International Journal of Engineering and Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 14 Issue 6 June 2025 || PP 71-81

Analytical and Computational Assessment of Performance of Flat and Toroidal Drone Propellers

A.A. Okon[1], I.O. Asuquo[2], A.E. Uyah[3], D.A. Jacob[4]
[1,2,3,4]*(Department of Mechanical and Aerospace Engineering, University of Uyo, Nigeria)*

ABSTRACT: *A Propeller converts the kinetic energy of a spinning shaft into lift to move an object through a fluid. This study used a computational simulation approach to assess the performance of 2, 3 and 4-blade configurations of flat and toroidal blade propellers. The propellers were designed using Autodesk Fusion 360 (CAD) and simulated in Autodesk CFD. Both propellers were simulated at 8,000 rpm in ambient air at 20°C. A detailed analysis of the propeller-generated lift, airflow velocity, power consumption, and lift efficiency was carried out. The results showed that the toroidal propellers significantly outperformed the flat propellers in lift, generating between 6 - 77% more thrust across all blade configurations, while significantly trailing it in efficiency, with the flat propellers generating between 45 - 64% more thrust per watt across all blade configurations. For drone technology, the high lift capabilities of the toroidal propellers could allow for smaller propeller sizes while maintaining or even exceeding the thrust levels of flat propellers. This could lead to more compact and lightweight drones, improving flight performance. However, the reduced efficiency of these propellers only makes them suitable for heavyweight applications with low range.*

KEYWORDS -*CFD, Flat, Power, Propeller, Toroidal*

Date of Submission: 15-06-2025 Date of Acceptance: 30-06-2025

I. INTRODUCTION

1.1 Introduction

Drones, also known as unmanned or unpiloted aerial vehicles (UAVs), have a rich history. They were initially used for military purposes and later expanded into civil applications. Before the advent of drone technology, product distribution was a challenge due to traffic, difficult terrains, high cost of fuel. Drones have become increasingly prevalent in transport due to technological advancements, reduced component costs, and improved battery power.In drone applications for transport, propeller design plays a critical role in determining thrust generation and energy efficiency. Traditional flat-blade propellers, while efficient, may be limited in their lift capabilities, especially for high-load applications. Additionally,traditional flat-blade propellers have sharp tips to improve aerodynamic efficiency, reducing drag. However, these sharp tips pose significant safety risks to people, as they can cause severe injuries if drones malfunction or collide with individuals.Considering the applications of drones in transportation, these challenges hindering widespread adoption must be addressed, and therefore call for a technological assessment of propellers to meet global human and urban development standards. Recently, toroidal propeller designs have shown promise in enhancing thrust and noise reduction, but lack sufficient analytical and computational performance validation. Despite their potential, there remains a gap in understanding how toroidal propellers compare to conventional flat blades in both lift and energy efficiency across different blade configurations. This study addresses this gap by systematically evaluating and comparing the performance of 2, 3, and 4-blade flat and toroidal propellers using computational simulations, aiming to inform future drone blade design for optimised performance. This work, therefore, sets out to evaluate Toroidal propellers.A toroidal drone propeller is a specialised type of propeller designed for drones, featuring a unique ring-shaped design. This design reduces noise and increases safety and thrust compared to flat propellers. Toroidal propellers can provide smoother and more stable flight characteristics due to their looped structure. A toroidal propeller, thus, represents a significant advancement in drone technology, merging efficiency with quieter operation.

The design of Toroidal propellers is characterised by a continuous, closed-loop blade design, with each loop resembling a torus or ring. Unlike flat propellers with discrete blades attached to a central hub, toroidal propellers feature pairs of blades that are connected at an end, forming smooth, continuous loops between pairs of blades.

1.2 Mathematical Framework

Thrust in any propeller, including toroidal propellers, is generated by accelerating air mass. According to Newton's Third Law of Motion, the force exerted on the air by the propeller (action) produces an equal and opposite force on the propeller itself (reaction), generating thrust.

$$T = m \cdot (V_{exit} - V_{inlet}) \dots (1)$$

Where:
T is the Thrust
m is the mass flow rate of air through the propeller.
V_{inlet} is the velocity of air approaching the propeller.
V_{exit} is the velocity of air exiting the propeller.
For a toroidal propeller, the mass flow rate m is given by:

$$m = \rho \cdot A \cdot V \dots (2)$$

Where:
ρ is the air density.
A is the effective cross-sectional area swept by the propeller.
V is the velocity of the air relative to the propeller.

The aerodynamic forces involved in thrust generation can be described using Bernoulli's principle and the conservation of momentum. The shape of the propeller blades accelerates the air over the top surface relative to the air along the bottom surface, thus creating a pressure difference between the top and bottom surfaces of the blade (Morgado, J., Abdollahzadeh, M., Silvestre, M. A. R., & Páscoa, J. C, 2015).To understand the forces acting on each propeller blade, the blade is studied in sections, analysing the forces due to pressure gradient on each segment (figure 1), and then, using the results from all the segments, determining the forces acting on the entire blade. This is the Blade Element Theory *(Auld et al., University of Sydney, 2006)*.

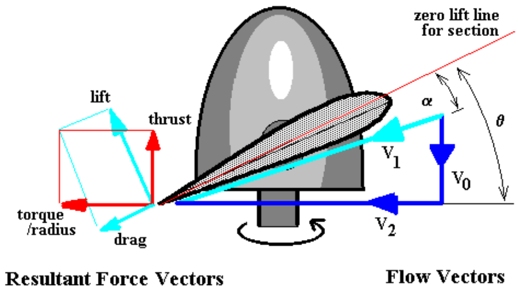

Fig. 1. Sectioned View of a Blade Element

Toroidal propellers have a looped, doughnut-like shape, uniquely influencing airflow compared to flat propellers. The toroidal shape minimises tip vortices - a primary source of drag in conventional propellers - by continuously curving the airflow on the blade back on itself. (Vu, X. D., Nguyen, A. T., Nha, T. L., Chu, Q., & Dınh, C. T, 2024).In conventional propellers, the high-pressure air from below the blade spills over to the low-pressure area above the blade at the tips, creating vortices that cause drag and reduce efficiency (Wang, Z., Ma, H., Zhong, Y., Yang, Y., & Zhang, Q, 2024). The toroidal design mitigates this by distributing the vortices that are generated by the propeller across the entire curved shape instead of just at the tips. This makes it effectively dissipate faster in the atmosphere. Thus, the vortex doesn't propagate as far, making it less likely to be heard. To accurately model the complex airflow around Toroidal Propellers, Computational Fluid Dynamics (CFD) was employed. These Simulations solve the Navier-Stokes equations for Fluid Flow. Mathematically:

$$\rho\,(\frac{\partial t}{\partial u} + (u \cdot \nabla)u) = -\nabla p + \mu \nabla^2 u \dots (3)$$

Where:
u is the velocity field.
p is the pressure field.
μ is the dynamic viscosity of the air.

Research has shown that a major factor that has limited the deployment of drones for their use in urban environments is the noise that they generate. Psychoacoustic experiments conducted in 2017 by NASA Langley Research Centre (Siddhartha and Stephen, 2022)showed that humans reported a higher level of sensitivity to noise produced by small multirotor drones than to noise from other traffic. Thus, quieter propellers could accelerate public acceptance and commercial adoption of drones. They proposed a "Quiet Toroidal Propeller", consisting of two blades looping together so that the tip of one blade curves back into the other. They claim that this closed-form structure minimises the drag effects of swirling air tunnels (i.e., vortices) created at the tips of blades and strengthens the overall stiffness of the propeller. These features reduce the propeller's acoustic signature. Additionally, their tests of prototype toroidal propellers on commercial quadcopters demonstrated thrust levels comparable to those of conventional propellers at similar power levels. Reduced sound levels allowed toroidal-propeller-equipped drones to operate without taxing human hearing at a distance half that of typical operation (Sebastian et al., 2019).

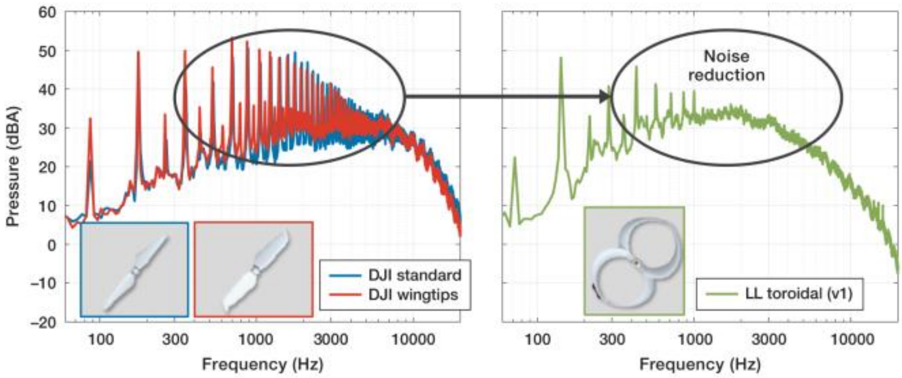

Fig. 2. The comparison between (a) Conventional propellers used on DJI's Quadrotors and (b) the Toroidal propeller shows the significant reduction of discernible noise achieved by the Toroidal propeller.

Separate research compared the performance variations of 3D-printed toroidal and standard propellers, focusing on the implications for drone propulsion systems. The project seeks to learn more about thrust efficiency, noise levels, and current consumption. Their 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 improved aerodynamics, resulting in decreased turbulence and noise (Aditya and Reetu, 2023).However, despite the existing research into Toroidal propellers, not much effort has been made toward a direct computational evaluation of Toroidal propellers relative to Flat propellers. Thus, this study sets out to evaluate the lift and energy efficiency characteristics of Toroidal propellers relative to Flat propellers in CFD, to enhance the knowledge frontier on Toroidal propellers.

II. MATERIALS AND METHODS

2.1 Materials

This study utilised Autodesk Fusion v2024 for solid modelling of the Flat and Toroidal propellers, Autodesk CFD for propeller performance analysis, and a computer with system specifications, Intel Core i7-6820HQ @ 2.71GHz CPU, 32GB RAM and 2TB storage.

2.2 Methods

2.2.1 Design specifications of the Flat and Toroidal propellers with CAD (Autodesk Fusion).

A 300mm diameter flat propeller was designed. In the design of the Flat propeller, a negative twist was applied to the propeller blade along its span, reducing the angle of attack from a high angle at the root (where air velocity is low) to a low angle at the tip (where air velocity is highest).

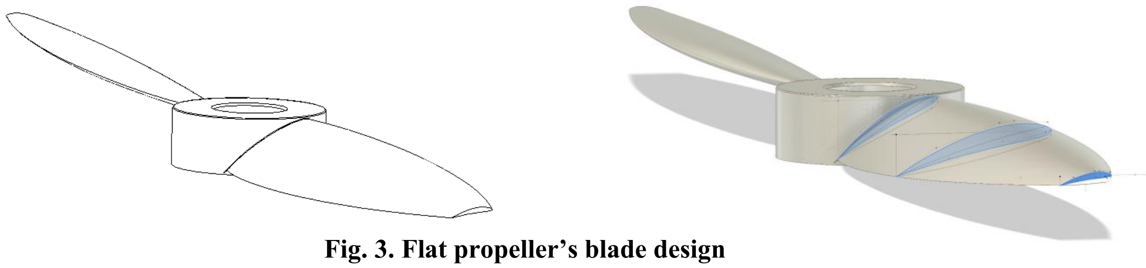

Fig. 3. Flat propeller's blade design

Fig. 4. Flat propeller's blade design with twist shown

Table 1: Design specifications of the Flat propellers

Parameter	Value
Blade Diameter	300mm
Hub Diameter	32mm
No. of Blades	2, 3, 4
Airfoil Profile	NACA 6412
Max Angle of Attack	30^{O}
Angle of Attack at Root (0.08R)	30^{O}
Angle of Attack at Midspan (0.48R)	15^{O}
Angle of Attack at Tip (1R)	5^{O}
Chord Length at Root	20mm
Chord Length at Midspan	28mm
Chord Length at Tip	9mm

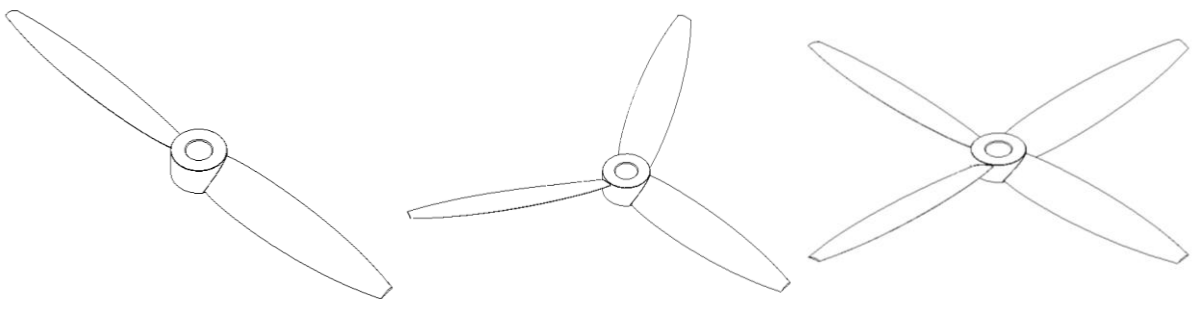

Fig. 5 - 7. Two, Three, and Four-blade Flat propellers

A 300mm diameter Toroidal propeller was designed. In the design of the Toroidal propeller, similarly, a negative twist was applied to the propeller's blade along its span. However, the angle of attack was only reduced from the root (where air velocity is lower) up to the midspan of the blade.

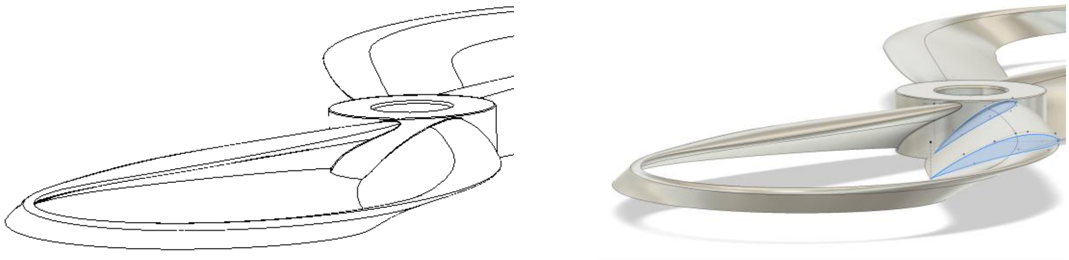

Fig. 8. Toroidal propeller's blade design showing the negative twist up to the midspan

Then, a positive twist was applied, increasing the angle of attack to 90° at the tip (where air velocity is highest).

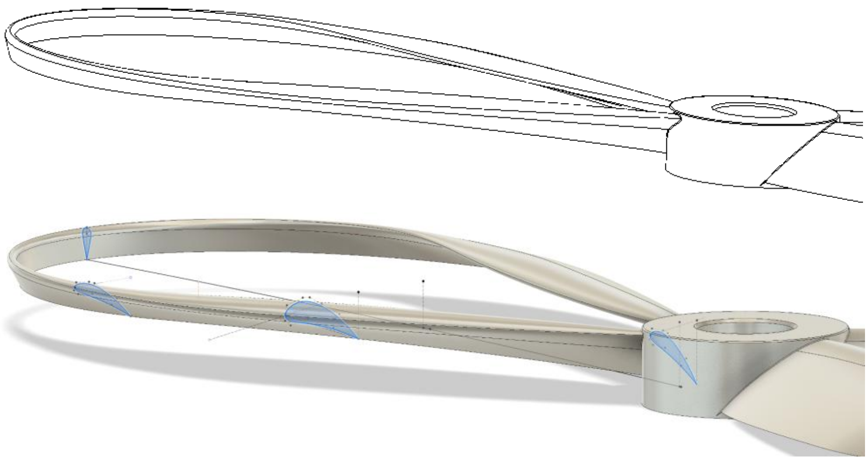

Fig. 9. Toroidal propeller's blade design showing the positive twist from the midspan to the tip

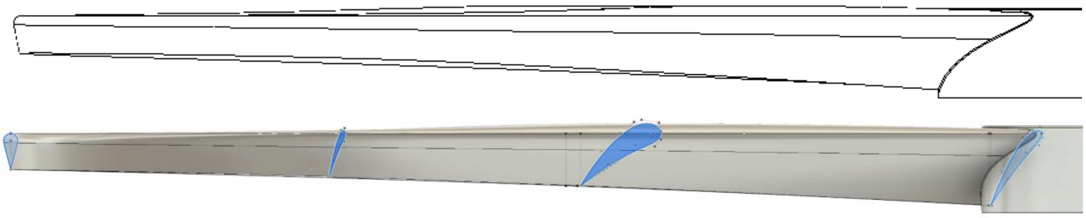

Fig. 10. Toroidal propeller's blade design showing the vertically symmetric airfoil at the tip

Table 2: Design specifications of the Toroidal propellers

Parameter	Value
Blade Diameter	300mm
Hub Diameter	32mm
No. of Blades	2, 3, 4
Airfoil Profile	NACA 6412
Max Angle of Attack	90^{O}
Angle of Attack at Root (0.08R)	30^{O}

Angle of Attack at Midspan (0.48R)	15^{O}
Angle of Attack at Tip (1R)	90^{O}
Chord Length at Root	20mm
Chord Length at Midspan	28mm
Chord Length at Tip	5mm

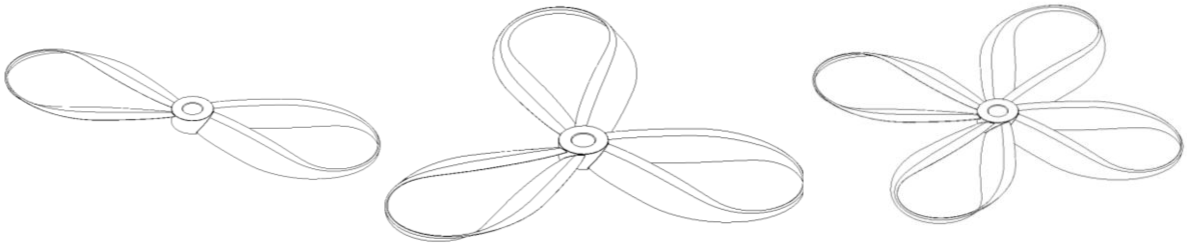

Fig. 11 - 13. Two, Three, and Four-blade Toroidal propellers

2.2.2 Simulation of the Flat and Toroidal Propellers with CFD Software (Autodesk CFD)

The Flat and Toroidal propellers were simulated at 8,000 RPM to study their performance. The simulation parameters are shown below:

Table 3: Simulation Setup

Parameter	Value
Propeller rotation	8000 rpm
Type of flow	SST k-Omega
Time	0.55 s
Fluid	Air
Density of air, ρ	1.225 kg/m^3
Gauge Pressure	0 Pa

The assumptions used in the simulation for simplification and accuracy are listed below:

- The actual boundary conditions used throughout the design are simply stated at the appropriate places.
- The aerodynamic characteristics of each section are independent of adjacent sections.
- The propellers are rigid. Aerodynamic effects such as blade flapping are neglected.

Table 4: Mesh Setup

Mesh options	Parameter
Volume mesh	Tetrahedral
Element size	4 × 10−2 m
Minimum face size	First Layer
Inflation option	Thickness
First layer height	1.3 × 10−5 m
Maximum layers/Growth rate	20/1.2

III. RESULTS AND DISCUSSION

3.1 Results

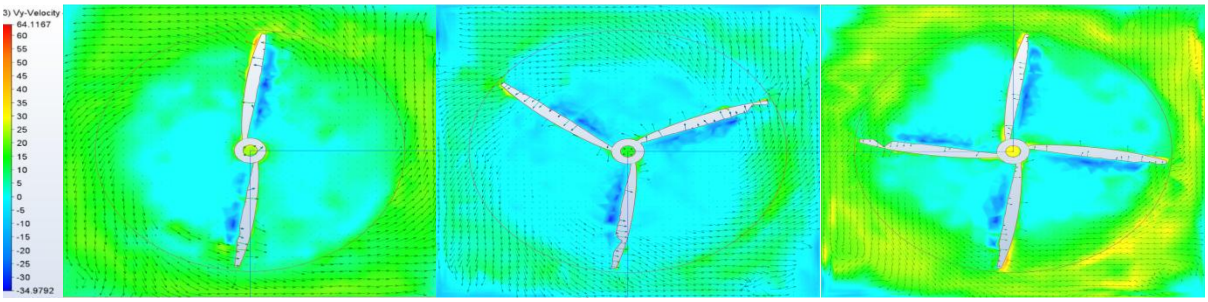

Fig. 14 - 16. Airflow Simulation around the Two, Three, and Four-blade Flat Propellers

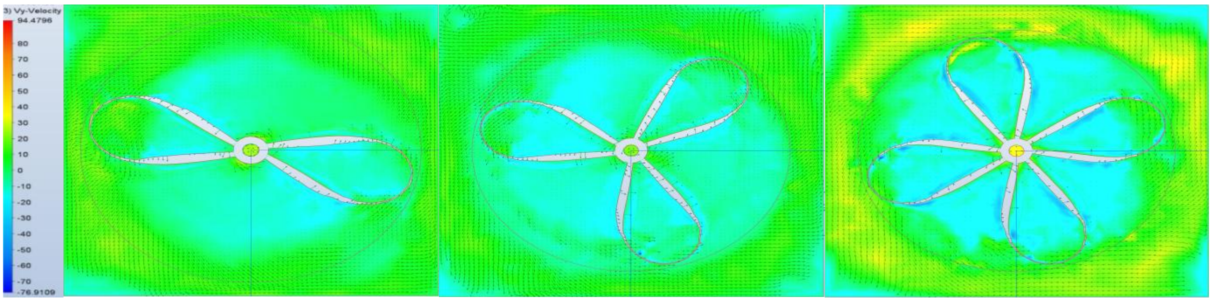

Fig. 17 - 19. Airflow Simulation around the Two, Three, and Four-blade Flat Propellers.

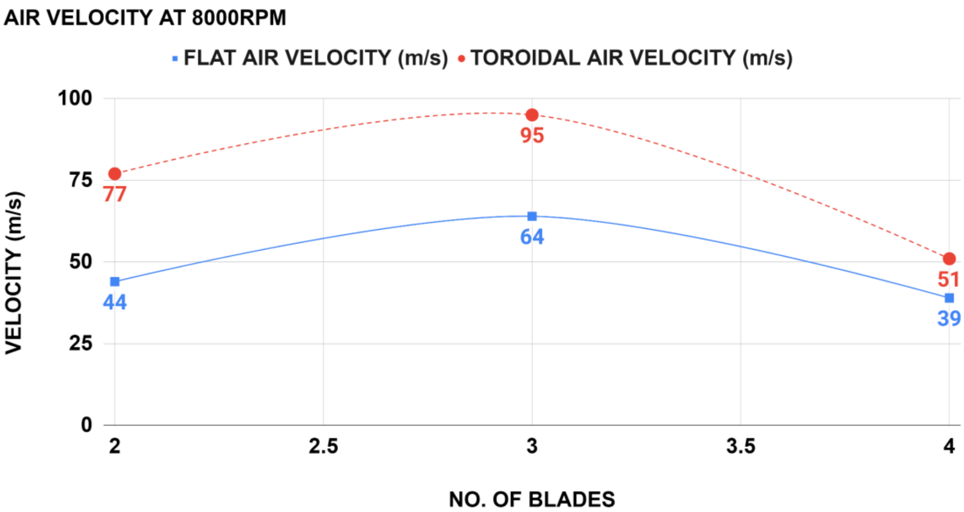

Fig. 20. Variation of Air Velocity with Blade Count for the Flat and Toroidal Propellers

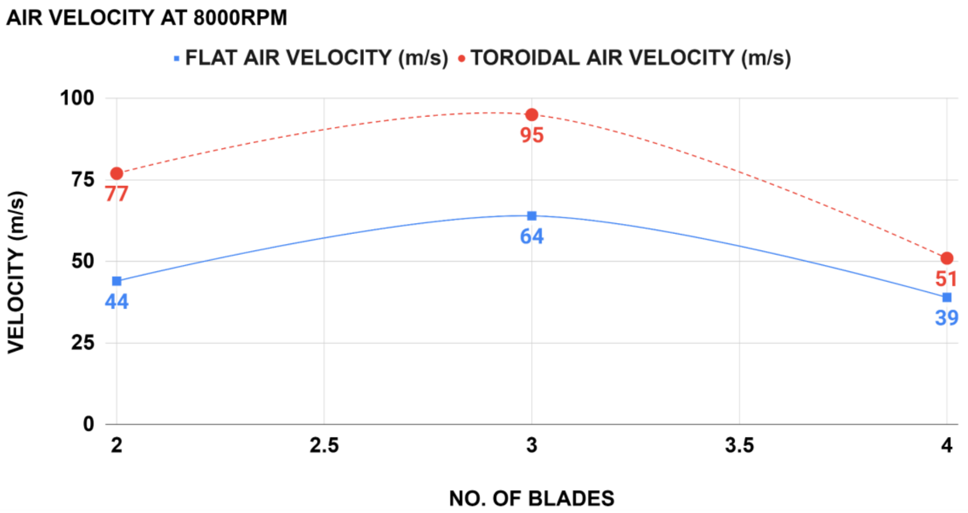

Fig. 21. Variation of Generated Lift with Blade Count for the Flat and Toroidal Propellers

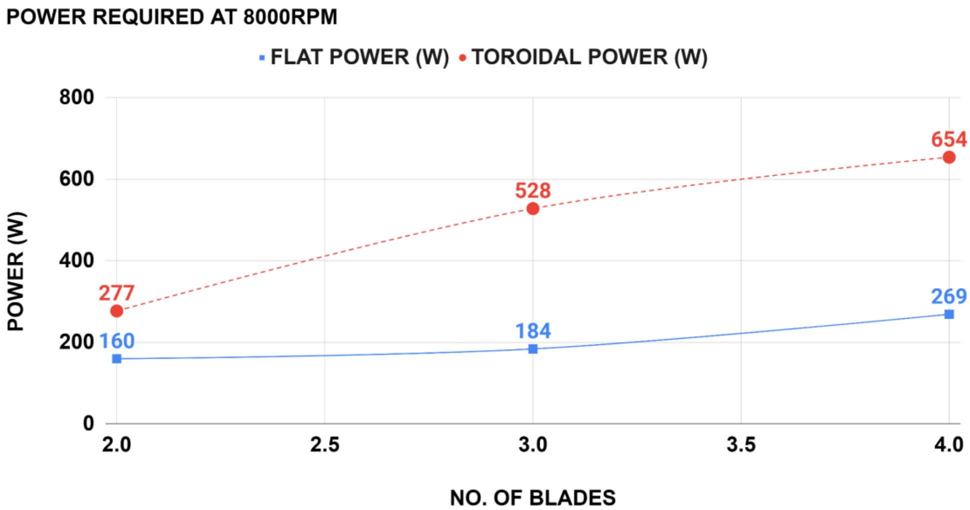

Fig. 22. Variation of Required Power with Blade Count for the Flat and Toroidal Propellers

The simulation results for the Flat and Toroidal propellers at 8,000 rpm are shown below:

Table 5: Simulation Results for CFD Analysis of Flat Propellers

Parameter	Value
No. of blades	2, 3, 4
Generated lift	5.1 N, 6.5 N, 8.4 N
Rotational speed	8000 rpm
Required Torque	0.19 N-m, 0.22 N-m, 0.32 N-m
Required Power	160 W, 180 W, 269 W

Table 6: Simulation Results for CFD Analysis of Toroidal Propellers

Parameter	Value
No. of blades	2, 3, 4
Generated lift	5.4 N, 11.5 N, 14.1 N
Rotational speed	8000 rpm
Required Torque	0.33 N-m, 0.63 N-m, 0.78 N-m
Required Power	277 W, 528 W, 654 W

3.1.1 Results Analysis

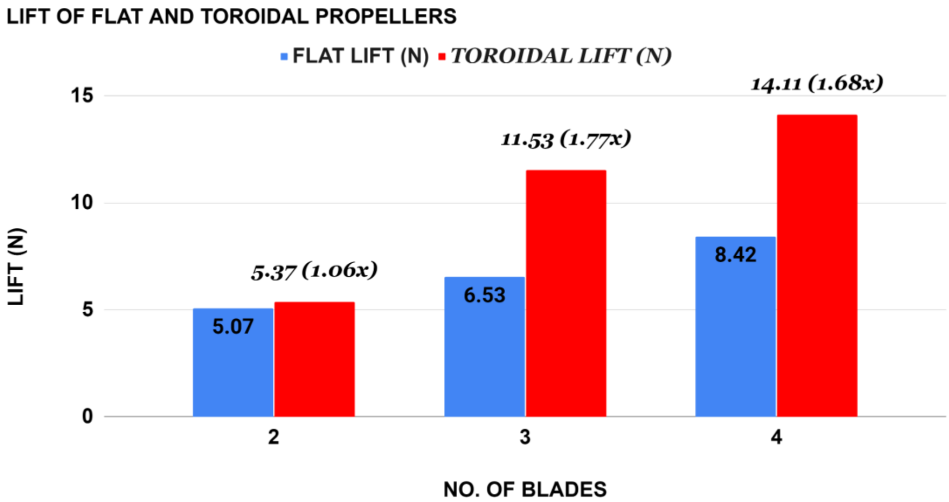

Fig. 23. Comparison of Lift Performance Between Flat and Toroidal Propellers

The chart above compares the lift generated by Flat and Toroidal propellers for different blade counts (2, 3, and 4). Flat propellers (blue) produce lower lift, increasing from 5.07 N (2 blades) to 8.42 N (4 blades). Toroidal propellers (red) generate slightly higher lift for 2 blades (5.37 N, 1.06x increase) but significantly more lift for 3 (11.53 N,1.77x) and 4 blades (14.11 N, 1.68x). This trend indicates that toroidal propellers provide increasing lift advantages as the blade count rises.

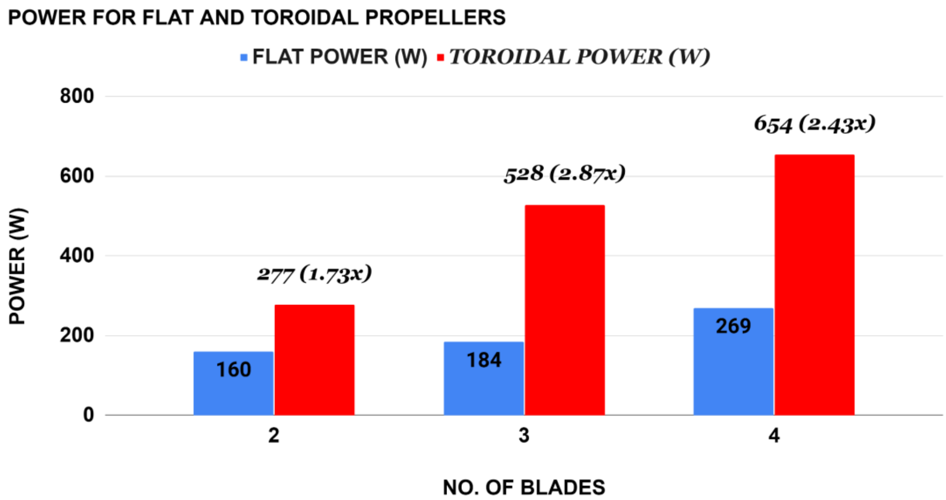

Fig. 24. Power Consumption Comparison Between Flat and Toroidal Propellers

The chart above compares the power consumption of Flat and Toroidal propellers across three blade configurations (2, 3, and 4 blades). Flat propellers (blue) have lower power consumption, starting at 160 W for 2 blades and increasing to 269 W for 4 blades. Toroidal propellers (red) require significantly more power, beginning at 277 W for 2 blades and rising to 654 W for 4 blades. This means that Toroidal propellers consume approximately 1.73 to 2.87 times the power of Flat propellers, showing an increasing trend with higher blade counts.

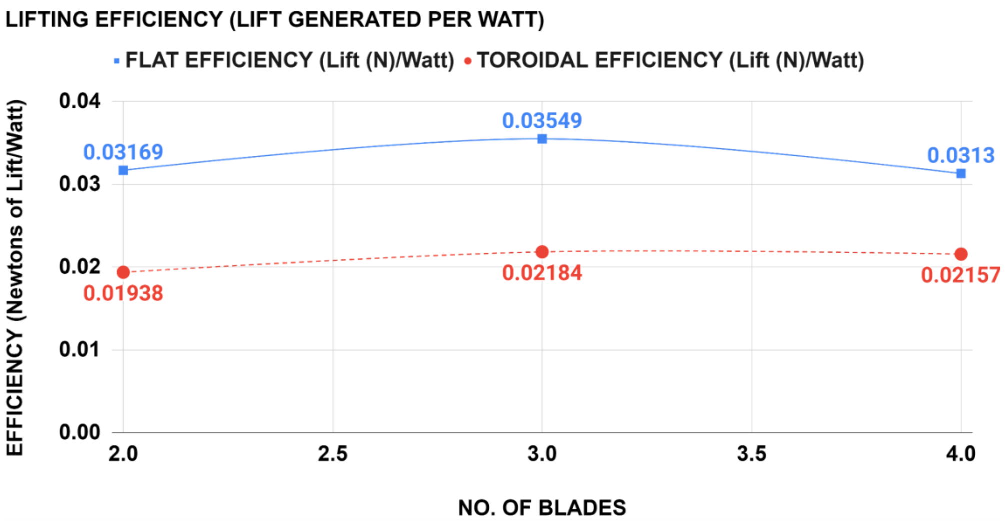

Figure 25: Efficiency (Lift per Watt) Comparison Between Flat and Toroidal Blades

The graph above illustrates the lifting efficiency of the Flat and Toroidal propellers, measured in terms of lift per watt across varying blade configurations, ranging from two to four blades.For Flat propellers (blue square markers), lifting efficiency begins at 0.03169 N/W in the two-blade configuration. As the number of blades increases, efficiency reaches its peak at 0.03549 N/W for the three-blade setup. Then, a slight decline follows, bringing efficiency down to 0.0313 N/W at four blades.Toroidal propellers (red circular markers) exhibit a similar trend, starting with a lifting efficiency of 0.01938 N/W in the two-blade configuration, and peaking at 0.02184 N/W for the three-blade setup. Then, a slight decline follows, bringing efficiency down to 0.02157 N/W at four blades. This shows that their overall efficiency performance is low compared to Flat propellers. This shows that although Toroidal propellers generate higher lift values, their power consumption is also significantly greater, leading to a lower lift-to-power ratio.The Simulation shows that for the same power consumption; the Flat propellers produce between 45 - 64% more thrust than the Toroidal propellers. The acoustic performance of the propeller is strongly influenced by the variation of the sound pressure at the leading edge of the propeller with time.

3.2 Discussion

This computational assessment of flat and toroidal drone propellers revealed significant differences in their aerodynamic and energy performance. Toroidal propellers consistently generated higher lift than their Flat counterparts across all blade configurations. For instance, the 3-blade Toroidal propeller produced 77% more thrust than the corresponding Flat propeller, highlighting the lift advantage of the Toroidal design, particularly as the blade count increases.However, this superior lift performance came at a substantial energy cost. The Toroidal propellers consumed significantly more power, with the 4-blade configuration requiring 654 W, more than double the 269 W used by the 4-blade Flat propeller. This disparity in energy consumption resulted in a much lower efficiency for Toroidal propellers. When measured in lift per watt, the Flat propellers were 45 - 64% more efficient, depending on the blade count.The increase in power consumption observed in Toroidal blades is attributed to their complex geometry (particularly the positive twist that was applied midspan, increasing the angle of attack to 90° at the tip where air velocity is highest, where the angle of attack should ideally be minimum), despite their benefits in noise reduction and reduced tip vortices. The results affirm that while toroidal propellers are promising for generating lift and improving aerodynamic smoothness, their low efficiency limits their practical deployment to scenarios where power availability is not a critical constraint.

IV. CONCLUSION

This study conducted an analytical and computational performance evaluation of Flat and Toroidal propellers across 2, 3, and 4-blade configurations using Autodesk Fusion and Autodesk CFD. The results demonstrate that Toroidal propellers outperform flat ones in terms of lift generation, making them suitable for applications requiring high thrust in compact designs. However, this performance comes at the cost of efficiency, with Toroidal propellers consuming substantially more power.The Flat propellers exhibited a better lift-to-power ratio, indicating higher energy efficiency, which makes them more suitable for long-range and energy-sensitive drone operations. These findings suggest that Toroidal propellers are better suited for short-range, high-load drone applications where compact size and noise reduction are priorities, while Flat propellers remain ideal for general-purpose and endurance-based drone missions.

REFERENCES

[1] Wang, Z., Ma, H., Zhong, Y., Yang, Y., & Zhang, Q., Blade aerodynamic force and tip region vortex spatial-temporal evolution study of a compressor cascade, *Aerospace Science and Technology, 145,* 2024, 108-864.

[2] Vu, X. D., Nguyen, A. T., Nha, T. L., Chu, Q., & Dınh, C. T., Numerical Aerodynamic and Aeroacoustic Analysis of Toroidal Propeller Designs, *International Journal of Aviation Science and Technology, 5(01),* 2024, 20-33.

[3] Morgado, J., Abdollahzadeh, M., Silvestre, M. A. R., & Páscoa, J. C, High altitude propeller design and analysis, *Aerospace Science and Technology, 45,* 2015, 398-407.

[4] R. MacNeill, D. Verstraete, Blade element momentum theory extended to model low Reynolds number propeller performance, *The Aeronautical Journal, 121(1240),* 2016, 835-857.

[5] R. Prajapati, B.P. Kumar, S. Kushwaha, S. Dhanapalan, Comparing toroidal propeller performance with different blade numbers at different RPM: CFD analysis and evaluation, *International Journal of Engineering Research & Technology, 13(04),* 2024, 2278-0181.

[6] A. Garg, R. Jain, An Empirical Study of Performance Variations: 3D Printed Toroidal Propeller vs. Traditional Propeller, *International Journal of Software & Hardware Research in Engineering, 11(10),* 2023, 2347-4890.

[7] D. Auld, *Aerodynamics for Students*, University of Sydney, Sydney, AU, 1995.

[8] S. Krishnamurthy, S.A. Rizzi, Feasibility Study for Remote Psychoacoustic Testing of Human Response to Urban Air Mobility Vehicle Noise, *Langley Research Center*, Lexington, KY, 2022, 047-773.

[9] S. Thomas, C. Strem, *Toroidal Propeller Technology Highlights*, Massachusetts Institute of Technology, Cambridge, MA, 2022.