Performance Evaluation of Conventional and Toroidal Propellers for Quadcopters

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Abstract - *A Quadcopter is a sophisticated mechatronic device characterized by complex dynamics, relying on controlling six degrees of motion using thrust generated by propellers driven by DC motors. The primary objective of this study is to conduct a comprehensive thrust force analysis comparing a conventional three-blade propeller with a toroidal propeller, assessing the thrust force generated by each design under varying angular speeds and velocities.*

To achieve this, 3D CAD models of both the three-blade conventional propeller and the toroidal propeller were meticulously designed using Onshape software. These models were then imported into SimScale software for fluid flow simulation, where the aerodynamic characteristics over the propellers were analysed under different angular speeds and free-stream velocities. The simulation data provides insights into how each propeller design affects thrust force generation and overall efficiency.

Additionally, this study evaluates and compares the efficiencies of both propeller types. Efficiency metrics consider factors such as thrust force output relative to power input. By systematically comparing these aspects across various operating conditions, the study aims to highlight the performance advantages and potential drawbacks of each propeller design in diverse flight scenarios.

This outlines a structured approach to quantify and analyse the thrust force capabilities of conventional three-blade propellers versus toroidal propellers using SimScale software. The findings are expected to contribute to advancements in propulsion technology, improving the efficiency and effectiveness of aerial vehicles, marine vessels, and industrial machinery.

Key Words: **3D CAD models, Aerodynamic characteristics, Angular speeds, Conventional three-blade propeller, Efficiency, Fluid flow simulation, Onshape software etc**

1.INTRODUCTION

The introduction of this thesis provides an overview of the research on propeller design for quadcopters, focusing on the role of propellers in enhancing UAV performance. It highlights the growing need for efficient propulsion systems as UAVs become integral in industries like photography, logistics, and surveillance. The study addresses the lack of comprehensive research comparing traditional 3-blade propellers to toroidal designs, particularly in terms of thrust and efficiency. This sets the foundation for the research objectives, which include a detailed analysis of both propeller types using advanced simulation tools to optimize their performance.

The problem statement emphasizes the need for improved propeller designs to meet the rising demands for UAV efficiency and performance. While conventional propellers are widely used, they may not always provide optimal thrust or efficiency under varying conditions. The study seeks to address this gap by comparing the aerodynamic and performance characteristics of conventional and toroidal propellers, particularly under different operational scenarios. The research will use advanced 3D modelling and fluid flow simulations to analyse the propellers and provide practical insights for propeller design in UAV applications.

The significance of the research lies in its potential to advance UAV technology by offering data-driven insights into propeller dynamics and performance. By focusing on both conventional and toroidal designs, this study aims to guide future propeller selection and optimization for various UAV applications. The scope includes designing and simulating propellers using CAD and CFD software, followed by an evaluation of thrust, efficiency, and potential design improvements, contributing to the development of more efficient UAV systems across diverse industries.

2. DESIGN USING ONSHAPE

1.1 Design of 3 blade Conventional propeller

The design process for the 3-blade conventional propeller begins by setting up a project in Onshape, ensuring consistent units of measurement for accurate modelling. The overall dimensions are defined, with a propeller diameter of 6 inches (152.4 mm) and a pitch of 4 inches (101.6 mm). The initial geometry is created by drawing concentric circles on the top plane to form the hub and blade base, followed by extruding these shapes to establish the blade profiles and hub geometry.

Next, additional planes are generated to define the blade profiles at different positions along the propeller. On these planes, the chord lengths and angles of the blade sections are defined, with airfoil profiles applied to ensure proper aerodynamic characteristics. Using the NACA 2412 series profile, the blade sections are then lofted together to form a smooth transition from the root to the tip. The blade is connected to the hub using a fillet to reduce stress concentrations and improve aerodynamic performance.

Once the blades are formed, the central hub cutout is created to allow for mounting, and the blade pattern is generated, arranging the three blades evenly using a circular pattern. Finally, the design is refined by applying fillets and chamfers to smooth surfaces, particularly at the leading and trailing edges of the blades, to reduce drag. These final touches ensure that the propeller meets the design specifications and is optimized for performance

1.2 Design of 3 blade Toroidal propeller

The design process for the toroidal propeller begins with defining the overall diameter of 6 inches (152.4 mm), ensuring that the propeller shares similar specifications with the conventional one for accurate comparison. After setting up a new project in the CAD software, the units are configured to millimetres (mm) for linear dimensions and degrees for angles to maintain consistency throughout the design. The initial step involves creating the hub by sketching a 12 mm diameter circle on the top plane and extruding it to a height of 10 mm, forming the central hub from which the blades will extend.

Next, construction and design circles are drawn on the same plane to define the outer boundary of the propeller and its profile. A helix is generated from the centre of the hub, serving as a guiding path for shaping the propeller blades. The helix, with a height of 10 mm, ensures that the blades follow the correct aerodynamic path. The Sweep tool is then used to form the propeller blades by sweeping the design circle along the helix curve, generating a 3D shape. The Shell tool is applied to this sweep, creating a 2 mm thick hollow structure, which forms the primary aerodynamic surface of the toroidal propeller.

Following this, the Circular Pattern tool is used to replicate the swept blade profile around the hub, placing two additional blades at 120-degree intervals. Unnecessary sections of the geometry are removed using the Split operation, leaving the desired propeller shape. Finally, the Boolean Add operation merges the blades with the hub to create a unified structure, and additional fillets and chamfers are applied to improve structural integrity and reduce stress concentrations. After verifying the overall dimensions, the toroidal propeller is refined and optimized for performance, ready for further analysis and simulation.

Figure 1 and Figure 2 depict the CAD models of the conventional 3-blade propeller and the toroidal propeller, respectively. Both models were created using Onshape, adhering to the design specifications and optimized for performance evaluation

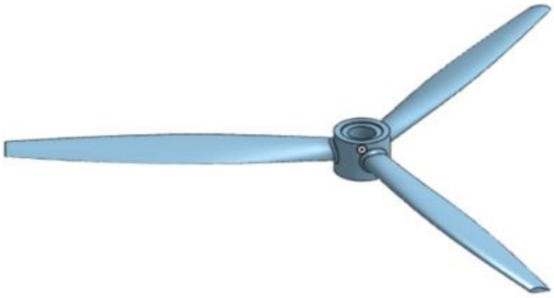

Fig -1: CAD model of a 3-blade conventional Propeller

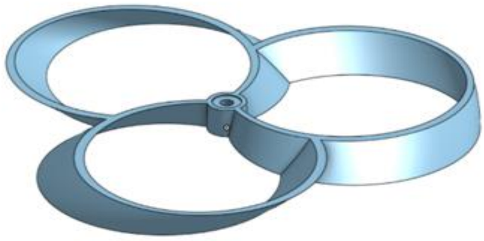

Fig -2: CAD model of a 3-blade Toroidal Propeller

3. CFD ANALYSIS USING SIMSCALE

This chapter explores the CFD simulations performed on the 3-blade conventional and toroidal propellers using the SimScale platform, aiming to analyse and compare their aerodynamic performance, focusing on key metrics like thrust, torque, and efficiency. The process began with the accurate import of 3D CAD models into SimScale, followed by the creation of rotating and static domains to capture the interaction between the propeller blades and the surrounding air. The rotating domain, represented as a cylindrical volume around the propeller, simulates the motion of the blades, while the static domain handles the surrounding fluid.

The MRF (Multiple Reference Frame) method was employed for efficient handling of the propeller's rotational effects, alongside selecting the k-ω SST turbulence model and steady-state conditions to ensure realistic analysis. Air was assigned as the working fluid, and the initial conditions set the fluid at rest to provide a stable baseline.

Critical boundary conditions were applied to reflect real-world operational dynamics. A velocity inlet condition was defined at the domain inlet to simulate airflow toward the propeller, while a pressure outlet condition was set to 0

Pa at the exit to ensure atmospheric pressure. Slip walls were used for the static domain to minimize friction and simulate an open-air environment, while no-slip walls were applied to the propeller surfaces to accurately model the interaction between the blades and the surrounding air.

The mesh was carefully refined, with a fineness of 8.1 and physics-based meshing techniques ensuring accuracy and computational efficiency. This well-structured simulation setup provides a solid foundation for the subsequent comparison of the aerodynamic performance of the conventional and toroidal propellers.

4. RESULTS

All the results from the simulations are presented in graphical form, providing a clear and comprehensive visualization for both the conventional and toroidal propellers

4.1 Thrust results comparison

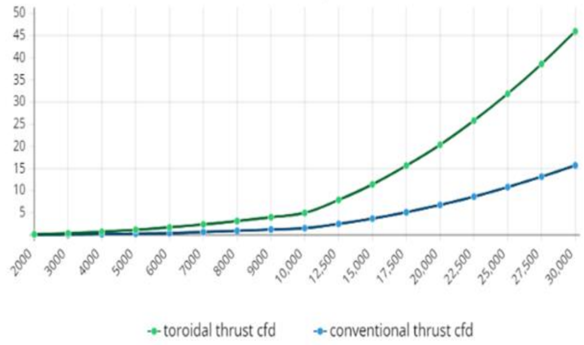

Chart -1: *Illustrating a graph between thrust vs rpm at 2 m/s*

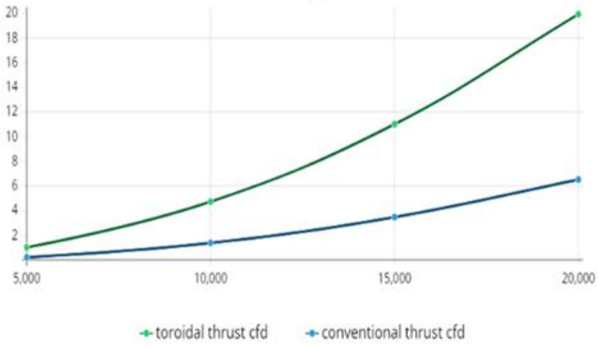

Chart -2: *Illustrating a graph between thrust vs rpm at 4 m/s*

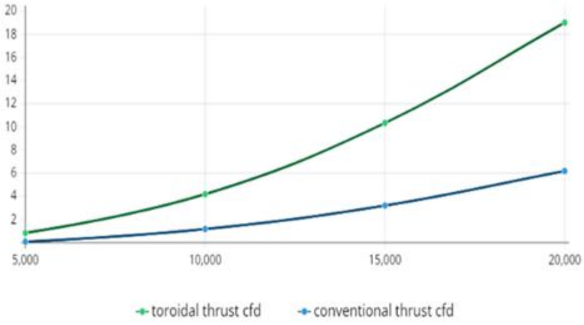

Chart -3: *Illustrating a graph between thrust vs rpm at 6 m/s*

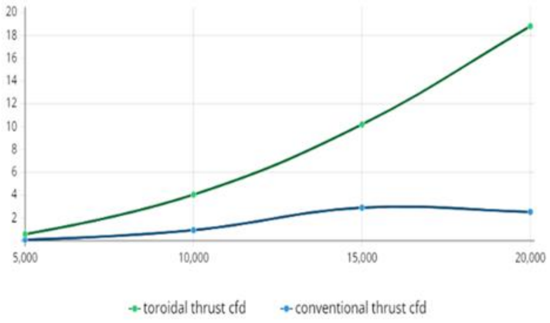

Chart -4: *Illustrating a graph between thrust vs rpm at 8 m/s*

4.2 Efficiency results comparison

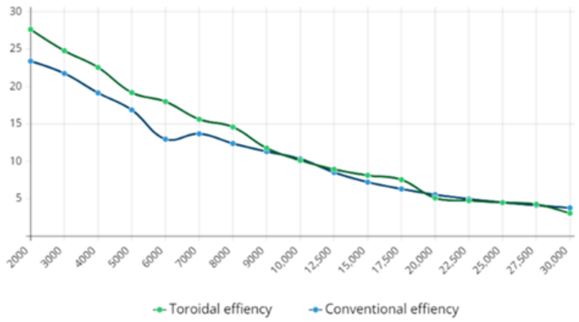

Chart -5: *Illustrating a graph between efficiency vs rpm at 2 m/s*

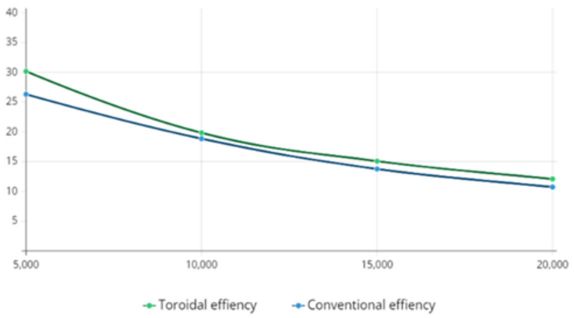

Chart -6: *Illustrating a graph between efficiency vs rpm at 4 m/s*

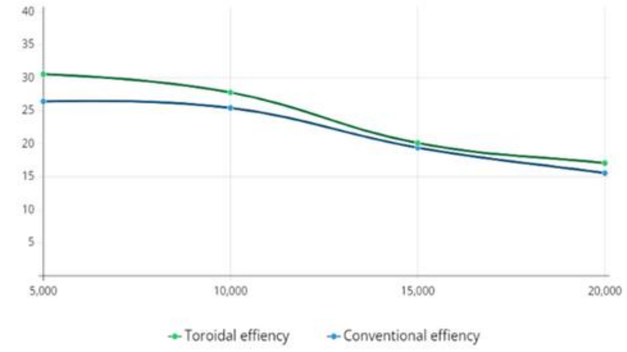

Chart -7: *Illustrating a graph between efficiency vs rpm at 6 m/s*

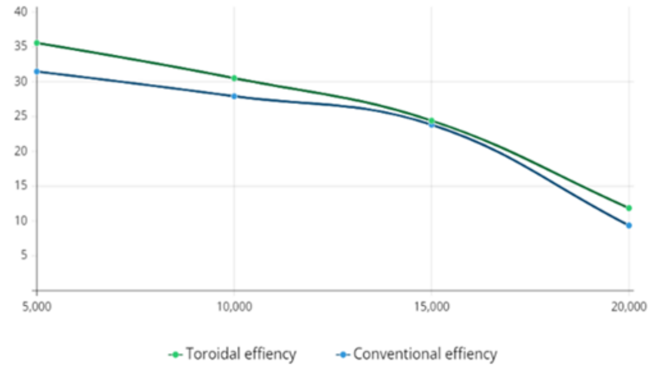

Chart -8: *Illustrating a graph between efficiency vs rpm at 8 m/s*

3. CONCLUSIONS AND RECOMMENDATIONS

The research conducted on the performance of conventional and toroidal propellers has provided significant insights into their operational characteristics and efficiencies. Key findings indicate that toroidal propellers consistently outperform conventional designs in various conditions, demonstrating superior thrust and efficiency. This underscores the importance of innovative designs in optimizing propulsion systems. The study also highlighted that increasing the number of blades enhances thrust generation for both propeller types, indicating that blade design is a critical factor in achieving optimal performance.

These conclusions not only align with existing literature but also have practical implications for applications in drone technology and other fields where propulsion efficiency is paramount. Based on these findings, several recommendations emerge for future propeller design. First, designers should prioritize toroidal configurations for high-performance applications, such as racing drones. Second, increasing blade count can enhance thrust generation, so designs should explore configurations with three or more blades while balancing thrust with drag. Additionally, focusing on advanced aerodynamic profiles and testing varied blade geometries will be crucial for maximizing efficiency. Material selection is also important, with a preference for lightweight, high-strength materials to improve thrust-to-weight ratios. Finally, while computational simulations are valuable, real-world testing is essential to validate findings and ensure designs perform well under various conditions.

Overall, the demonstrated advantages of toroidal propellers could pave the way for their adoption in more advanced aerial vehicles, contributing to enhanced operational capabilities and advancements in the field of aerial propulsion technology.

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