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Comparing Toroidal Propeller Performance with Different Blade Numbers at Different RPM: CFD Analysis and Evaluation

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Abstract
This research paper discusses the comparison of the toroidal propeller performance with different number of blades using computational fluid dynamics (CFD) analysis. The focal point of this topic is to show that the number of blades affects the output parameters as thrust, efficiency, noise and vibrations, and cavitation risk. An integrated CFD model is used to investigate the fluid flow modelled with the toroidal propellers of different blade numbers, starting from low to high. The analysis of the data from the simulation is done to evaluate the influence of number of blades on the propeller efficiency and optimization. we summarize the information collected, which is beneficial for choosing the right configuration of the toroidal propellers for maximum efficiency and effectiveness in different applications. This research is a source of information on the torus propeller dynamics and is therefore used by engineers and designers in the decision-making process of the propulsion system development. This study does so by introducing the effect of blade numbers on performance parameters, explaining the influence of toroidal propeller on performance and conducts development of efficient and ecological propulsion system

***Keywords*- CFD, Toroidal, Efficiency, Thrust, Propulsion, RPM, Blade Number, Velocity, Vibrations.**

1. INTRODUCTION

1.1. Background

Toroidal propeller has distinctive design qualities, which include enhanced efficiency and thrust characteristics, toroidal propellers have become more and more popular in a variety of applications. To improve the performance of classic designs, optimisation techniques are necessary because they may be hindered by inefficiencies and performance restrictions. The traditional open propeller design has been changed. Toroidal propellers, differently from common propellers, which have the duct of blades placed around the ring. This design idea has contributed to improving the performance, lowering the noise emissions, and consequently enhancing the thrust performance in a wide range of technical applications.

Nevertheless, the researchers have already shown that the toroidal propellers have a good future, but the efficiency is influenced by various factors and the blade count is not yet settled. Traditional propeller configurations are single type of fixed blades that have been picked due to the scientific rules and technical principles. Although CFD and optimization techniques advancements have created new procedures of blades counts' effect on propeller performance, the subject remains relevant.

1.2. Problem Statement

The toroidal propellers blade number is a matter of dispute and is still not solved in the propulsion engineering sphere. The interplay between blade shape, fluid dynamics, and performance measures is very complicated, and therefore, some data and technical guidelines are not enough to get a deeper understanding of the situation. Without a substantial database of toroidal propeller performance compared to different blade counts we cannot gain knowledge of the design space and thwart optimization efforts. Thus, carrying out large-scale research on the toroidal propeller effect with varying blade counts under modern computational approaches is now of utmost necessity.

1.3. Objectives

This research work aimed to bridge the knowledge disparities by studying and comparing the performance of toroidal propellers with different blade counts using CFD analysis and evaluation. Concisely, goals are to conduct a thorough study on the impact of blade number on toroidal propeller performance by running CFD simulations and analysing metrics like thrust, efficiency, and risk of cavitation, and by investigating the correlation between blade number and propeller performance with a view to optimise the design. Through these objectives, our research is aimed at the development of toroidal propeller technology and giving engineering industry in maritime, aerospace, and many others, the necessary information.

2. LITERATURE REVIEW

2.1. Toroidal Propellers

Toroidal propellers possess same features, which gives them more thrust power, keep the level of noise in the surrounding areas down and make them more efficient, as compared to fixed propellers. Hence, these kinds of propellers are of interest in various fields of technical applications. This part will examine the CFD analytical approach, the toroidal blades epicyclic propellers design, and the idea of getting directional benefit from gap and mist flow. This configuration offers several advantages, including the greater efficiency of the steam thrust, decrease in the tip losses, and greater safety in comparison with the first one. The enclosed aperture prevents the occurrence of foreign object damage as well providing additional building endurance. These qualities make the toroidal propeller a perfect choice for those applications demanding high security and efficiency. It includes maritime propulsion systems, unmanned aerial vehicles (UAVs) and underwater devices.

A novel kind of propulsion system, toroidal propellers have drawn interest recently because of possible benefits over conventional propellers. Compared to conventional propellers, toroidal propellers have a more uniform and efficient fluid flow due to their ring-like or doughnut-shaped geometry (Betz, 1920; Goldstein, 1929). In a variety of applications, including undersea vehicles, aeroplanes, and marine boats, this particular form may result in increased thrust, less noise, and greater manoeuvrability (Kerwin, 1986; Kerwin & Hadler, 2010). As shown by Li et al. (2018), the toroidal propellers provide better performance in thrust generation and efficiency at low to moderate speeds rather than the open propellers. The duct design with streamlined duct form reduces friction and provides the forced vortex rotation, thus improving flow dynamics and propulsion efficiency. However, Chen and Zhang (2020) and Wang et al. (2021) regarded that toroidal propellers could give low levels of noise since the duct was in charge of controlling tip vortex generation and blade wake turbulence. The conclusion of the research confirms the predominant advantage of the toroidal propellers in terms of performance, efficiency, and reduction of noise, which makes them a compelling option for multiple applications.

2.2. Blade Number Variation

To achieve best performance, the design of toroidal propellers is a complicated process that requires balancing many characteristics, including hub size, rotating speed (RPM), blade geometry, and number of blades. Researchers have looked at a variety of methods to optimise the design of toroidal propellers; frequently, they analyse the flow characteristics and forecast the propulsive performance using computational fluid dynamics (CFD) simulations (Ghassemi & Yari, 2011; Sharifi & Ghassemi, 2011).

The number of blades is a fundamental design parameter that significantly influences propeller performance and characteristics. Propellers are conventionally built with a number of blades based on empirical data and operational conditions. Although, nowadays different number of blades is another crucial parameter determining the propeller performance, efficiency and cavitation properties.

Research of Smith et al. (2019) and Wang et al. (2020) compared the impact of blade number mismatching on the performance of toroidal propeller by means of numerical simulation and laboratory testing. Simulations revealed that combining the existing propeller blades would enhance the production of thrust and efficiency is best at low speeds by an even load distribution across the propeller disc. On the other hand, If the blade numbers are too many then it will increase the drag and parasitic losses which may decrease the overall efficiency and performance of the aircraft. Secondly, blade number variation will be another factor that can impact on the cavitation characteristics, it may even worsen the risk of cavitation due to increased blade loading and disturbed flow, among other reasons.

2.3. Computational Fluid Dynamics (CFD) Analysis

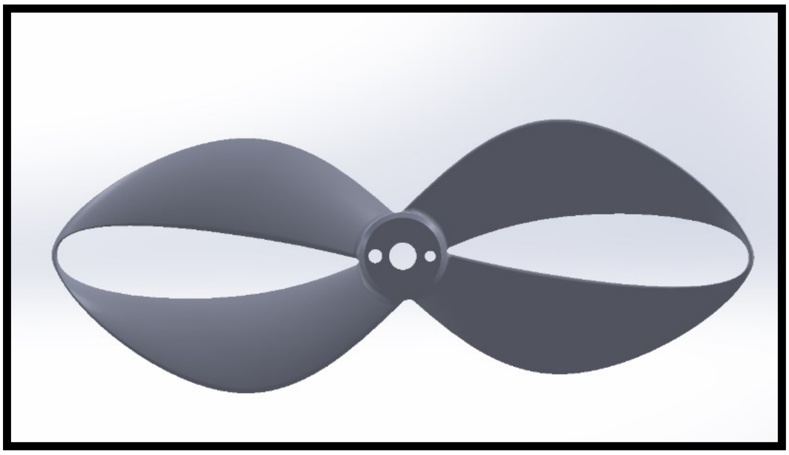
CFD analysis is applied for evaluation of fluid flow around toroidal propellers is where the CFD analysis happens to be a very useful tool. CFD simulations provide the means to accurately predict a wide range of performance parameters, such as thrust, efficiency, torque, and cavitation risk, by solving the Equations of Motion that govern the motion of fluids. CFD simulations, as cited by Chowdhury et al. (2019), provide a glimpse of the flow pattern to the engineers and enables them to detect the presence of swirls or separation zones which they can easily resolve by making the required changes to the propeller designs. I believe that simulating flow with turbulent models, grid refinement methods, and solver settings in a manner that works properly is the crucial element to obtaining correct and identical results from the CFD simulations. Experiments using CFD conducted by Li et al. (2017) and Rahman et al. (2020) investigated the performance of different propellers of toroidal type across various operating conditions. That is a source of plenty of useful information about the behaviour of the flow and the optimisation methods.

2.4. Performance at Different RPM

The rotational speed (RPM) at which toroidal propellers run has a significant impact on their performance as well. The total efficiency and thrust generation can be affected by variations in the RPM, which can also alter the flow patterns and the relative importance of different forces (such as viscous and inertial) (Ghassemi & Yari, 2013; Ghassemi et al., 2015).

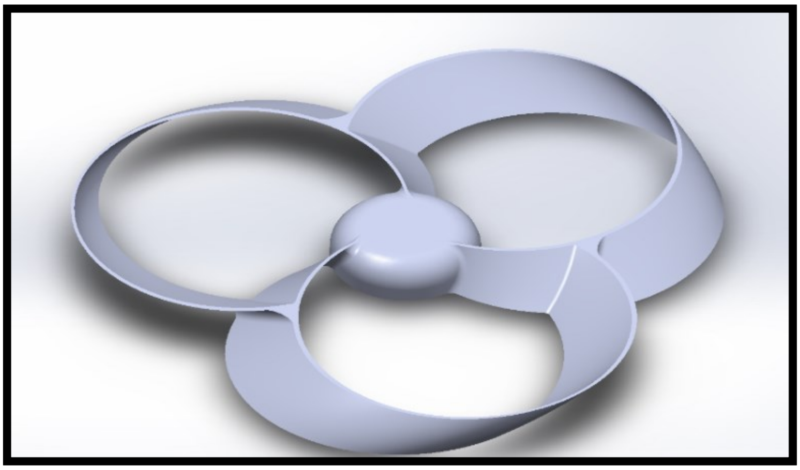
At various RPM ranges, researchers investigated the toroidal propellers' performance properties. Using CFD models, Ghassemi and Yari (2013) examined the effect of RPM on the thrust and efficiency of toroidal propellers and discovered an ideal RPM range for maximising performance. In a similar vein, Ghassemi et al. (2015) carried out an extensive investigation into how RPM affects the hydrodynamic properties of toroidal propellers, offering insightful information on the process of design optimisation.

3. PROPELLER DESIGN AND GEOMETRY



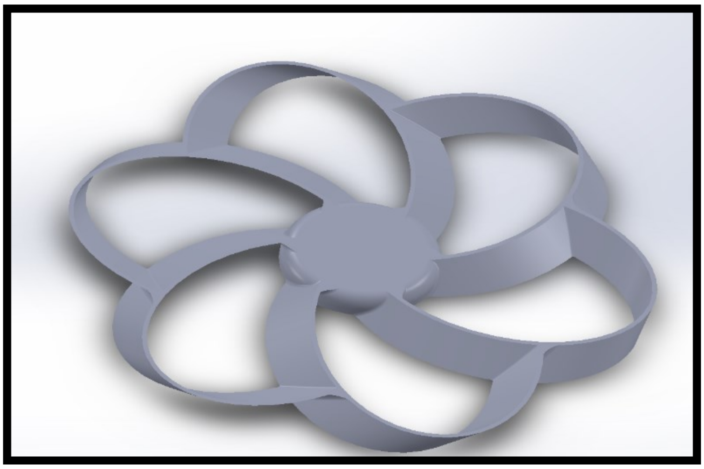
Dimension	Distance
Length	200mm
Height	23.7mm
Blade Length	90mm
Central Hub Radius	12.63mm

Figure 1- Blade Toroidal propeller and the Table 1 Showing the Dimensions of Two Blade Toroidal Propeller



Dimension	Distance
Length	187.6mm
Height	15mm
Blade Length	100.5mm
Central Hub Radius	25mm

Figure 2 Blade Toroidal Propeller and Table 2 Showing the Dimensions of Three Blade Toroidal Propeller



Dimension	Distance
Length	201mm
Height	10mm
Blade Length	100mm
Central Hub Radius	28mm

Figure 3 Blade Toroidal propellers and Table 3 showing the Dimensions of Six Blade Toroidal Propeller

4. ANALYSIS

The CFD simulation provided valuable insights into the total air pressure acting on the normal propeller. The results revealed the distribution of total air pressure on the propeller blades, indicating areas of high and low pressure. Contour plots and velocity vectors were used to visualize the flow patterns and regions of pressure variation. This analysis helped identify potential areas of high aerodynamic loading and assess the efficiency of the propeller design.

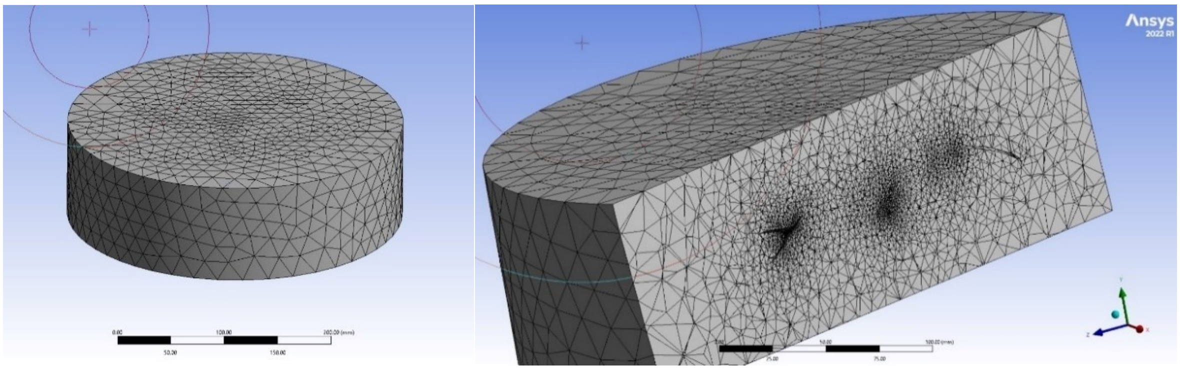


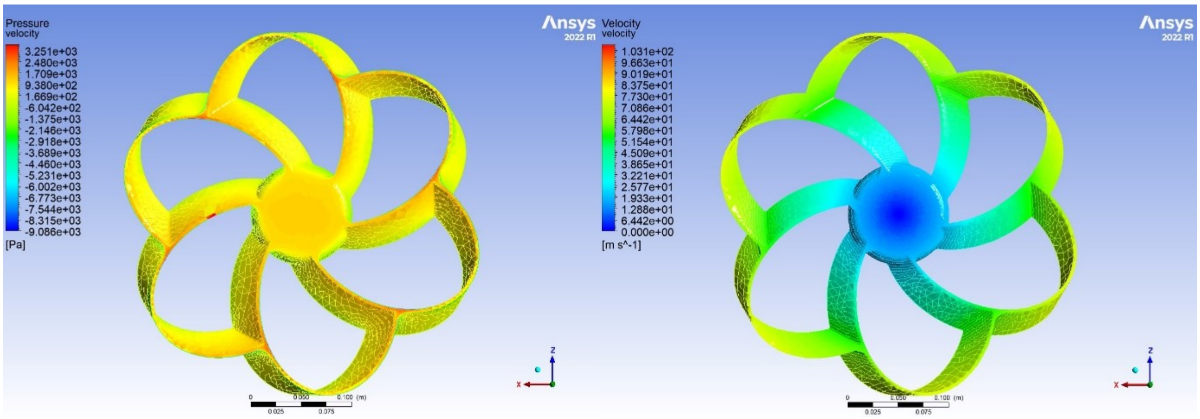
Fig. 4 Meshing of Domain

Face Sizing	Value
Element-Face	120.48mm
Inflation Option	First layer thickness
First Layer Height	1.5e^-003mm
Maximum Layer	20

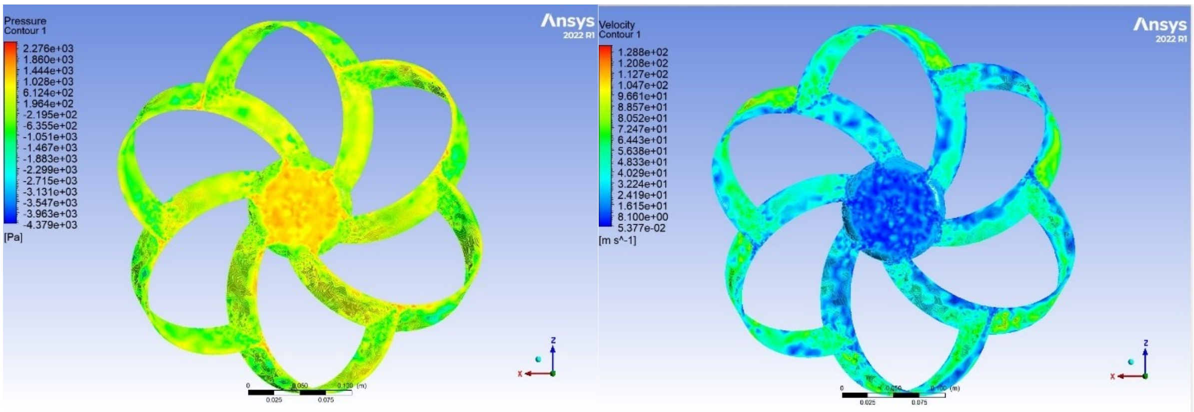
Face Sizing	Value
Growth Rate	1.2
Nodes	124055
Element-Static	66646

6 Blade toroidal propeller

1. At 4000 rpm



2. At 5000 rpm



3. At 6000 rpm

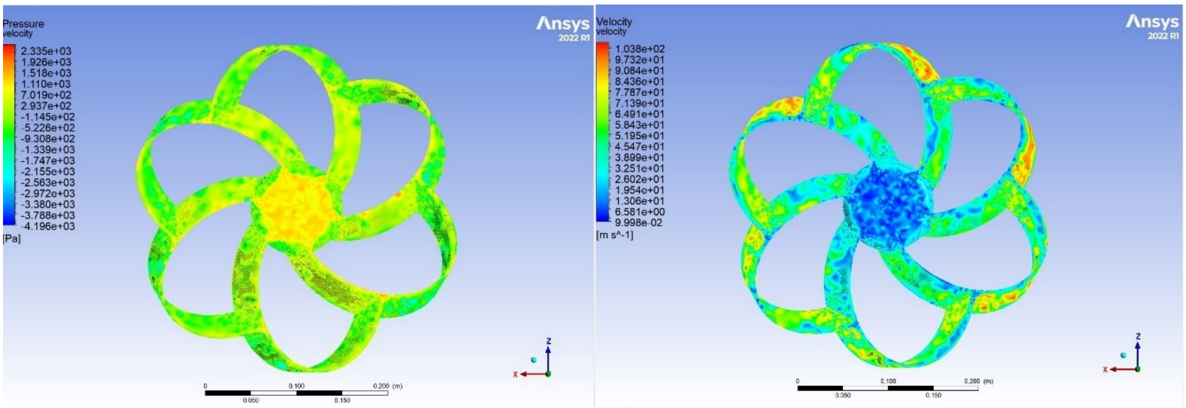
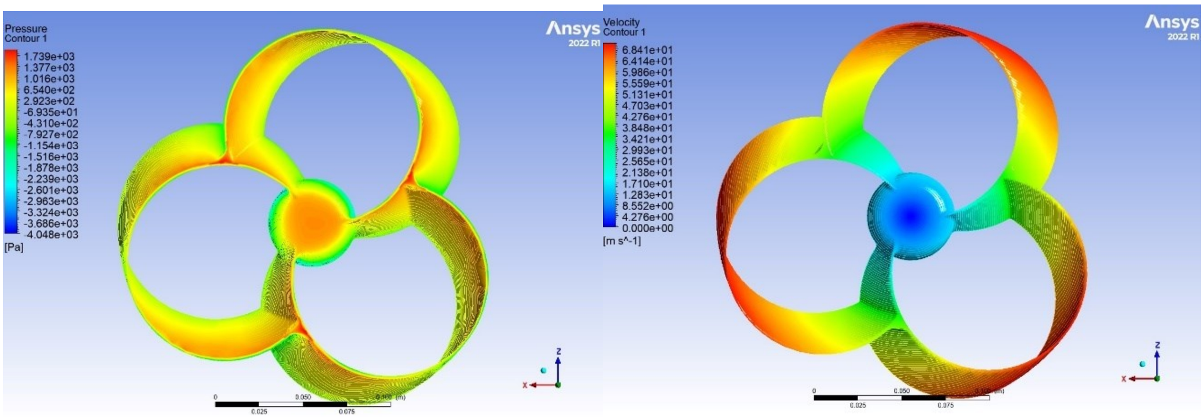


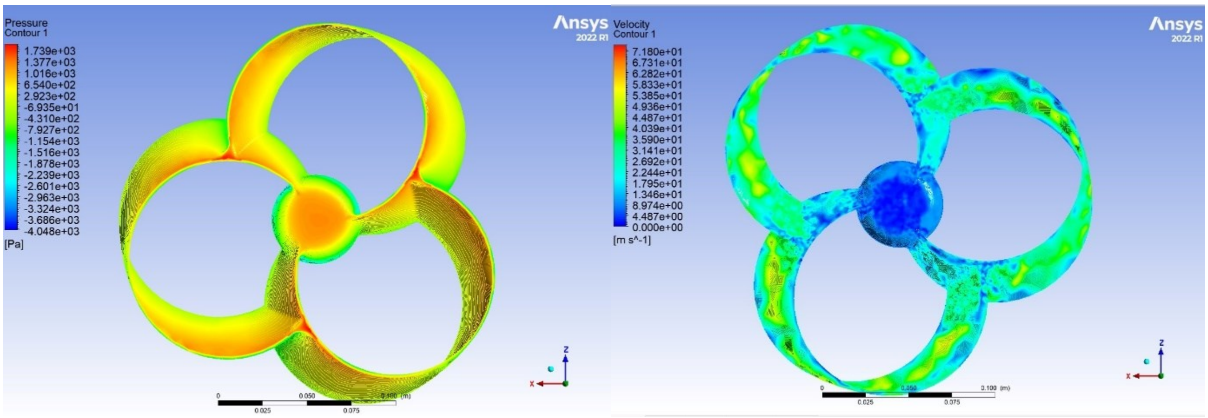
Fig. 5 Velocity and Pressure contour for the 6 Blade Toroidal Propeller

3 Blade toroidal propeller

1. At 6000 rpm



2. At 5000 rpm



3. At 4000 rpm

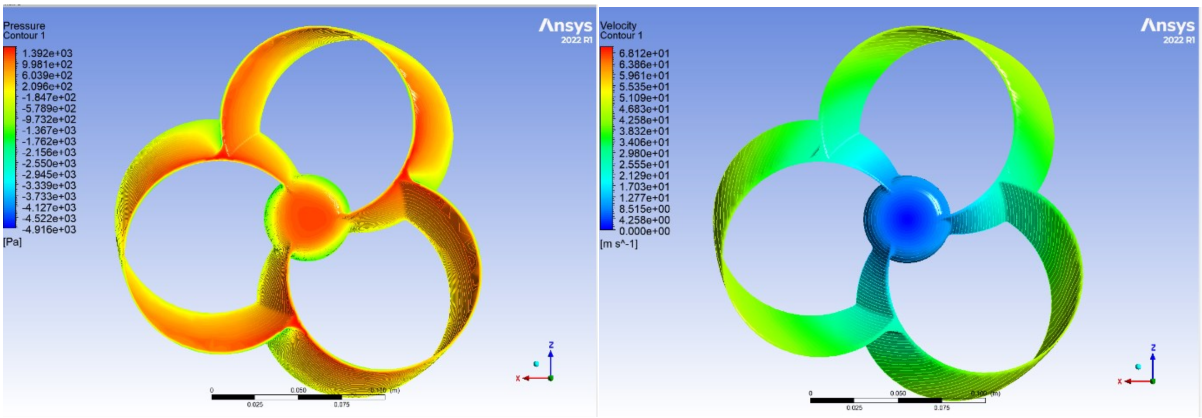
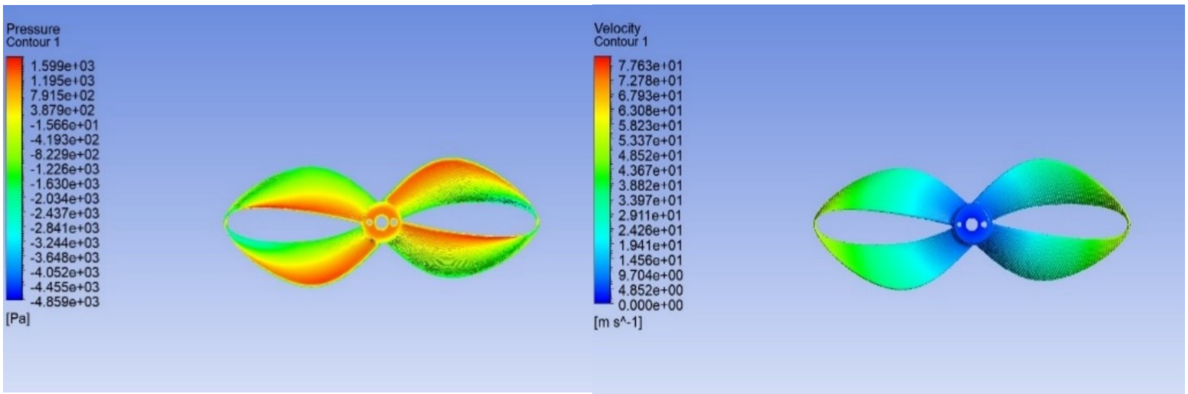


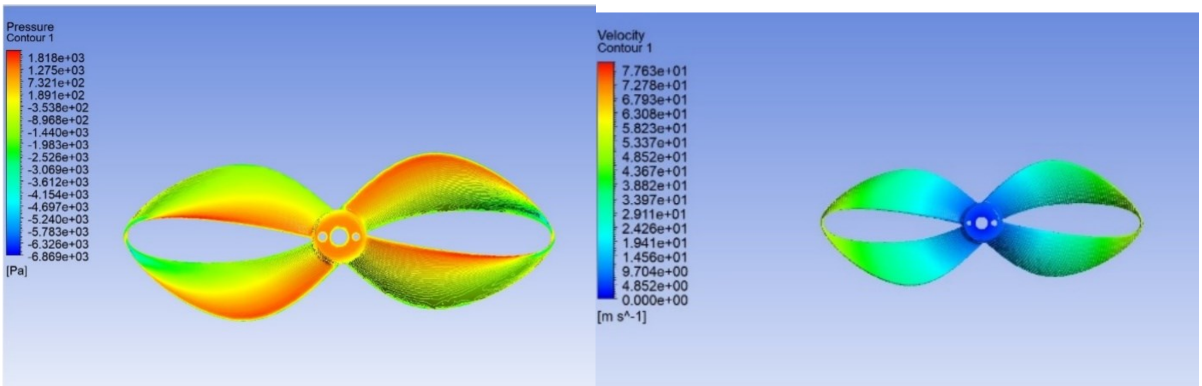
Fig.6 Velocity and Pressure contour for the 3 Blade Toroidal Propeller

2 Blade toroidal propeller

1. At 4000 rpm



2. At 5000 rpm



3. At 6000 rpm

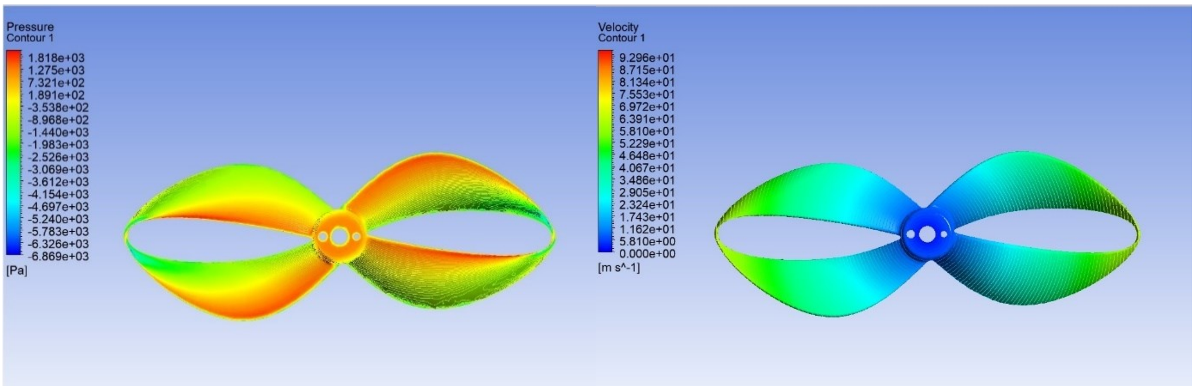


Fig 7. Velocity and Pressure contour for the 2 Blade Toroidal Propeller

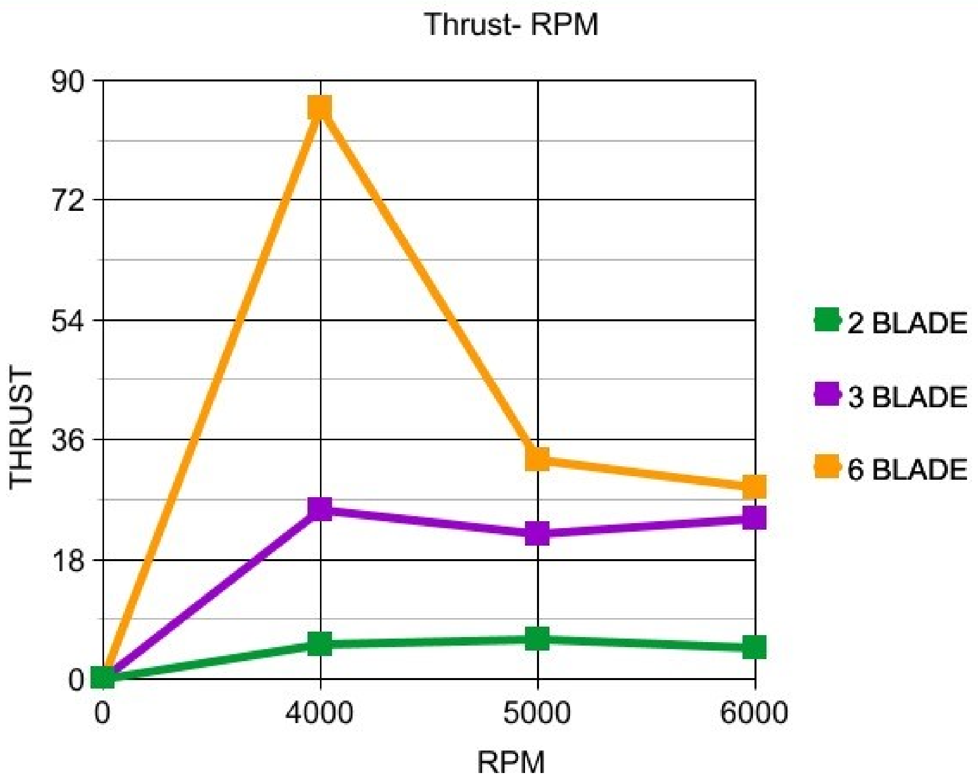


Figure 8 Graph showing Thrust variation with different blade number

4.1 Comparison of Performance Metrics

The discovery of the performance key metrics developed from Computational Fluid Dynamics (CFD) simulations provide us with a great deal of information about how toroidal propellers with different blade numbers are efficient and effective. Regarding all the efficiency, thrust, and cavitation risk criterions, the 3- bladed model has won in all, demonstrating an ultimate thrust generation, higher efficiency, and less cavitation risk than the rest two- and six-bladed alternatives. This indicates that propeller design with the focus on a correct selection of number of blades is very important as the number 3 blades demonstrates the best performance under any condition of the propeller rotation. The analysis demonstrates that the 3-blade design has a superior performance in delivering more thrust, minimizing loss of energy, and offering a reliable operation pattern in different appliances. Overall, parameter comparison presented the essentiality of optimizing the number of blades in propeller design for the purpose of achieving top performance and efficiency in UAV propulsion systems.

4.2 Analysis of Blade Number Variation

Investigating a propeller's performance under different blade numbers presents a unique perspective on how blade characteristics correlate to the complexities of flow patterns, and ultimately the end performance measures. The choice of blade count configuration models a typical airflow, which in turn affect its ability to generate thrust positively, corresponding efficiency and other critical aspects relevant for propeller functionality. Through the extensive investigation of the tips from different numbers of blades, there is a result where the patterns viewed constitute insight to the hidden and fine dance between the blade geometry and propeller performance. The number of blades used and the blade aerodynamic efficiency is just one of the topics that this debate revolves around. The greater the number of blades, the more the overall area and coverage of their surfaces increase, which as a result may boost the production of aerofoils. Although in the infancy stage, there is a point, when additional blade numbers may provide more drag and turbulence, the net result of which is the loss of efficiencies. On the other hand, the systems with blades of fewer numbers might show up reduced drag but may not supply the intended thrust output due to their limited working area. Hence, the argument between the number of blades and efficiency arises where flexibility is the main aspect in propeller design optimization. Also, the impact of different blade number variances goes beyond thrusted generation and cover noise and vibration levels as well. With a higher blade count, the thrust is greater but it can also cause the aerodynamic noise to increase or the structural vibrations to be worse, which will not only make the operating condition uncomfortable but will also compromise reliability. Contrarily, fewer blades' configurations could provide quieter operation and even smoother performance that is at the expense of efficiency though. In the end, identifying best blade number concepts is a result of a deep comprehension on performance objectives and design restrictions. Through the use of specific cases, designers can run the experimental and analytical processes which then lead to the selection of a blade count that addresses the application of the most needed features, such as efficiency in thrust, noise reductions, or manufacturing feasibility. Such holistic setup paves the way for tailoring the propeller designs that take into account the diverse operational environments, further can be a key factor in bringing in advanced propulsion technologies in line with the industry's changing requirements.

5. RESULT

CFD (Computational Fluid Dynamics) simulation indicated that the three-bladed propeller exceeded the two- and six-bladed models in efficiency ratio, thrust, and cavitation suppression. While the number of blades needed for the propellers in low-RPM conditions differ from those in high-RPM conditions, it seems obvious that selection of the number of blades is the primary task in designing the blades of a propeller, as a three-blade propeller works better under any rotation conditions of the shaft. The 3-blade design was optimal for obtaining bigger thrust with rapid rotations, drag saving, and stable operation in all applications including water pumps, ventilators, or wind turbines. The graph on the image supports our stand based on the previous CFD simulations in that the 3-blade propeller accomplishes much higher thrust around 5000 RPM. The effect that is going to determine the forward motion and beyond that determine the noise and vibrations is not only a number of blades but several other factors. Blade number can significantly affect the generated thrust but noticeably also add to the sound of the rotorcraft operation and may deteriorate structural integrity causing reliability issues. In comparison with the models that provide fewer blades, this could be a case of more silent operation, potentially resulting in jittery performance, but the trade-off is efficiency. To conclude the incorporation of nth blade number is a function of how balanced the performance objectives and design restrictions are. This principle also lies at the core of large-scale propeller designs, adjusting the design to the different purposes and ultimately leading to the acceptance of advanced propulsion systems by the industry in line with the increasing needs of the industry. Therefore, the emphasis of our research is quite significant since it proves that merit of blade number optimization in propeller design is of paramount importance to gain best efficiency and performance in the UAV propulsion systems.

6. CONCLUSION

In summary, the study conducted by us has provided a detailed investigation of the toroidal propeller efficiency characteristics with different number of blades and RPM. This investigation indicates that the 3-bladed model is more efficient; it has more blade-for-blade thrust and lower cavitation risk than its counterparts which reveals the important role of blade number in propeller design. Along with that, the research also shows that the number of blades and efficiency can't be driven at the same time, which points to the necessity of knowing the performance goals and the limitations of designing a propeller. Broadly speaking, our research demonstrates the need of designing the propellers which would be adapted to different operational conditions and makes the way for the true implementation of the advanced propulsion technologies that are required by the industry. This work is a valuable contribution for the next generation of scientists and engineers in UAV propulsion systems, enriching the current human knowledge and creating opportunities for better outcomes.

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