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An Empirical Study of Performance Variations: 3D Printed Toroidal Propeller vs. Traditional Propeller

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***Abstract*— This empirical study compares the performance variations of 3D printed toroidal propellers and standard propellers, with a focus on the implications for drone propulsion systems. The project seeks to learn more about thrust efficiency, noise levels, and current consumption. The results show that toroidal propellers, particularly those with three blades, generate more thrust with the same or less current consumption as conventional propellers. Toroidal designs' distinctive blade curvature improves aerodynamics by decreasing turbulence and noise. These discoveries have important implications for improving drone motor efficiency, battery consumption, and environmental sustainability.**

Keywords*— Drone Propulsion, Toroidal Propellers,Performance Comparison, Drone Technology, Propulsion Systems

I. Introduction

In recent years, the Drone industry has seen substantial modifications as a result of technology improvements aimed at improving efficiency, sustainability, and performance. Among these breakthroughs, additive manufacturing, specifically 3D printing, has emerged as a promising option for generating complicated geometries and optimizing various components. This study compares the performance parameters of 3D-printed toroidal propellers and traditional propellers in order to provide insights that could potentially revolutionize Drone propulsion systems.

The primary goal of this study is to empirically compare the performance differences between 3D-printed toroidal propellers and conventional propellers in Drone propulsion. This topic was chosen due to the growing need to address sustainability problems, improve energy efficiency, and modernize propulsion technologies in the Drone sector. This study intends to shed light on the potential benefits and drawbacks of adopting toroidal propellers over traditional counterparts by harnessing the capabilities of 3D printing technology to build complicated shapes.

The conclusions of this study have significant implications for both the Drone sector and society as a whole. A thorough study of the performance differences between 3D-printed toroidal propellers and conventional propellers should pave the way for more informed decision-making when developing and selecting propulsion systems. This, in turn, has the potential to improve motor efficiency, Battery consumption, and, as a result, lessen the environmental imprint of Drone operations. Contributing to ongoing efforts to develop more sustainable transport options and reduce the environmental impact of global trade and travel are among the broader societal ramifications.

This study's overarching goal is to scientifically examine and compare the performance characteristics of 3D-printed toroidal propellers and traditional propellers. The following particular objectives have been developed to achieve this goal: To create 3D-printed toroidal propellers with various specs. Under controlled conditions, do extensive experimental testing on toroidal and conventional propellers. To examine and contrast the performance metrics of the two propeller types, including thrust and noise behavior.

One of the most interesting aspects of this study is the examination of toroidal propellers via the lens of 3D printing technology. While toroidal propellers are a departure from standard designs, their use in conjunction with the additive printing process adds a new dimension to propulsion engineering. The combination of unique manufacturing techniques with atypical propeller shapes is at the heart of this study's innovation, providing new insights into the capabilities of modern propulsion systems.

II. Literature Review

A pioneering work by Adrian Ieta et al.[1] explores into the unknown terrain of multi-coaxial contra-rotating propellers with a 12.6 cm diameter in the world of rotary ionic engines (RIEs). Working within regulated air circumstances, the inquiry aims to uncover advantageous configurations that are primed for upscaling and critical to the evolution of rotary ionic drones. Notably, these propellers, which contain pin-emitter electrodes surrounded coaxially by a cylindrical collector electrode, demonstrate their potential by producing up to 40 mN of axial thrust. The research elucidates the interaction of thrust-to-power dynamics, revealing unique insights that link propeller kinetic energy-to-power ratios and the impedance of the voltage-current gap. Furthermore, a comparison of RIE arrays—from single to multi-coaxial propeller units—provides insight into increased thrust densities and weight efficiency, presenting a compelling avenue for future explorations.

Roberto Muscari et al.[2] have conducted a thorough examination in the field of turbulent flow simulations, employing both a Reynolds-Averaged Navier-Stokes (RANS) technique and Detached Eddy Simulation (DES) to investigate the behavior of an isolated marine propeller in uniform flow. The study proves that RANS accurately forecasts propeller performance while DES provides better insight into wake structures, particularly the formation of tip vortices, by studying thrust, torque, and wake dynamics under various loading circumstances. Notably, the DES approach exhibits the ability to capture complicated vortex interactions and energy transfer processes, proving its reproducibility. This study emphasizes the significance of mesh resolution and provides useful information for selecting appropriate turbulence modeling methodologies in marine engineering investigations.

Giulio Dubbioso et al.[3] attempted to assess the efficacy of a numerical framework based on Reynolds-averaged Navier-Stokes Equations (RANS) for analyzing propeller performance in off-design conditions in the field of naval hydrodynamics. The research focuses on the effects of such situations on vessel design and operational efficiency. The CNR-INSEAN E779A propeller model is used to study maritime propeller behavior under oblique flow conditions using unsteady RANS equations and a dynamically overlapping grid technique. The research adds vital insights into propeller functionality by investigating hydrodynamic loads and pressure distribution on the blades and hub across diverse loading circumstances, including tight maneuvers. Notably, grid convergence analysis helps to validate numerical simulations.

Stefano Gaggero et. al[4] look into the critical domain of adverse operational scenarios, such as wave-induced motion and maneuvering, in the context of maritime safety, propellant efficiency, and dynamic responsiveness. The study emphasizes the possible impact of propeller inflow changes on thrust, torque, and in-plane stresses, with consequences for hull-vibratory loads, propulsion system stress, and overall ship dynamics. The research seeks to forecast and analyze these occurrences during the design phase by using a boundary element method (BEM) propeller solver, which is often used in optimization processes. Comparisons with unstable Reynolds-averaged Navier-Stokes (uRANS) simulations and experimental data from model-scale free-running tests support the BEM solver's effectiveness, paving the way for informed decision-making in computational fluid dynamics (CFD) simulations.

Asad Asghar et al.[5] proposes a novel technique inspired by nature in the field of propeller enhancement, combining bioinspired passive flow management via the integration of tubercles on the leading-edge region of the propeller blade. This technique has shown encouraging results not just in propeller performance improvement, with efficiency increases of up to 6%, but also in reducing propeller acoustic emissions through a series of trials. The study investigates various tubercle configurations and their effects on propeller efficiency and noise characteristics, revealing directional and high-frequency broadband noise changes. This study demonstrates how biomimetic design ideas have the potential to revolutionize propeller technology and its accompanying noise characteristics.

Giulio Dubbioso et al.[6] investigates the behavior of the INSEAN E779A propeller under oblique flow situations using a dynamic overlapping grid technique. The study sheds insight into propeller performance in terms of global loads by investigating a wide range of angles of incidence and changing loading circumstances. Notably, non-symmetric inflow conditions cause considerable in-plane stresses, which are especially noticeable during off-design scenarios such as ship maneuvering. Despite the lack of experimental validation in oblique flow, careful open-water testing and grid-level evaluations corroborate the accuracy of simulations. The study's findings indicate that Computational Fluid Dynamics (CFD) has the potential to be a valuable tool for developing and validating low-order propeller models, hence lowering computational complexity during hull maneuver simulations.

Max Liben et al. [7] propose a revolutionary analytical design method that utilizes a ring motor surrounding the outer diameter of the propeller in this pioneering work. This method is strategically aligned with optimizing aerodynamic efficiency for larger diameter, lower-speed propellers, resulting in lower battery energy consumption in electric rotorcraft. The research cleverly solves the issues faced by low rotational speeds by developing a high-torque-density machine design that eliminates the requirement for gearing while exploiting spatial arrangement for increased torque density without the use of liquid cooling. The analytical investigation, aided by Finite Element Analysis, validates the design's viability. The resultant design, tailored for heavy-lift drones, features a 400mm diameter propeller generating 225N thrust at 1650rpm, achieving a noteworthy 6 kW mechanical power output with exceptional efficiency and specific torque characteristics.

Max Liben et al.[8] offers a unique technique for electric rotorcraft employing a ring motor encircling the propeller's outer diameter in this study. The concept tries to optimize battery energy use by taking advantage of the potential aerodynamic benefits of larger-diameter propellers at lower rotating speeds. The study addresses the issue of lower rotational speeds by proposing a high-torque-density machine design that eliminates the requirement for gearing and takes advantage of the spatial layout for increased torque density without the use of liquid cooling. The final prototype caters to heavy-lift drones and is subjected to extensive performance testing using an analytical design method and Finite Element Analysis (FEA). The study identifies major areas for development and provides an air-cooled design, torque density of 6.25 N-m/kg total mass, and 11.1 N-m/kg active mass.

Axel Schulz [9] investigates the feasibility of constructing a low-noise drone propeller using computational fluid dynamics (CFD) simulations in this thesis. LES turbulence modeling and an aeroacoustic analog within OpenFOAM are used to modify a commercial drone propeller with serrations along its trailing edge. The improved propellers had lower sound pressure levels than the unmodified counterpart, illustrating the promise of CFD-based design. The study recognizes limitations in scenario coverage and alteration breadth, providing the path for future research to investigate various propeller changes and operating circumstances.

Michael OL et al. [10] examine small unmanned aerial vehicles and compare wind tunnel testing and analytical forecasts for a variety of propellers. To determine critical quantities such as thrust and torque coefficients, as well as blade efficiency, the study employs intricate iteration including blade-element methods, momentum theory, and sectional airfoil analysis. To handle low Reynolds number effects, a sizeable aerodynamic lookup table is used, which improves accuracy. Despite slight variations, the analysis shows that uniform inflow velocity increment assumptions exhibit negligible loss of precision. The study emphasizes the importance of exact propeller twist and chord distributions, as well as careful consideration of Reynolds-number effects, especially for smaller diameter and low advance ratio circumstances. The work sheds light on the function of Reynolds number effects in explaining data scatter and investigates propeller coefficient scaling, so adding to a better understanding of propeller performance.

III. METHODODLOGY

A systematic technique to evaluating the performance characteristics of a regular (normal) propeller, a 3D printed toroidal propeller with three blades, and another variant with two blades were used in the methodology for performing experimental testing of different propeller designs. To achieve accurate measurements and dependable results, the experiment was carried out in a controlled atmosphere. The system includes a weighing scale for measuring thrust, an RPM control mechanism, and current consumption sensors. A controller circuit is also developed, as shown in Figure 3, which includes a BLDC motor, an Arduino Nano for motor control, a current sensor, a potentiometer for RPM adjustment, and a steady 12-volt power supply.

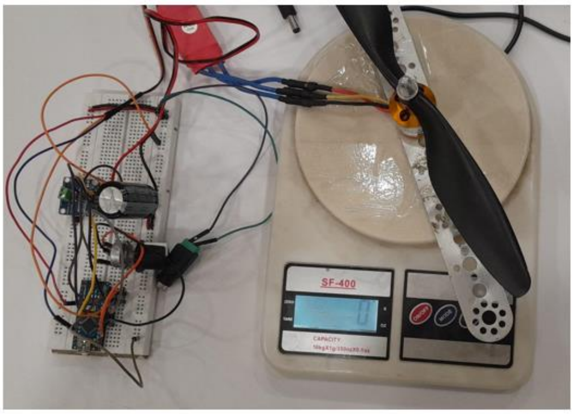

Fig:1 Experimental Setup of Normal Propeller

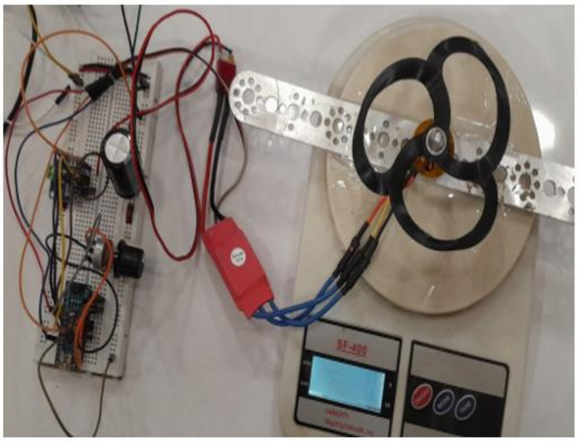

Fig: 2 Experimental Setup of Toroidal Propeller

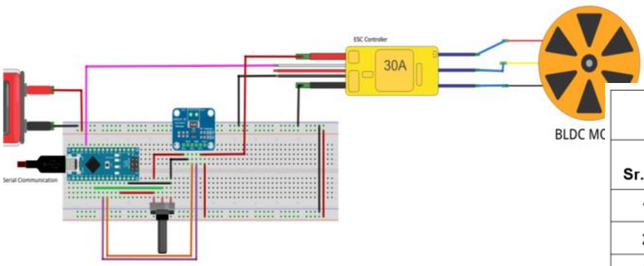

Fig: 3 Schematic circuit diagram for controlling BLDC Motor

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The technique begins with attaching a standard propeller to the motor shaft and controlling the motor's RPM with a potentiometer while concurrently recording real-time current data via the Arduino Nano's serial monitor. This procedure is done for each RPM value to create a thorough dataset. Following that, the toroidal propeller with three blades and the variation with two blades were tested in the same manner. To ensure accuracy and dependability, each test is repeated numerous times, and the order of testing is randomized.

The collected data was analyzed and organized into a simple table, providing thrust, noise values, and related current readings for each propeller type. The results are interpreted, with an emphasis on current consumption trends regarding RPM fluctuations for each propeller design. This comprehensive methodology attempts to provide insights into the relative performance of various propeller types as well as their possible consequences for diverse applications.

IV. Results

V. Experimental Reading of various types of propeller

			Regular Propeller		Toroidal Propeller (3 Blades)		Toroidal Propeller (2 Blades)	
Sr.No.	Voltage (V)	Current (Amp.)	Thrust (N)	Noise (DB)	Thrust (N)	Noise (DB)	Thrust (N)	Noise (DB)
1	12	1.6	20	23	31	17	28	34
2	12	2	35	33	39	22	28	37
3	12	2.5	47	38	42	27	31	40
4	12	2.7	58	45	47	30	35	42
5	12	3	69	48	52	34	38	47
6	12	3.5	83	53	56	43	40	48
7	12	3.9	95	55	60	47	45	51
8	12	4.3	107	62	65	51	46	53
9	12	4.8	115	67	70	58	52	57
10	12	5	120	72	73	63	52	58

According to the statistics in the table 1, as current consumption grew for all propeller types, so did the thrust create. This correlation is consistent with basic propulsion principles, in which a larger current draw allows the engine to spin the propellers faster, resulting in increased thrust. The intriguing component, though, is the variance in thrust generated by the various propeller designs.

The toroidal propeller with three blades consistently outperformed the regular propeller and the toroidal propeller with two blades across a wide range of current consumption levels. This result implies that the toroidal design's blade configuration improves thrust efficiency. The toroidal blades' distinctive curvature and shape are believed to improve aerodynamic properties, allowing for better airflow interaction and reduced turbulence. As a result, the toroidal propeller produces more thrust while consuming comparable or even lower currents than a regular propeller.

Noise reduction is critical in many applications that utilize propellers, particularly in terms of environmental effect and user comfort. According to the data in the table, toroidal propellers with three and two blades consistently produced less noise than standard propellers at equivalent current consumption levels.

The toroidal propeller's unusual shape appears to minimize blade-vortex interactions and turbulence, which accounts for the noise decrease. These elements contribute significantly to noise generation in traditional propellers. The curvature of the toroidal design and the optimized blade form is believed to contribute to smoother airflow patterns, minimizing noise-producing phenomena. This noise reduction is especially promising for noise-sensitive applications such as drones, electric vehicles, and marine propulsion systems.

According to the current consumption data, the various propeller designs have differing levels of efficiency in converting electrical power to thrust. While toroidal propellers produced equivalent or more thrust at specific current consumption levels, they also exhibited the potential for enhanced energy economy. The capacity to create more thrust while consuming the same or even lower current is beneficial for increasing battery life and boosting overall system efficiency.

VI. Conclusion

Finally, this empirical study investigated the performance differences between 3D printed toroidal propellers and regular propellers. The study sought to shed light on the thrust generation, noise levels, and current consumption of these propeller designs. The results demonstrated the advantages of toroidal propellers, particularly those with three blades, in terms of thrust efficiency and noise reduction. The toroidal blades' distinctive curvature and shape appeared to optimize aerodynamic interactions, resulting in higher thrust levels while using equivalent or lower currents than conventional propellers. The toroidal design's capacity to reduce turbulence and blade-vortex interactions also contributed to lower noise emissions.

Following these discoveries, several intriguing options for further research appear. Toroidal propeller design parameters can be fine-tuned to improve thrust efficiency and noise reduction. Real-world flight testing would be required to validate these findings, and coordinated multi-disciplinary research might provide a comprehensive understanding of propeller dynamics.

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