increases. Among the tested designs, the vertical winglet consistently generates the highest thrust at each RPM level, followed by the wingtip fence, backswept winglet, and finally the no-winglet case. This suggests that winglets help in improving propeller efficiency by mitigating tip vortex losses, with vertical winglets being the most effective in enhancing aerodynamic performance.

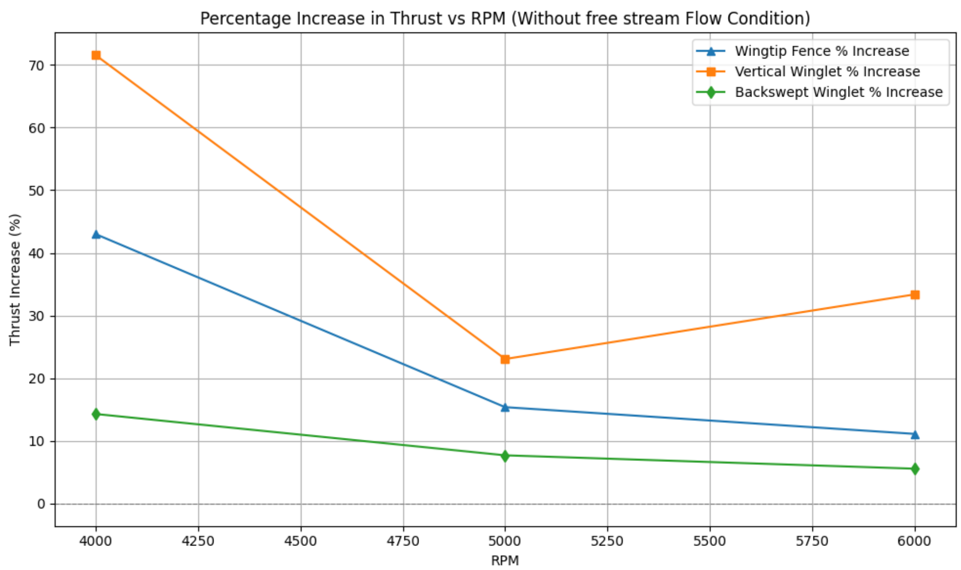


**Fig 6.6. Graph of Thrust increment% vs RPM for Different propeller winglets**

The second graph illustrates the percentage increase in thrust for each winglet design relative to the no-winglet configuration. The vertical winglet shows the highest percentage improvement, especially at lower RPMs, with a peak increase of over 70% at 4000 RPM. However, as RPM increases, the relative benefit decreases, indicating that the impact of winglets becomes less pronounced at higher propeller speeds. The backswept winglet consistently provides the smallest percentage gain. This trend suggests that while winglets significantly enhance thrust at lower speeds, their relative advantage diminishes as RPM increases, possibly due to the dominance of other aerodynamic effects.

## 6.2 Thrust measurements and Performance Comparison with Freestream Flow

### 6.2.1. Propeller without winglet

**Table 6.5 Thrust vs RPM for No Winglet Propeller**

| RPM | Thrust (N) |
|---|---|
| 4000 | 0.0321 |
| 5000 | 0.0654 |
| 6000 | 0.0873 |

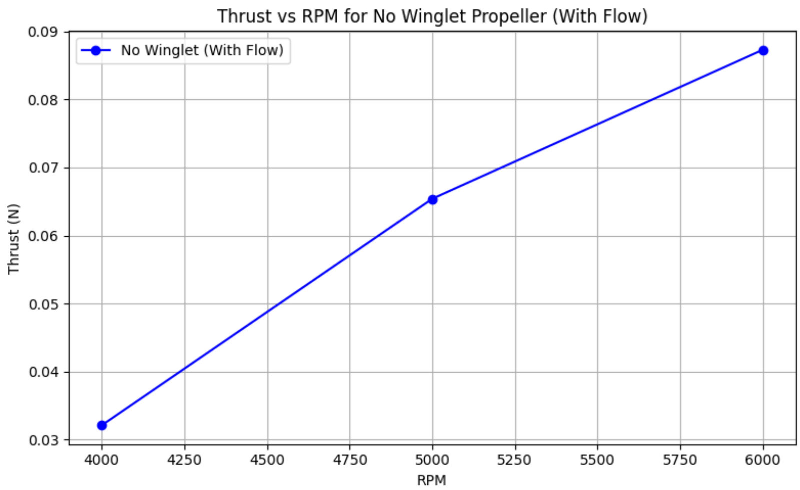


**Fig 6.7. Graph of Thrust vs RPM for no winglet propeller**

This graph shows the performance of a propeller without a winglet under a freestream flow condition of 20 m/s, simulating realistic airflow within a jet tunnel. As RPM increases, the thrust also increases linearly, demonstrating that higher rotational speeds enhance aerodynamic force generation even in the presence of external airflow. This configuration serves as a baseline reference for evaluating the impact of winglet designs. Since it represents the unmodified or standard propeller under flow conditions, it allows for a direct comparison to assess how much thrust improvement is achieved with various winglet modifications in similar aerodynamic environments.

### 6.2.2 Propeller with vertical winglet

**Table 6.6 Thrust vs RPM for Vertical winglet**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.0534 | 66.3% |
| 5000 | 0.0815 | 24.6% |
| 6000 | 0.1342 | 53.7% |

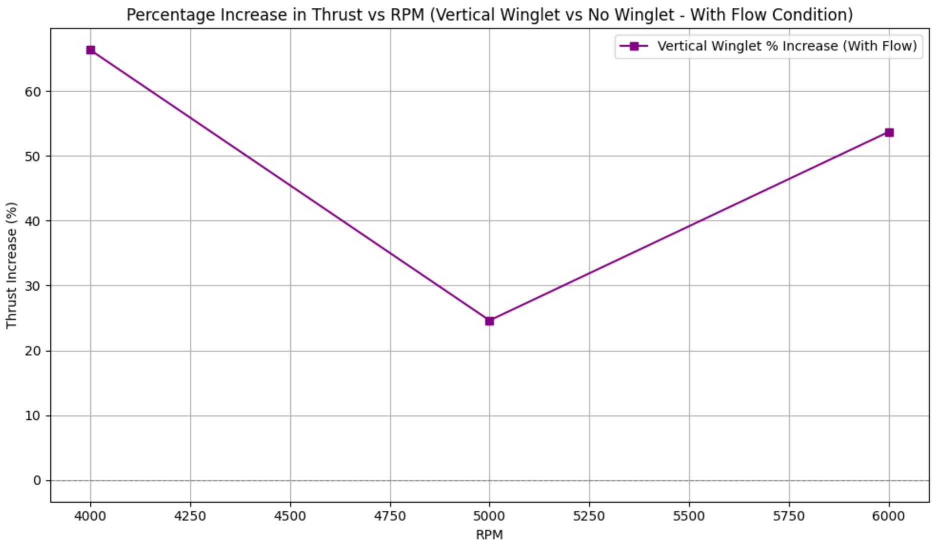


**Fig 6.8. Graph of Thrust increment% vs RPM for vertical winglet**

The graph for the vertical winglet shows a significant improvement in thrust across all RPM values compared to the no-winglet case. The highest increase is observed at 4000 RPM with a 66.3% improvement, which may be due to the more pronounced tip vortex reduction at lower rotational speeds. Although the increase dips to 24.6% at 5000 RPM, it rises again to 53.7% at 6000 RPM. This pattern suggests that the vertical winglet is effective in optimizing thrust at both low and high RPM ranges.

### 6.2.3 Propeller with wingtip fence

**Table 6.7 Thrust vs RPM for Wingtip fence**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.04556 | 41.8% |
| 5000 | 0.0763 | 16.7% |
| 6000 | 0.0953 | 9.2% |

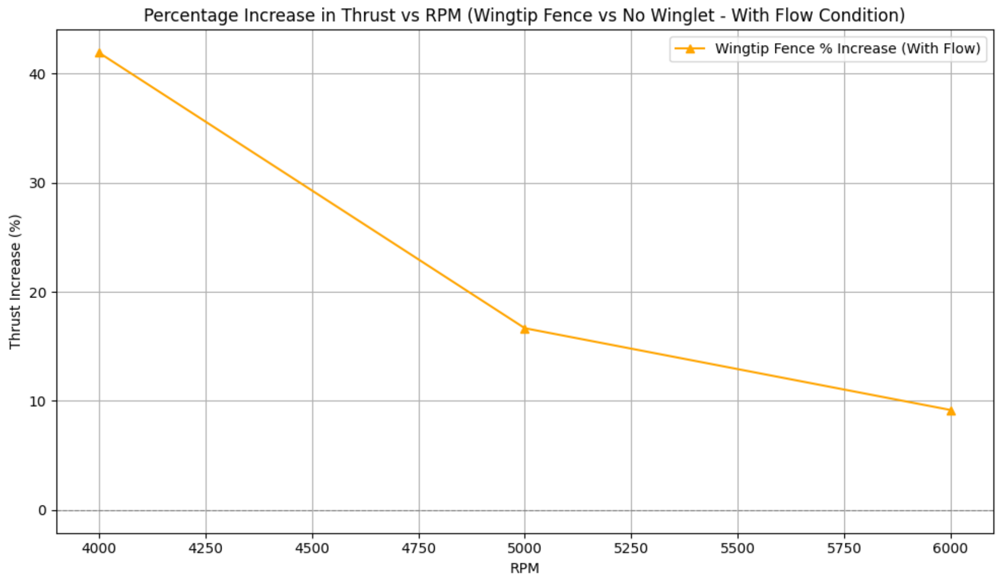


**Fig 6.9. Graph of Thrust increment% vs RPM for Wingtip fence**

The wingtip fence provides a moderate thrust improvement over the baseline. The largest benefit is observed at the lowest RPM, with a 41.8% increase. However, the effectiveness of the wingtip fence diminishes as RPM increases, dropping to just 9.2% at 6000 RPM. This trend indicates that while wingtip fences reduce induced drag and enhance performance at lower speeds, their impact is less substantial at higher RPMs where other aerodynamic effects dominate.

### 6.2.4 Propeller with Backward swept

**Table 6.8 Thrust vs RPM for Backward swept**

| RPM | Thrust (N) | Thrust increment (%) |
|---|---|---|
| 4000 | 0.0352 | 9.6% |
| 5000 | 0.0679 | 3.8% |
| 6000 | 0.0913 | 4.6% |

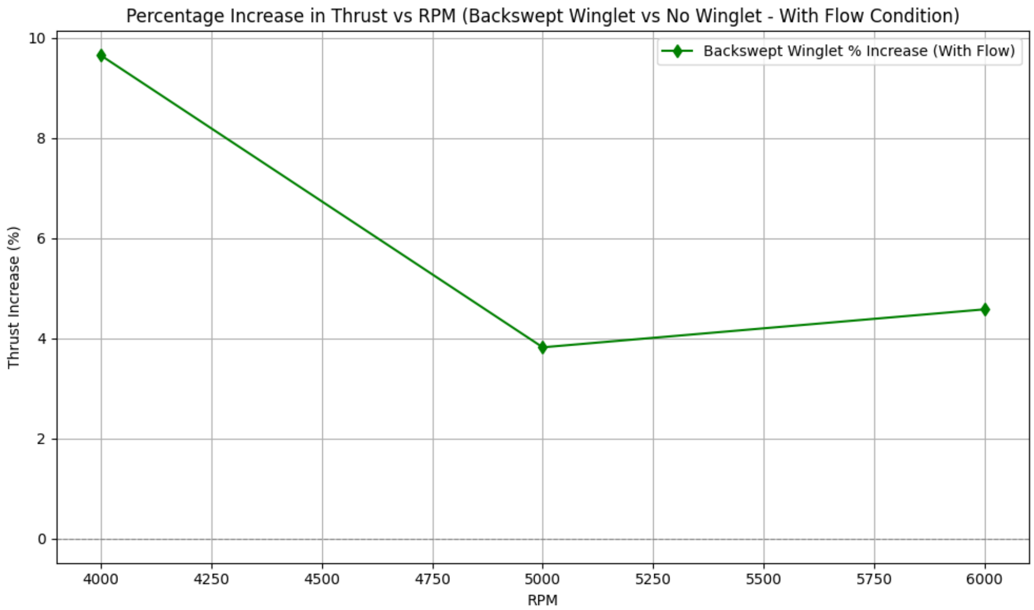


**Fig 6.10. Graph of Thrust increment% vs RPM for Backward swept**

The backswept winglet shows the smallest percentage increase in thrust compared to the other configurations. At 4000 RPM, the thrust gain is only 9.6%, and it reduces further at 5000 RPM before slightly improving again at 6000 RPM. The overall low increase suggests that the backswept design may not be as effective at mitigating tip vortices or enhancing lift under flow conditions, possibly due to less favorable flow redirection or energy recovery at the tip.

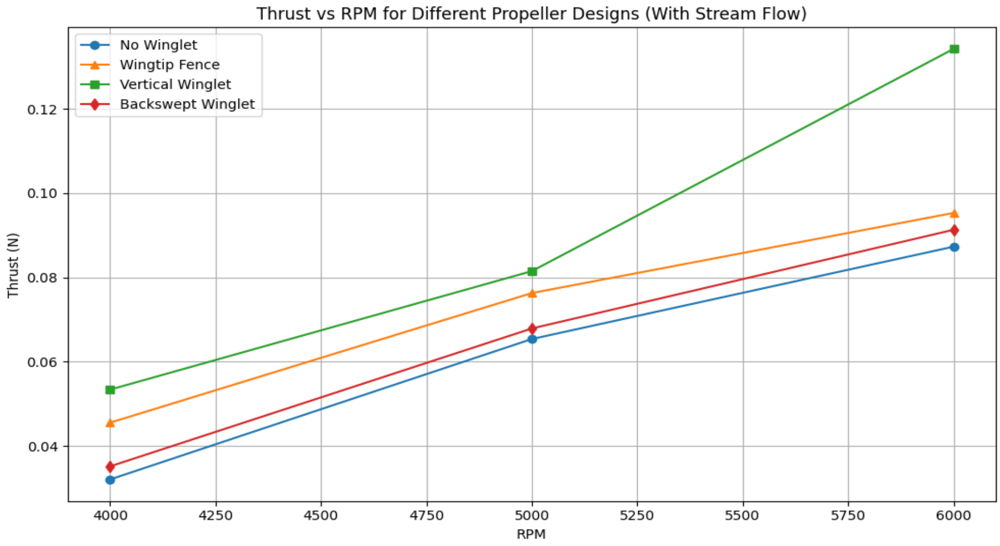


**Fig 6.11. Thrust  vs RPM for Different propeller winglets with freestream flow**

This graph illustrates the variation in thrust with RPM for different propeller designs under stream flow conditions. It shows that all designs produce increasing thrust as RPM increases, but the rate and magnitude differ significantly. The vertical winglet consistently delivers the highest thrust across all RPMs, indicating superior aerodynamic efficiency in managing tip vortices and improving propeller performance. The wingtip fence and backswept winglet also show performance gains over the baseline (no winglet), but to a lesser extent. This demonstrates that the inclusion of any winglet design contributes positively to thrust generation, with vertical winglets offering the most pronounced benefit.

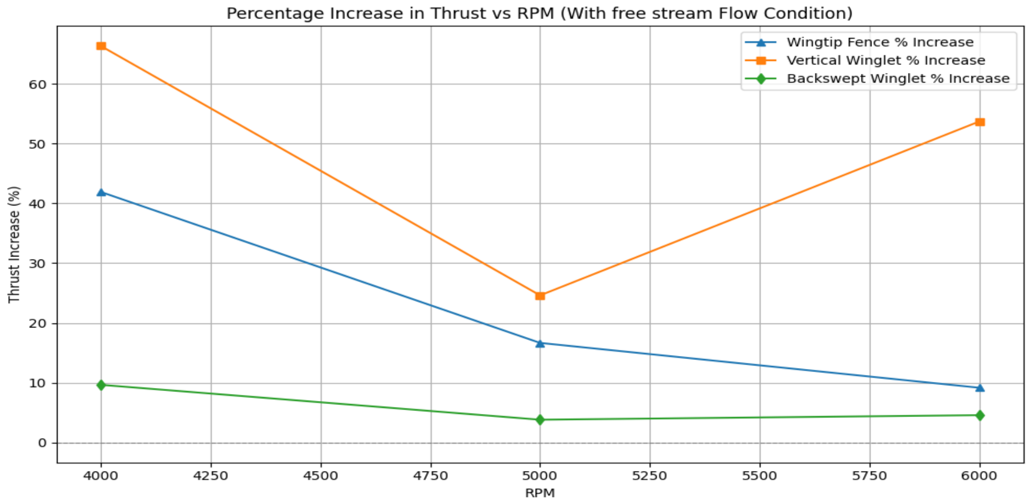


**Fig 6.12. Thrust increment% vs RPM for Different propeller winglets with freestream flow**

This graph presents the percentage increase in thrust compared to the no-winglet configuration for each winglet design across varying RPMs. It reveals that the vertical winglet yields the highest percentage gain, especially at lower and higher RPMs, peaking at 67% at 4000 RPM and maintaining a strong performance at 6000 RPM. The wingtip fence shows a moderate but consistent improvement, while the backswept winglet delivers the least percentage increase, maintaining a marginal advantage throughout. This pattern confirms that winglet efficiency is both design- and RPM-dependent, with vertical winglets being most effective in reducing induced drag and enhancing thrust under stream flow conditions.

# CHAPTER 7

# CONCLUSION

This study confirms that winglet designs significantly enhance the aerodynamic performance of UAV propellers. Through experimental testing, it was observed that all winglet-equipped propellers generated more thrust than the no-winglet baseline, especially under freestream flow conditions. The vertical winglet consistently outperformed other configurations, delivering the highest percentage increase in thrust across all tested RPMs. The wingtip fence also showed noticeable improvement, particularly at lower speeds, while the backswept winglet offered the least enhancement.

The findings highlight the critical role of winglet geometry in reducing tip vortices and improving overall efficiency. Among the tested options, the vertical winglet is the most effective design due to its ability to sustain thrust gains across a wide RPM range. Therefore, for UAV applications that demand higher thrust and better energy efficiency, it is recommended to adopt vertical winglets in propeller design. This approach can lead to improved flight performance, longer endurance, and better handling characteristics in various operational conditions.

# CHAPTER 8

# FUTURE ENHANCEMENT

For future work, computational fluid dynamics (CFD) analysis is recommended to gain a deeper understanding of the aerodynamic behavior of various winglet configurations under different flight conditions. This will allow for detailed visualization of airflow, pressure distribution, and vortex formation around the propeller blades, which is not easily captured through experimental testing alone. Additionally, expanding the study to include a wider range of winglet geometries—such as split winglets, curved winglets, or adaptive winglets can offer insight into further performance optimization.

Future enhancements can also involve testing under different freestream velocities and angles of attack to simulate realistic UAV operating environments. Incorporating materials and manufacturing feasibility analysis would help translate these aerodynamic improvements into practical UAV applications. Moreover, optimization algorithms and machine learning could be employed to automatically determine the best winglet shapes for specific mission profiles. These steps will contribute to the development of more efficient, robust, and versatile propeller systems for next-generation UAVs.

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