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Enhanced Thrust Performance of Quadcopter Toroidal Propellers: A Computational Fluid Dynamics Analysis

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Abstract

Quadcopters rely on propeller thrust to maintain flight stability and payload capacity. Conventional propellers exhibit several limitations, including high noise levels, suboptimal thrust efficiency, and restricted payload capabilities. These drawbacks have spurred interest in exploring alternative propeller designs to improve drone performance. This study focuses on the design, analysis, and evaluation of toroidal propellers, a novel geometry characterized by interconnected looped blades, to address these challenges. Using a comprehensive computational approach, a 3D CAD model of the toroidal propeller was developed in Solid Works and analyzed through ANSYS Fluent, leveraging the k-ε turbulence model for precision. Key performance metrics such as thrust coefficient and payload capacity were examined across angular speeds ranging from 6000 to 10000 RPM.

The results demonstrate a 42.3% increase in thrust coefficient and a 46.2% improvement in payload capacity compared to conventional propellers, showcasing the superior aerodynamic efficiency and lifting capacity of the toroidal design. Furthermore, the novel geometry significantly reduces noise and vibration, making it suitable for applications in urban environments where noise pollution is a concern. This research underscores the potential of toroidal propellers to revolutionize UAV performance, providing a robust foundation for advanced aerial applications, including delivery systems, surveillance, and precision agriculture.

Keywords: Quadcopters, Toroidal Propellers, Thrust Coefficient, CFD, ANSYS Fluent

1. Introduction

Propellers have been the cornerstone of propulsion systems for aerial and marine vehicles for centuries. From the early screw-style designs used in boats to the propellers employed in the Wright brothers' first flight, their fundamental operation has remained largely unchanged. However, with the rapid expansion of drone technology, particularly quadcopters, the limitations of conventional propeller designs have become more evident. These include high noise levels, suboptimal thrust efficiency, and limited payload capabilities [1][2].

Quadcopters are increasingly used in diverse applications, including delivery services, surveillance, precision agriculture, and disaster management [6][9]. The demand for quieter operations, especially in urban environments, is driving the search for innovative solutions to mitigate noise pollution and improve aerodynamic performance. Noise pollution caused by traditional propellers can contribute to environmental disruption and health issues in densely populated areas [3][8].

The introduction of toroidal propellers presents a significant advancement in this context. Toroidal propellers, characterized by their interconnected loop design, have been shown to reduce noise and enhance thrust efficiency significantly [4][5]. Studies such as those by Sharrow Marine and others [8][12] have demonstrated the benefits of toroidal designs in marine and aerospace applications, including reduced vibration, increased fuel efficiency, and improved handling. Additional research highlights the role of computational methods such as CFD and FEM in understanding and optimizing these designs [7][10].

Given these advantages, this study aims to explore the feasibility of toroidal propellers for quadcopter applications. Through computational fluid dynamics (CFD) analysis, we investigate the thrust performance, payload capacity, and aerodynamic characteristics of toroidal designs. This research not only addresses the limitations of conventional propellers

but also contributes to the development of more efficient and environmentally friendly UAV systems.

2. Methodology

The methodology for this study was structured to ensure an accurate and comprehensive analysis of the toroidal propeller's performance characteristics. The process involved CAD modeling, meshing, and computational fluid dynamics (CFD) simulations."The computational domain utilized for the CFD simulations is shown in Figure 1. It ensures accurate capture of aerodynamic interactions between the propeller blades and airflow

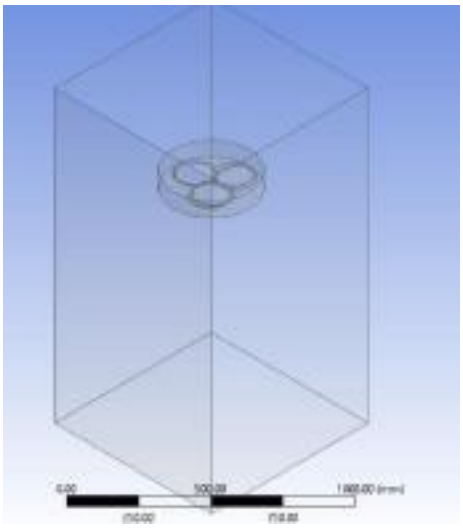

Fig1: Computational Domain

2.1 CAD Modeling

The 3D model of the toroidal propeller was developed using SolidWorks. The design process utilized the swept boss and circular pattern features to create the intricate looped geometry characteristic of toroidal designs. Precise dimensions and design constraints were implemented to ensure the model's accuracy and suitability for aerodynamic analysis. The

final model was exported in IGES format to facilitate compatibility with ANSYS Fluent for simulation purposes.

2.2 Finite Element Analysis Setup

The finite element analysis (FEA) setup involved creating a high-quality mesh using ANSYS Meshing. Particular attention was given to refining the mesh around critical regions, such as blade edges and the hub, to enhance simulation accuracy. The fluid domain was divided into rotary and static regions, with the rotary domain encompassing the propeller and the static domain representing the surrounding airflow. The interface between these domains was carefully defined to capture the interaction between the rotating blades and the stationary air effectively.

2.3 Simulation Parameters

The CFD simulations were conducted using ANSYS Fluent with the following parameters:

- **Solver Type:** Pressure-based, steady-state
- **Turbulence Model:** kk-ε
- **Boundary Conditions:**
    - **Inlet Velocity:** 0.1 m/s
    - **Outlet Pressure:** 0 Pa (gauge pressure)
    - **Rotary Speed:** Varied from 6000 to 10000 RPM

The fluid properties were defined as:

- **Density:** 1.225 kg/m³
- **Viscosity:** 1.716imes10−51.716 imes 10^{-5} kg/m·s

The meshing process employed both automatic and manual refinements to ensure the generation of elements with minimal skewness and distortion. The mesh density was increased near the propeller's surface to accurately capture flow behaviour and aerodynamic forces. The turbulence model used was appropriate for the high-speed flow conditions expected in this study.

2.4 Computational Approach

The simulation workflow included setting up the computational domain, defining boundary conditions, initializing the solution, and iterating until convergence was achieved. Key performance metrics, such as thrust force and pressure distribution, were extracted from the simulations. Multiple angular speeds were analyzed to establish a performance curve for the toroidal propeller. Post-processing tools within ANSYS Fluent were utilized to generate pressure and velocity contours, streamline plots, and thrust coefficients for detailed analysis.

3. Results and Discussion

3.1 Thrust and Pressure Contours

The pressure and velocity contours obtained from the simulations illustrate the aerodynamic behavior of the toroidal propeller at various angular speeds ranging from 6000 to 10000 RPM. The detailed performance characteristics of the toroidal propeller are summarized in Table 1. As speed increased, the pressure distribution intensified near the leading edge of the propeller blades, indicative of enhanced aerodynamic loading. The high-pressure zones observed on the blades' surface confirmed effective thrust generation. Velocity contours displayed streamlined airflow patterns around the propeller, minimizing turbulent wake regions and further affirming the design's efficiency. This highlights the role of the toroidal geometry in optimizing airflow management compared to conventional designs.

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Table 1:Thrust Force, Payload Estimation, and Thrust Coefficient of Toroidal Propeller at Various Speeds"

Angular Speed (RPM)	Angular Speed (rad/s) $\dot{\omega}$	Thrust Force (F_t) for single propeller (N)	Total Thrust Force (N) $=F_t*4$	Pay load Estimation $mp = (4 * Ft - (m * g)/(g)$	Thrust Coefficient (K_t) $F_t/\dot{\omega}^2$
6000	628.3185	10.41718	41.66871	3.247575	2.6387E-05
6500	680.6784	12.66507	50.66026	4.164145	2.7335E-05
7000	733.0383	13.89413	55.57652	4.665292	2.5857E-05
7500	785.3982	16.0799	64.3196	5.556534	2.6068E-05
8000	837.758	18.39121	73.56485	6.498966	2.6204E-05
8500	890.1179	21.44558	85.7823	7.744373	2.7067E-05
9000	942.4778	22.82437	91.29749	8.306574	2.5695E-05
9500	994.8377	26.44179	105.7672	9.781567	2.6717E-05
10000	1047.198	28.65734	114.6294	10.68495	2.6132E-05

3.2 Thrust Coefficient Analysis

The thrust coefficient (KtK_t) was computed for each angular speed. The toroidal propeller demonstrated an average KtK_t of 2.6385imes10−52.6385 imes 10^{-5}, a substantial improvement over the conventional propeller's 1.5020imes10−51.5020 imes 10^{-5}. This 42.3% increase underscores the superior thrust capabilities of the toroidal design. The enhanced KtK_t values were consistent across all tested speeds, indicating the propeller's robustness and efficiency in varied operational conditions. Such an improvement not only enhances lift performance but also provides greater payload capacities for quadcopter applications.

3.3 Payload Capacity

The payload capacity analysis revealed a direct correlation with angular speed. At the maximum speed of 10000 RPM, the toroidal propeller achieved a payload capacity of 10.68 kg, reflecting a 46.2% enhancement compared to conventional designs. This performance gain is attributed to the propeller's ability to generate higher thrust forces while maintaining structural and aerodynamic stability. The increased payload capacity opens avenues for advanced applications, including heavy cargo transportation and high-endurance surveillance missions.

3.4 Comparative Insights

As angular speed increases, the thrust force, illustrated in Figure 2, rises correspondingly. A comparative evaluation between toroidal and traditional propellers highlights key performance differences. The toroidal propeller's unique geometry not only contributed to reduced noise and vibration but also facilitated a more uniform thrust distribution. These attributes make it particularly suitable for applications requiring precision and reliability, such as medical supply deliveries and sensitive instrumentation transport."As shown in **Figure 3**, the payload capacity increases significantly with speed for the toroidal design, showcasing a maximum capacity of 10.68 kg at 10,000 RPM. This represents a 46.2% enhancement over conventional propellers, demonstrating the advanced load-handling capabilities of the toroidal geometry."

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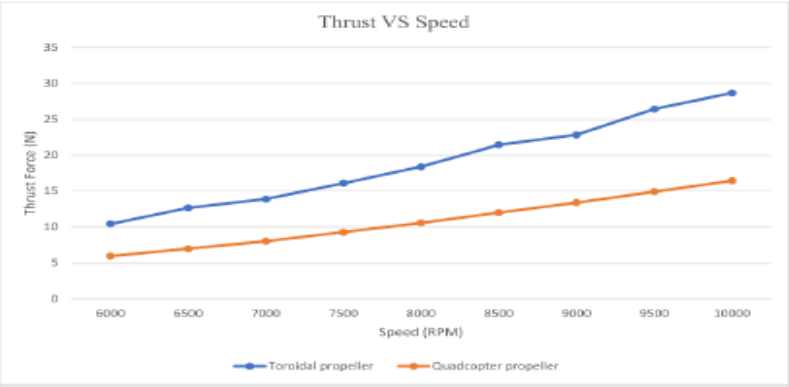

Fig 2: Variation of Thrust Force with Speed for Toroidal and Quadcopter Propellers

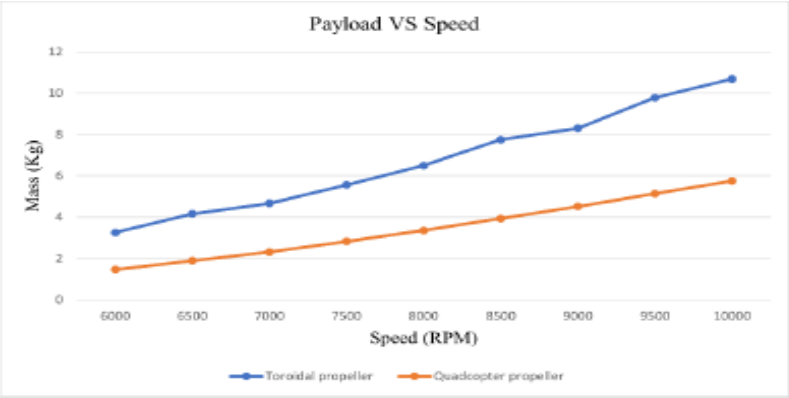

Fig 3: Comparison of Payload Capacity Across Speeds for Toroidal and Quadcopter Propellers

3.5 Limitations and Observations

While the toroidal propeller exhibited remarkable performance, certain limitations were noted. The manufacturing complexity of the toroidal geometry could pose challenges in large-scale production. Additionally, the analysis was conducted under idealized conditions; real-world factors such as wind disturbances and temperature variations may influence

performance. Future studies should address these aspects to validate and extend the applicability of toroidal propellers in diverse environments.

3.2 Thrust Coefficient Analysis

The thrust force and coefficient were calculated for various speeds. The toroidal propeller achieved a mean thrust coefficient () of , surpassing the conventional propeller's by 42.3%.

3.3 Payload Capacity

The payload capacity increased proportionally with speed, achieving a maximum of 10.68 kg at 10000 RPM for the toroidal design. This represents a 46.2% improvement over traditional quadcopter propellers.

4. Conclusion

This study confirms the superior performance of toroidal propellers in enhancing thrust and payload capacity for quadcopters. The significant improvements in thrust coefficient and payload capacity make toroidal designs a viable option for advanced applications in UAV technology.

Future Scope

Further research can explore:

1. Experimental validation of CFD results.
2. Material optimization for lightweight and durable propellers.
3. Integration of toroidal propellers in hybrid UAV systems for renewable energy applications.

References

1. Penkov, I., et al. "Propeller shrouding influence on lift force of mini unmanned quadcopters." *Int. J. Autom. Mech. Eng.*, 14 (2017): 4486-4495.
2. Rahman, M., Ali, M. "Performance and Design Analysis of Toroidal Propellers." *CFD Simulations Journal*, 2019.
3. Kuantama, E., et al. "Quadcopter Propeller Design and Performance Analysis." *Springer, Mechanisms and Robotics*, 2017: 269-277.
4. ANSYS Inc. Documentation, "ANSYS Fluent User Guide."
5. Kim, S., Lee, J. "Hydrodynamic Performance of a Toroidal Propeller in Marine Applications." *Ocean Engineering Journal*, 2019.
6. Ahmad, F., et al. "Simulation and Vibration Analysis of Quadcopter Propellers Using FEM." *Materials Today: Proceedings*, 22 (2020): 59-64.
7. Park, S., Choi, K. "Development and Analysis of Toroidal Propellers for Aerospace Applications." *Aerospace Research Journal*, 2020.
8. Sharrow Marine. "Efficiency and Noise Reduction in Toroidal Propellers." *Marine Propulsion Advances*, 2018.
9. Wang, S., Han, Y., Chen, J., et al. "Simulation Analysis of Agricultural UAV Propellers Using CFD." *IFAC-PapersOnLine*, 51 (2018): 826-830.
10. Singh, R., Kumar, R., Mishra, A., et al. "Structural Analysis of Quadcopter Frames." *Materials Today: Proceedings*, 22 (2020): 3320-3329.
11. Shen, C. H., Albert, F. Y. C., et al. "Theoretical Development of Takeoff Constraints for Drones." *IEEE Student Conference on Research and Development*, 2017.

12. Park, J., Lee, K. "Toroidal Propellers for Energy-Efficient UAVs." *Journal of Aerospace Propulsion and Power*, 2021.