

TOROIDAL PROPELLER DESIGN - A COMPARATIVE STUDY ON THRUST GENERATION, VORTEX BEHAVIOUR, AND WIND DISPERSION

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ABSTRACT: Propellers have been fundamental in various fields, including aviation, marine transportation, and drone applications, for generating thrust by accelerating fluid or air. Their design and efficiency significantly impact performance, making them a crucial element. Toroidal propellers represent an innovative approach to propulsion systems, characterized by a unique ring-shaped configuration. This study introduces a novel Toroidal propeller design, which was conceptualized and modelled using SolidWorks CAD software and subsequently simulated using Ansys Fluent CFD software. The design was standardized at a fixed diameter to facilitate a comparative investigation to determine the most effective design based on parameters such as thrust generation, vortex behaviour, and wind dispersion. Various design configurations were explored, with adjustments made to the number of blades and attack angles. Additionally, the optimal rpm for operation was identified as a critical variable, with its influence on propeller performance thoroughly examined. A mesh independence test was performed to ensure the accuracy and reliability of the results obtained. The findings of the study revealed that the Tri-bladed propeller exhibited the highest thrust generation initially but suffered from a notable decline in thrust during operation. Conversely, the Toroidal propeller consistently demonstrated superior performance, generating higher thrust levels while exhibiting reduced vortex formation and a broader wind dispersion pattern across all configurations. However, operating at 8000 rpm resulted in increased thrust generation, albeit with compromised stability due to a skewed airflow. Ultimately, the Twin-bladed Toroidal propeller, configured with a 35° attack angle, emerged as the optimal design, showcasing minimal vortex formation, consistent, and relatively high thrust generation, particularly at 6000 rpm.

KEYWORDS: *Toroidal; CFD; Attack angle; Trust; Vortex.*

1.0 INTRODUCTION

Paragraph: use this for the first paragraph in a section, or to continue after an extract. The propulsion technology, spanning from the early 1800s to the 1900s. In particular, the propellers, used in aviation, maritime, and renewable energy, and latest applications in drone technology. Conventional propellers in drones, characterized by fixed pitch blades, face challenges such as energy loss, induced drag, noise production, potential structural stress, and reduced control and stability due to the formation of vortices at the blade tips. In response to these challenges, we explore the use of toroidal propellers, to address the limitations of conventional propellers, for potential improvements in efficiency, noise reduction, and environmental impact by managing airflow and reducing vortices. This study aims to design and analyze propellers in both conventional and toroidal configurations using SolidWorks and Ansys (Fluent) simulation. It will evaluate the effects of propeller design, number of blades, and blades, angle of attack on thrust generation and vortex behavior.

The propeller stands as a pivotal component in drone technology [1], facilitating acceleration and transferring motor-generated torque into thrust via its rotating blades [2]. Thrust arises from pressure differentials created between the blade's upstream and downstream, inducing momentum opposing aerodynamic forces on the structure [3]. The "Kutta-Jukovsky theorem"

highlights the necessity of vorticity for lift force generation on revolving propeller blades [4]. Notably, severe vortices occur at blade tips due to differing air pressures, causing lift force reduction to zero. These vortices induce downwash, impacting propeller behaviour and lift [5].

Critical parameters influencing thrust, vortices, and noise in propellers include: i). Attack angle: Angle between chord line and fluid velocity direction, ii). Twisting: Originating from wing torsion when the span's axis parallels the wing's axis, iii) Number of blades: Individual blades attached to the propeller's hub, iv) Blade area: Total exposed surface area of propeller blades, v) Design layout: Structural arrangement encompassing blade positioning, orientation, shape, and hub-blade distribution. CAD enables precise modelling, refining, and iterating propeller components with increased accuracy and reduced reliance on physical prototypes. Notably, software such as CATIA and Autodesk Inventor and SolidWorks facilitate intricate propeller designs, each offering unique features and pricing structures. CFD is indispensable in propeller development, offering insights into aerodynamic behaviour and facilitating performance optimization. It enables visualization of airflow patterns, eliminating the need for physical prototypes [6]. Mesh generation, a fundamental CFD step, divides geometry into discrete elements, facilitating detailed analysis of fluid flow behaviour [7]. Turbulence models like the SST $k-\omega$ and $k-\epsilon$ models are crucial for simulating turbulent flows accurately. Each model possesses unique strengths and limitations, with the choice depending on specific flow requirements and computational resources available [8]. Establishing boundary conditions is essential for accurately simulating fluid flow in CFD. Conditions such as no-slip, axisymmetric, inlet, outlet, and periodic boundaries delineate different zones within simulations, guiding flow behaviour and achieving accurate solutions [9].

2.0 RESULTS AND DISCUSSION

This study systematically investigates various propeller designs to determine the most efficient configuration. Performance evaluation focuses on thrust generation and vortex formation, crucial factors influencing overall propeller effectiveness.

2.1 Case 1

A conventional propeller design with twin blades operating at a 30° attack angle and 6000 rpm was studied. The results illustrated a notably streamlined flow pattern, evident in both the streamline and vector profiles. The Streamlines Produced, depicted in Figure 1 (a), vividly demonstrate the fluidity and coherence of the flow, underscoring its streamlined character. Additionally, the Vector Profile, displayed in Figure 1 (b), reinforces the observation of a smooth flow pattern. However, despite the overall streamlined flow, the experiment unveiled regions of significant vortex turbulence, as depicted in Figure 2. These vortex formations exhibited a wide and irregular distribution throughout the flow field, presenting areas of complexity and turbulence amidst the otherwise smooth flow. Furthermore, the experiment documented a maximum air velocity of 4.92 m/s. This data point, coupled with the measured thrust force of 72.44 N at the 5-second mark, underscores the system's ability to generate substantial force under these specific flow conditions. The combination of these quantitative results and the visual representation from the figures offers a comprehensive understanding of the flow dynamics observed in Case 1 of the experiment.

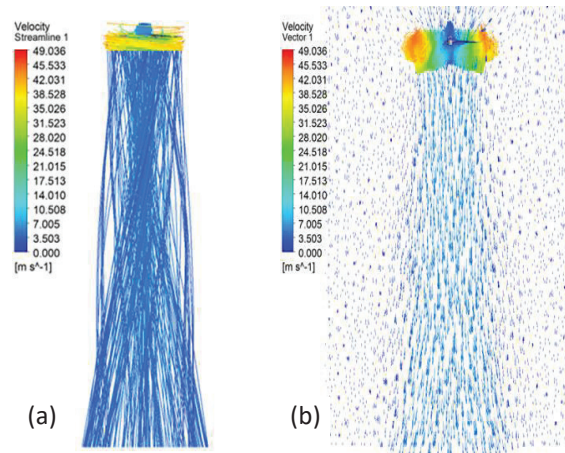


Figure 1: (a) Streamlines produced for twin-bladed conventional propeller (b) Vector profile generated for twin-bladed conventional propeller

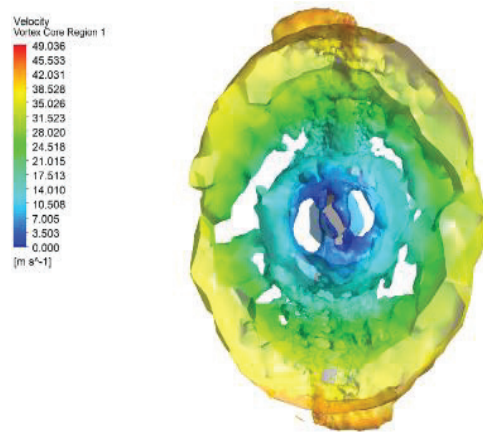


Figure 2: Vortex formations for twin-bladed conventional propeller

2.2 Case 2

For the Tri-Bladed conventional propeller operating under similar conditions, the outcomes exhibited a less streamlined flow pattern characterized by a narrower air spread and increased vortex turbulence. Despite achieving a higher air velocity of 5.24 m/s, the recorded thrust force of 73.24 N fell slightly below expectations, likely attributable to heightened turbulence. The simulation results for the Tri-Bladed conventional propeller design at a 30° attack angle and 6000 rpm depicted a comparatively less streamlined flow, evidenced by the limited air distribution and its skewness to one side, as depicted in both the Streamlines Produced (Figure 3 (a)) and the Vector Profile (Figure 3 (b)). These figures collectively underscore the constrained air distribution within the flow.

Significantly, the results revealed pronounced vortex turbulence formations, as illustrated in Figure 4. Additionally, the experiment measured a maximum air velocity of 5.24 m/s, indicating relatively high-speed air movement compared to Case 1, despite the restricted spread. Furthermore, the thrust force generated was documented at 73.24 N at the 5-second mark. This measurement fell below expectations for a Tri-bladed propeller design, which typically anticipates enhanced performance due to the presence of an additional blade compared to Case 1.

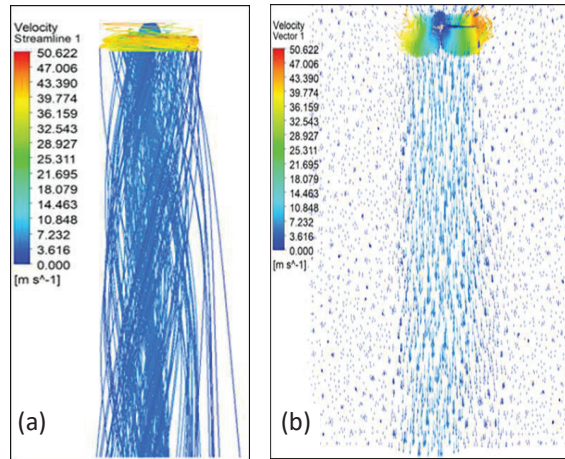


Figure 3: (a) Streamlines for tri-bladed conventional propeller (b) Vector profile for tri-bladed conventional propeller

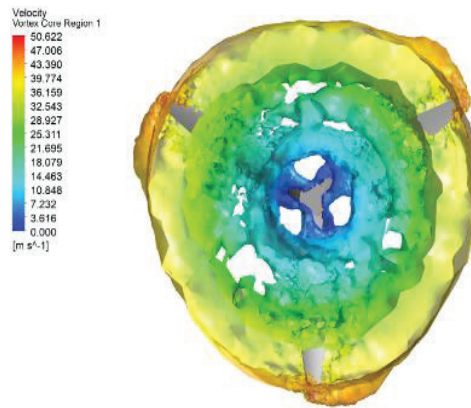


Figure 4: Vortex formations for Tri-bladed conventional propeller

2.3 Case 3

The twin-bladed toroidal propeller exhibited a uniformly streamlined flow with minimal vortex turbulence, indicating efficient airflow and force generation capabilities at 6000 rpm. The design achieved a maximum air velocity of 4.93 m/s and a thrust force of 74.31 N, as shown in Figure 5 (a) and (b), which illustrate the smooth and even flow and regular uniform air movement, respectively. The experiment revealed that the toroidal fan blade designs had low vortex turbulence, as depicted in Figure 6, in comparison to the Vortex formation by the twin-bladed conventional propeller. Quantitatively, the maximum air velocity and thrust force of 4.93 m/s and 74.31 N, respectively, were achieved at the 5-second mark, demonstrating the system's strong airflow and force generation capabilities.

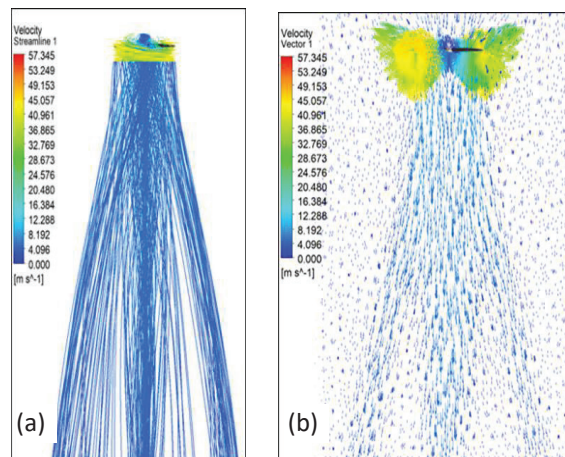


Figure 5: (a) Streamlines for twin-bladed toroidal propeller (b) Vector profile for twin-bladed toroidal propeller

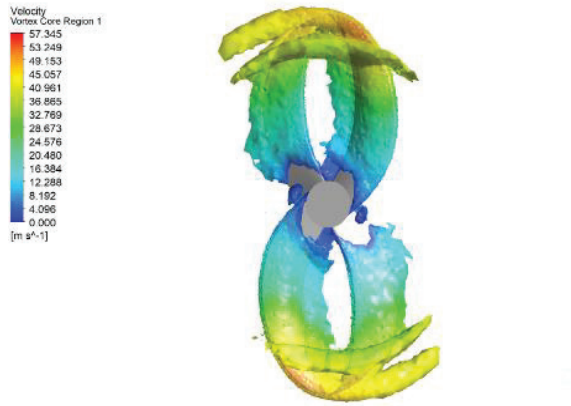


Figure 6: Vortex formations for twin-bladed toroidal propeller

2.4 Case 4

The tri-bladed Toroidal propeller displayed a distinctive flow pattern with asymmetric airflow through the blades. Interestingly, the vortex turbulence was relatively low compared to the conventional design, which is a promising feature for force production at 6000 rpm. The configuration achieved a high air velocity of 8.05 m/s and a significant thrust force of 447.29 N, highlighting its potential for force production. In the case of the Tri-bladed Toroidal propeller, a unique and non-uniform yet streamlined flow was observed, which was particularly evident in the way air flowed asymmetrically through the blades. This skewness in airflow, depicted in Figure 7 (a), could lead to imbalances during flight, a key point to be considered during propeller development. Complementing this observation, Figure 7 (b) illustrates the Vector Profile generated, providing further insight into the behavior of the flow in terms of direction.

Furthermore, the design recorded a relatively low level of vortex turbulence, as shown in Figure 8, compared to the Tri-bladed conventional design. This is a significant finding, as it suggests that the design could be more efficient in terms of energy consumption and noise reduction.

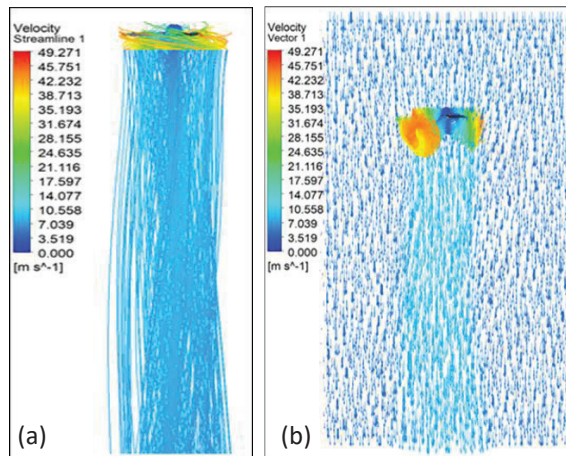


Figure 7: (a) Streamlines for tri-bladed toroidal propeller
(b) Vector profile for tri-bladed toroidal propeller.

In terms of quantitative results, the experiment achieved a maximum air velocity of 8.05 m/s, which is relatively high compared to all the previously discussed designs. Additionally, a significant thrust force of 447.29 N was generated at the 5-second mark, indicating the potential of the design in force-producing capability. This finding suggests that the Tri-bladed Toroidal propeller could be a promising alternative to traditional propeller designs, particularly in applications where high thrust force and efficient energy consumption are critical factors.

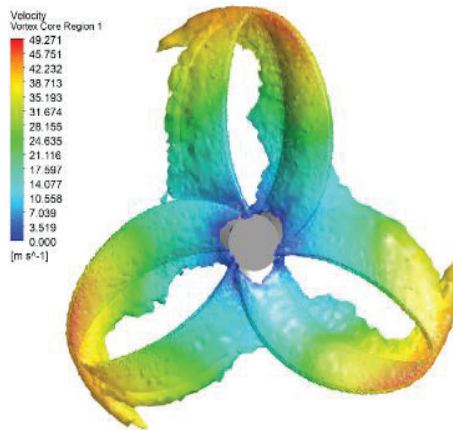


Figure 8: Vortex formations for Tri-bladed toroidal propeller

2.5 Case 5

The twin-bladed toroidal propeller, when operating at 8000 rpm, exhibited a uniform flow but encountered a sudden decrease in air velocity upon exit. Despite this fluctuation, the design achieved a maximum air velocity of 7.04 m/s and a thrust force of 88.04 N, indicating effective force generation capabilities.

At an angle of 30° and operating at 8000 rpm, the simulations revealed several noteworthy findings. The propeller produced a relatively uniform and streamlined flow at higher rpm's of 8k, as shown in Figure 9 (a), which illustrates the Streamlines Produced. This figure highlights the consistency and uniformity of the flow at these higher revolutions. The Vector Profile generated, shown in Figure 9 (b), further visualizes the streamlined nature of the airflow. However, the experiment also identified a critical issue: a sudden dip in air velocity was observed as the air flowed out of the propeller, which could potentially cause imbalances during flight. This unexpected decrease in velocity is a point of concern that needs to be addressed during propeller development. In terms of quantitative results, the experiment measured a maximum air velocity of 7.04 m/s, indicating the propeller's capability at higher rpm's. In terms of thrust, the propeller generated a significant force of 88.04 N at the 5-second mark, demonstrating its effectiveness in producing thrust.

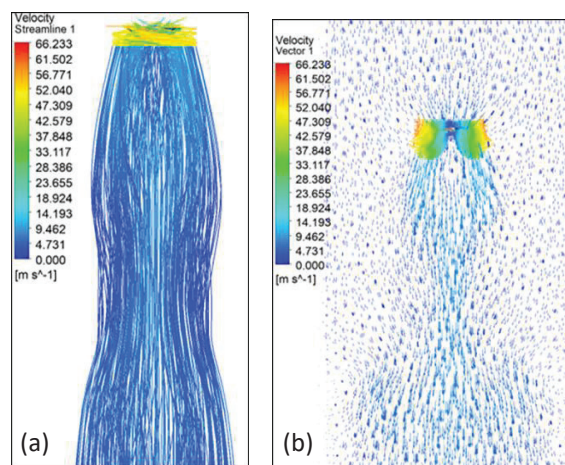


Figure 9: (a) Streamlines for Twin-bladed toroidal propeller at 8000 rpm
(b) Vector profile generated for Twin-bladed toroidal propeller at 8000 rpm

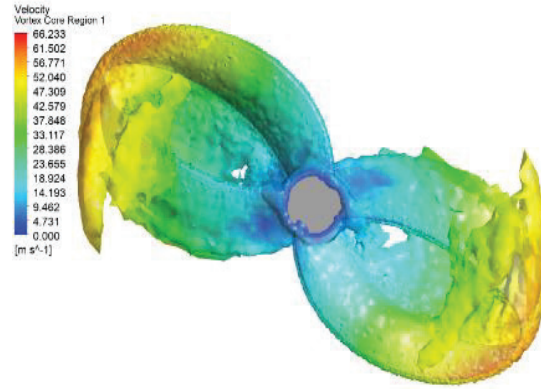


Figure 10: Vortex formations for Twin-bladed toroidal propeller at 8000 rpm

Lastly, Figure 10, which visualizes the Vortex Formations, provides additional insight into the complex flow dynamics, particularly focusing on the areas where turbulence and vortices are more pronounced. This information is crucial for optimizing the design and improving the overall performance of the propeller.

2.6 Case 6

The twin-bladed toroidal propeller, when operating at 6000 rpm and a 35° angle of attack, exhibited a uniform flow with minimal vortex turbulence. This configuration significantly increased the thrust force to 231.32 N, highlighting the impact of blade angle on performance. At 6000 rpm and a 35° angle of attack, the twin-bladed toroidal propeller produced a more uniform and streamlined flow, as shown in Figure 11, which displays the Streamlines Produced, highlighting the flow's uniformity. Additionally, the Vector Profile, as shown in Figure 12, visualizes the spread of the flow, indicating its adequacy in covering a larger take-off area for a drone.

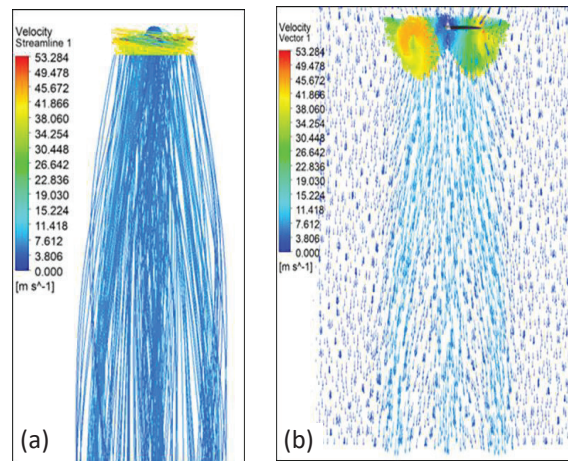


Figure 11: (a) Streamlines for twin-bladed toroidal propeller at 35°
 (b) Vector profile generated for twin-bladed toroidal propeller at 35°

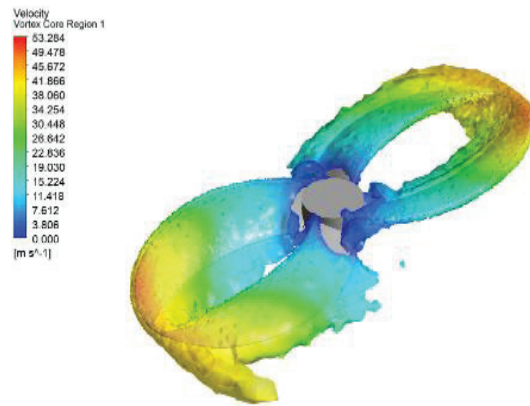


Figure 12: Vortex formations for twin-bladed toroidal propeller at 35°

Remarkably, the vortex turbulence observed was also minimal, a crucial aspect depicted in Figure 12, focusing on the Vortex Formations. This finding is significant, as it suggests that the design could be more efficient in terms of energy consumption and noise reduction. A significant finding of the experiment was that increasing the blade angle to 35° amplified the thrust force by more than threefold. This adjustment led to a maximum air velocity of 5.91 m/s and a notable thrust force of 231.32 N, achieved at the 5-second mark. These outcomes underscore the effectiveness of the blade angle modification in enhancing the overall performance, especially in terms of thrust force.

In summary, the twin-bladed toroidal propeller operating at 6000 rpm and a 35° angle of attack exhibited a uniform flow with minimal vortex turbulence, significantly increasing the thrust force and highlighting the impact of blade angle on performance. The design's minimal vortex turbulence and uniform flow suggest that it could be more efficient in terms of energy consumption and noise reduction, making it a promising alternative to traditional propeller designs.

3.0 ANALYSIS

A comparative examination of propeller performance identified Case 4 and Case 6 as standout configurations, showcasing superior thrust force generation and uniform airflow. This analysis underscored the importance of optimizing both attack angle and rpm to enhance performance. To provide a comprehensive evaluation for engineering decisions regarding fan designs for drones, a comparative analysis was conducted on the performance of each propeller design.

Figure 13 illustrates the performance of the propellers across all cases, focusing on their ability to accelerate air and achieve velocity as it passes through. This graph visually depicts the streamlined airflow patterns generated by each propeller design, aiding in the evaluation of their efficiency. It's noteworthy to emphasize the consistent variation in velocities depicted in Figure 13 across Cases 1, 2, 3, 4, and 6, with Case 4 achieving the highest air velocity. However, Case 5 deviates from this consistency, experiencing a sudden drop in air velocity at 0.7m.

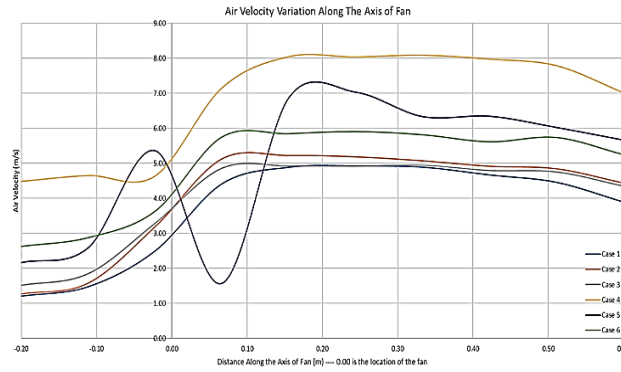


Figure 13: Velocity variation in upstream

Figure 14 depicts the performance of each propeller in terms of providing downward thrust to the airflow over time, offering valuable insights into the consistency of lift force variation during drone take-off. Notably, Case 4 and Case 6 excel in generating downward thrust force over time, while the remaining cases show similar levels of thrust force production, as illustrated in Figure 14. This comparison provides a clear indication of the variations in thrust generation among different propeller designs.

Furthermore, Figure 15 displays the measurement of wind spread 0.5m away from the hub for each propeller. This graph showcases the variation in wind spread and the distance of airflow upon exiting each propeller. It is crucial to recognize that propellers generating a more uniform wind spread tend to be more efficient in thrust generation, enhancing stability and control while optimizing performance. Understanding the relationship between downward thrust force and wind spread can lead to improved propeller design and selection, ultimately enhancing the overall performance and efficiency of drone operations.

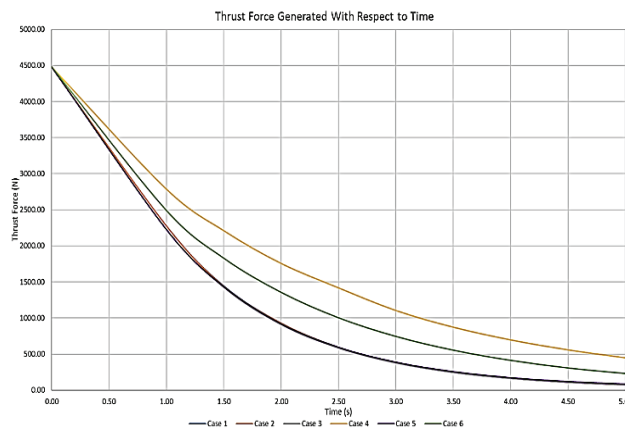


Figure 14: Thrust force variation with time

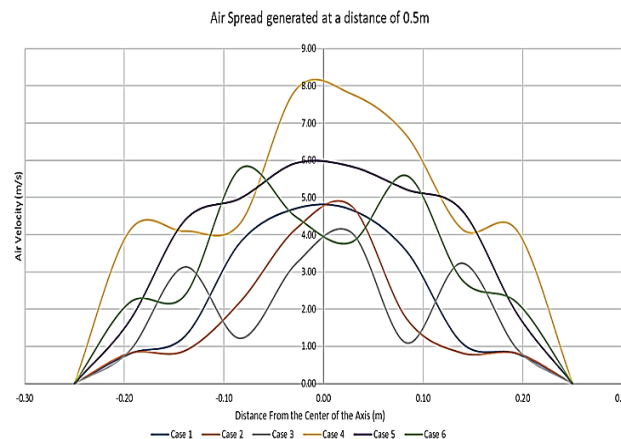


Figure 15: Wind spread 0.5m away from the hub

4.0 CONCLUSION

In summary, the series of simulations conducted has yielded valuable insights into the optimal design and operational parameters for drone propellers. Among the standout findings is the superior performance of the twin-blade toroidal fan design in generating streamlined airflow and effective downward thrust. However, while the tri-blade toroidal propeller (case 4) initially seemed promising, further analysis through vector and streamline diagrams revealed non-uniform and asymmetric airflow patterns, potentially leading to operational imbalances. This indicates the need for further refinement and development of the tri-blade design.

Analysis of blade attack angles revealed a critical discovery: a blade angle of 35° , as demonstrated in case 6, generates significantly higher thrust and lift compared to smaller angles. Conversely, a 30° angle was found insufficient in allowing adequate airflow to hit the blade surface, resulting in reduced lift. However, exceeding 35° could lead to increased drag, thereby negatively impacting lift. This underscores the importance of optimizing attack angles for maximum aerodynamic efficiency.

The simulations identified 6000 rpm as the ideal rotational speed for propellers. Higher rpm's, such as those tested in case 5, were found to generate excessive turbulence, posing challenges to flight stability. This insight is particularly relevant for drones with smaller blade sizes, where maintaining 6000 rpm can enhance stability and performance.

In conclusion, the toroidal design, particularly the twin-blade configuration, offers superior performance in terms of streamlined airflow and thrust generation. Optimizing attack angle and rpm further enhances propeller efficiency, with 6000 rpm identified as the ideal rotational speed for stability and performance. These insights serve as valuable guidance for future propeller design and optimization endeavours.

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