

# EFFECT OF BIO-INSPIRED NEUROPTERA PROPELLER DESIGN ON THE AERODYNAMIC PERFORMANCE FOR SMALL QUADCOPTER USING CFD SIMULATION

## Article history

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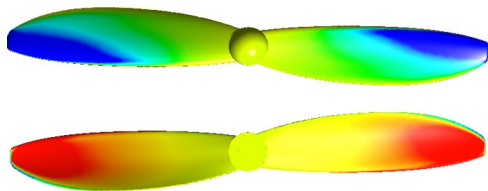
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## Graphical abstract



## Abstract

A small quadcopter drone is a lightweight, highly maneuverable flying device that uses four rotors for stability and control, making it ideal for various applications. Bio-inspired design is an innovation approach that mimics natural structures, processes, or systems to develop more efficient, sustainable, and adaptive solutions in engineering and technology. In context with small quadcopter drones, mimicking natural structures such as insect wings or bird feathers may enhance aerodynamic efficiency. Neuroptera wings are typically elongated and oval-shaped, lace-like structures that enhance stability, and lift during flight, as seen in insects like lacewings. The Neuroptera design was evaluated against the conventional DJI Phantom Pro propeller at rotational speeds of 3000, 5000, and 7000 RPM, focusing on thrust generation and pressure distribution. Both propellers were designed in Solidworks software with constant overall dimensions while the CFD simulations were conducted in ANSYS (Fluent) software using the Reynolds-Averaged Navier-Stokes (RANS) equations with the *k*-*SST* turbulence model. Results revealed that the Neuroptera propeller produced consistently higher thrust, with increases of approximately 74% across all RPM levels, highlighting its superior aerodynamic efficiency. Pressure contour analysis showed a smoother and more uniform distribution in the Neuroptera design, reducing turbulence and energy losses, while the Phantom Pro exhibited localized pressure gradients. The Neuroptera's enhanced performance suggests significant potential for improved aerodynamic performance. This study demonstrates the advantages of bio-inspired design in drone propellers and provides a foundation for further optimization, including the incorporation of serrated features for even greater aerodynamic benefits.

Keywords: Aerodynamic; Bio-inspired; Computational Fluid Dynamics (CFD); Mesh Number; UAV Propeller

## Abstrak

Sebuah dron kuadkopter kecil ialah peranti terbang yang ringan dan sangat mudah dikawal, menggunakan empat rotor untuk kestabilan dan kawalan, menjadikannya ideal untuk pelbagai aplikasi. Reka bentuk berinspirasi bio adalah pendekatan inovatif yang diilhamkan daripada struktur, proses, atau sistem semula jadi bagi membangunkan penyelesaian yang lebih cekap, lestari, dan adaptif dalam kejuruteraan serta teknologi. Dalam konteks dron kuadkopter kecil, diilhamkan daripada struktur semula jadi seperti sayap serangga atau bulu burung boleh meningkatkan kecekapan aerodinamik. Sayap Neuroptera biasanya berbentuk panjang dan oval dengan struktur seperti renda yang meningkatkan kestabilan dan daya angkat semasa penerbangan, seperti yang dapat dilihat pada serangga seperti serangga renda. Reka bentuk Neuroptera telah dinilai berbanding bilah kipas konvensional DJI Phantom Pro pada kelajuan putaran 3000, 5000, dan 7000 RPM, dengan tumpuan kepada penjanaan tujahan dan pengagihan tekanan. Kedua-dua bilah kipas direka menggunakan perisian SolidWorks dengan dimensi keseluruhan yang tetap, manakala simulasi CFD dijalankan dalam perisian ANSYS (Fluent) menggunakan persamaan Reynolds-Averaged Navier-Stokes (RANS) dengan model pergolakan  $k-\omega$  SST. Keputusan menunjukkan bahawa bilah kipas Neuroptera menghasilkan tujahan yang lebih tinggi secara konsisten, dengan peningkatan sekitar 74% merentasi semua tahap RPM, menonjolkan kecekapan aerodinamiknya yang unggul. Analisis kontur tekanan menunjukkan pengagihan yang lebih lancar dan seragam dalam reka bentuk Neuroptera, mengurangkan pergolakan serta kehilangan tenaga, manakala Phantom Pro menunjukkan kecerunan tekanan setempat. Prestasi yang dipertingkatkan oleh Neuroptera mencadangkan potensi yang signifikan untuk penambahbaikan aerodinamik. Kajian ini membuktikan kelebihan reka bentuk bio-diilhamkan dalam bilah kipas dron dan menyediakan asas untuk pengoptimuman lanjut, termasuk penggunaan ciri bergerigi bagi manfaat aerodinamik yang lebih besar.

**Kata kunci:** Aerodinamik; Berinspirasi Bio; Dinamik Bendalir Pengiraan (CFD); Nombor Jaring; Bilah Kipas UAV

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## 1.0 INTRODUCTION

The aerodynamic performance of drones plays a pivotal role in optimizing their overall performance. Key factors such as thrust generation, power consumption, stability, and noise are heavily influenced by the design of the propellers [1]. Propellers are one of the most critical components of a drone, as they determine how efficiently the drone can generate lift and maneuver through the air [2]. Traditionally, drone propellers have a relatively simple design, with fixed pitch blades and uniform geometries. However, advancements in aerodynamics have shown that optimizing propeller blade shapes, angles, and materials can significantly improve the drone's energy efficiency and stability in flight [3].

Despite these advancements, there are still several challenges in drone aerodynamics. One of the most common issues is energy inefficiency, where a large amount of the input energy is wasted as drag or in the form of tip vortices [4]. These vortices are turbulent flows that form at the tips of propeller blades, and they can cause increased drag and reduce the overall efficiency of the drone. Drone stability in turbulent air and adverse weather conditions is another ongoing challenge, as propellers often struggle to maintain

efficient lift generation in fluctuating wind conditions [5]. To overcome these aerodynamic limitations, this study suggests a bio-inspired propeller design named Neuroptera.

Neuroptera is an order of insects commonly known as "net-winged insects." This diverse group includes various species such as lacewings, antlions, and owls and flies. In the context of aerodynamics and drone technology, "Neuroptera" refers to a bio-inspired propeller design modeled after the wing structure of these insects [6]. Researchers and engineers have studied the wing patterns and aerodynamics of insects like lacewings and dragonflies, whose wings are known for their efficient flight characteristics [7]. The

Neuroptera propeller design was chosen over other bio-inspired options because its wing-like geometry offers a practical balance of aerodynamic efficiency and noise-reduction potential, making it highly suitable for UAV propeller performance and aeroacoustics studies. [8], [9]. Bioinspired propeller designs enhance aerodynamic performance by optimizing lift production, reducing drag, and improving thrust efficiency through nature-inspired blade geometries and microstructures. These designs minimize flow separation and turbulence, allowing for smoother airflow and better pressure distribution across the

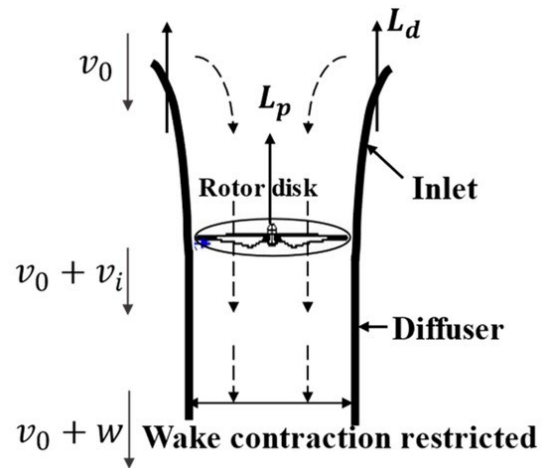
propeller surface. By controlling wake interactions and mitigating tip vortex cavitation, they reduce energy losses and enhance stability, resulting in more efficient thrust generation and prolonged propeller lifespan. Additionally, the strategic design of ducted multi-propeller configurations and refined blade tip geometries optimizes aerodynamic interactions, improving maneuverability, stability, and efficiency in both hovering and forward flight conditions [9][10][11].

A study on experimental investigation into the aerodynamic performance of bioinspired small-scale propeller planform published by Foad Molsen *et al.* [9] shows that the Neuroptera-inspired propeller demonstrates significant aerodynamic advantages over conventional designs. Its thrust coefficient is markedly higher, enabling greater lift generation while operating with reduced drag. At a hover thrust of 3N, the Neuroptera propeller achieves a power loading of 0.25 N/W, a 47% improvement over the baseline propeller's 0.17 N/W. This efficiency is further supported by its optimized rotational speed of 4860 RPM, which is 36.6% slower than the baseline, reducing energy consumption while maintaining thrust. The Figure of Merit (FoM) is a performance index that relates the thrust produced to the power consumed, and it is important in this study to objectively compare the aerodynamic efficiency of the Neuroptera propeller against the conventional DJI Phantom design across different Rotation per minute (RPM). The propeller's FOM reaches 4.06, a 45.5% improvement over the baseline 2.79, highlighting its exceptional overall efficiency in converting mechanical input power from motor into useful thrust [9].

In addition, a study by Noda *et al* [10] on development of bio-inspired low-noise propeller for a drone compares the bio-inspired low-noise propeller with a conventional Phantom 3 propeller in terms of noise levels, aerodynamic performance, and power consumption. The modified propeller, featuring an aluminum plate at the trailing edge (positioned at 0.8R), reduced noise by approximately 2.4 dB across a frequency range of 200 Hz to 20,000 Hz. Despite a slight decrease in efficiency (FOM dropping from 0.64 to 0.62), the propeller maintained similar aerodynamic performance, with a slight lift increase (3.11N to 3.58N) [10].

Moreover, a research on the aerodynamic performance of a bioinspired ducted multi-propeller configuration for quadrotor drones using CFD simulations and a surrogate model was done by Li *et al* [11]. Inspired by natural flight mechanisms, the design optimizes propeller placement to enhance lift force and efficiency. The results show that small tip distances negatively impact aerodynamic performance due to interference, while a certain height difference between propellers improves efficiency. The optimized bioinspired ducted configuration, featuring a minimal tip distance and an appropriate height difference, significantly enhances lift force and FOM efficiency based on Equation 1 under Chapter 2, offering insights for high-performance UAV design [11]. Figure 1 shows

the schematic diagram of the ducted-propeller aerodynamic principle. Rotor disk and downwash in hovering state.



**Figure 1** schematic diagram of the ducted-propeller aerodynamic principle. Rotor disk and downwash in hovering state [11]

This study focuses on the effect of bioinspired propeller design on the aerodynamics effects of small quadcopter drones. Further research into the simulation of bioinspired propellers, like the Neuroptera design, is crucial for advancing their development and performance. Research on aerodynamic effects in bioinspired drone propeller design is essential for maximizing lift, minimizing drag, and improving overall efficiency. Computational Fluid Dynamics (CFD) simulation enables precise analysis of airflow patterns, vortex formation, and pressure distribution around bioinspired blade geometries, helping to identify optimal designs. Additionally, CFD allows for the evaluation of unsteady aerodynamic effects, such as dynamic stall and wake interactions, which are critical for improving propeller efficiency and stability in real-world flight conditions [12].

## 2.0 METHODOLOGY

### 2.1 Propeller Modelling

Neuroptera wing shapes are highly aerodynamic, with their long and narrow structure to minimize drag and maximizing lift as shown in Figure 2. The slight curvature of the wings helps generate lift while reducing resistance during flight [13].

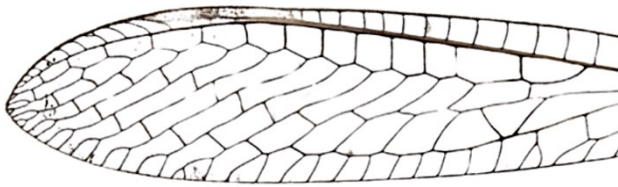


Figure 2 Neuroptera wing shape [13]

For this study, the Neuroptera shaped propeller was designed on top of the existing DJI Phantom Pro propeller which is commonly available in the market. While DJI does not explicitly reveal the exact airfoil type being used in their drones but product sources indicate a diameter of about 230–240 mm. Based on common design principles it is estimated to use an airfoil similar to NACA 4412 which is a moderately cambered, low drag, and efficient airfoil profile [14]. Figure 3 shows the drawing of a Phantom Pro propeller created for this study using SOLIDWORKS software.



Figure 3 DJI Phantom Propeller a) Top view; b) Front view; c) Side view

The 9450-type propeller being used by DJI is approximately 240mm in overall diameter or 120mm in blade length with the width of 30mm at maximum [14]. For geometric simplification, the propeller model was generated by adapting the chord length and scaling the vein thickness proportionally to maintain structural resemblance while reducing modeling complexity. Compared to the real Neuroptera wing, where the chord length tapers sharply with intricate vein networks of varying thickness, the drawing simplifies this by using a smoother chord profile and uniformly scaled vein thickness, preserving the overall morphology while making the geometry feasible for propeller design and simulation. The Neuroptera-inspired propeller was scaled to match the motor torque limits by adjusting chord length and vein thickness proportionally. After scaling, the maximum chord is 30 mm, with vein thickness scaled proportionally to 0.3 mm. This ensures that at 3000 rpm (0.031 Nm), 5000 rpm (0.088 Nm), and 7000 rpm (0.174 Nm), the motor torque remains below the continuous limit of 0.2 Nm. These RPMs fall within the typical operating range for small UAV and drone propellers, as reported in experimental studies [15]. These adjustments do not affect the aerodynamic or aeroacoustic results because the scaling preserves the overall wing planform, flow characteristics, and structural stiffness similar to Neuroptera wings, which have thicker veins near the base and thinner toward

the tip. The propeller uses the blade twist from a DJI propeller combined with the bio-inspired Neuroptera wing shape. This approach simplifies the twist while preserving the natural flow characteristics of the wing. Figure 4 shows the dimension of the DJI Phantom Pro propeller and the Neuroptera propeller which was derived from it. The overall diameter, width and airfoil profile remained constant during the design modification from DJI Phantom Pro to Neuroptera. The surface area of DJI Phantom Pro and Neuroptera were 17693 mm<sup>2</sup> and 18592 mm<sup>2</sup> respectively. The slight change in overall surface area which is under 5% is due to the difference in the overall propeller shape modifications.

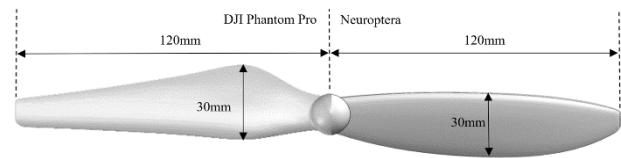


Figure 4 Dimension of DJI Phantom Propeller and Neuroptera Propeller

## 2.2 Simulation Configuration

The propeller model created at SOLIDWORKS, imported to ANSYS Fluent solver for this project. Enclosure and a refinement box were added surrounding the propeller and boundary conditions set as shown in Figure 4. Both the enclosure and refinement box were created on the z-axis, using the center of the propeller as the starting point. For the report definition setup, the direction for thrust were given at the forward direction to allow this simulation to study the performance of propeller during forward flight condition which important during maneuvering. Since it is a forward motion, the downstream enclosure is set wider compared to upstream. Reynolds-Averaged Navier-Stokes (RANS) equations with the *k-omega SST* turbulence model were used for the setup. The Reynolds number in the Fluent simulation ranges from  $5.6 \times 10^5$  at the root to  $2.6 \times 10^6$  at the tip, covering all operating speeds from 3000 to 7000 rpm. An article published by Yao *et al.* [15] proves that using the RANS equation is ideal for studying the aerodynamic effects of propellers as it efficiently predicts flow behavior while capturing turbulence effects with reasonable accuracy at a lower computational cost than high-fidelity methods. Moreover, while low Reynolds number UAV propellers often exhibit laminar or transitional flow, advanced turbulence models like SST *k-omega* and LES were employed to capture detailed aerodynamic phenomena. Aravind Seeni's study demonstrated that the two-equation standard *k-omega* model effectively predicts performance in such regimes [16]. Additionally, LES can provide high-resolution unsteady flow information, including vortices and tip vortex dynamics, which are crucial for aeroacoustic and aerodynamic analysis. Steady-state rotating reference frame used as it is a

computationally efficient method that accurately predicts average aerodynamic performance of the propeller. For low-Re UAV propellers, where the primary interest is thrust, torque, and overall efficiency, the unsteady effects have a relatively minor influence on the mean values. This allows to focus on performance and design trends without the high computational cost of full transient simulations, while still providing results consistent with experimental data [15][16].

Inlet, outlet and symmetry were set as shown in Figure 5. Enclosures (A and C) were used to define the boundaries of a domain that surrounds a geometry while refinement box (B) added to locally refine the mesh in the specified region, ensuring a higher resolution of elements in critical areas without increasing the overall mesh size excessively which will lead to higher computational effort [16][17]. Dogrul et al. (2023) conducted a CFD self-propulsion calibration on a marine propeller, focusing on capturing the near-wake flow while maintaining computational efficiency using similar RANS turbulence modeling within a rotating inner cylinder and stationary outer domain framework. The boundary conditions positioned the inlet  $\sim 1.5 D$  upstream (similar to  $\sim 350$  mm) and the outlet  $\sim 2.5 D$  downstream (similar to  $\sim 600$  mm), which closely matches the dimensions selected for this study. The chosen parameter ensures the propeller, boundary layers and near-field aerodynamic sources are fully captured while keeping blockage and wall-interference minimal and the mesh computationally tractable [18]. Table 1 shows the parameters used to create the enclosure and refinement box setup.

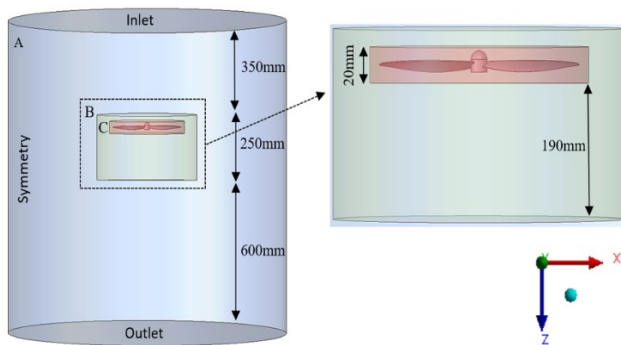


Figure 5 Enclosure and boundary condition setup

Table 1 Parameters of enclosure and refinement box

Type	Cylinder radius (mm)	Cylinder height (mm)
Enclosure (A)	600	1200
Refinement Box (B)	350	250
Enclosure (C)	10	20

A grid independence study in ANSYS simulations is a key step in verifying the accuracy and reliability of your computational results. It ensures that the solution to your simulation does not significantly depend on the size or quality of the computational mesh. Commonly, three or more grid resolutions are chosen, including a coarse, medium, and fine grid. A convergence study is performed to assess whether the results stabilize as the grid is refined, indicating grid independence [18][19]. By comparing the thrust obtained from the experiment by Moslem et al. [9] with the results of numerical analyses conducted using three different meshes, the validity of the CFD outcomes generated by ANSYS software is confirmed. To validate the results, significant mesh parameters were adjusted to create coarse, medium, and fine mesh configurations, as outlined in Table 2, where coarse mesh requires the least computational effort for simulation while fine mesh being the most. Additionally, the parameters set during the setup process are detailed in Table 3 below.

Table 2 Meshing parameters used for validation

Type/ Parameter (mm)	Coarse	Medium	Fine
Mesh element size	60	40	20
Elements number	917,756	1,318,574	2,343,558

Table 3 Parameters used for setup process

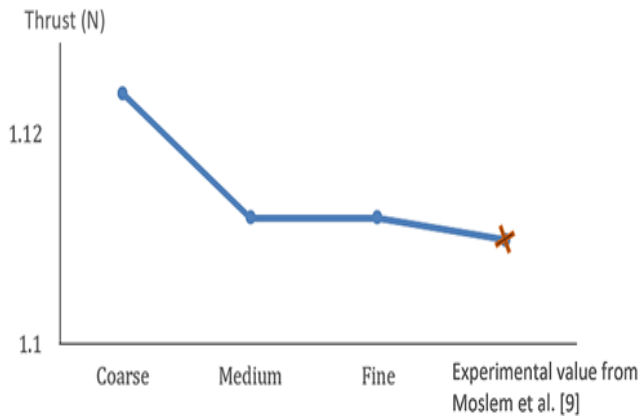
Parameter	Value
Number of iterations	1000
Rotational Per Minute (m/s)	3000

The changes in mesh parameters created a difference in the mesh type, the total mesh element number and the thrust for each case. The changes in result for each type of mesh were recorded as shown in Table 4 and the comparison between the thrust for 3000 RPM as mentioned in the article and recorded via experiment as shown in Figure 6.

Table 4 Results recorded for different mesh type

Mesh Type/ Result	Coarse	Medium	Fine	Experimental value from Moslem et al. [9]
Thrust(N) for 3000RPM	1.124	1.112	1.112	1.11

### 2.3 Grid Independence Study and Validation



**Figure 6** Thrust values at 3000 rpm for coarse, medium and fine meshes with the experiment by Moslem *et al.* [9]

As shown in Figure 6, the value of thrust for 3000RPM started to converge after the medium mesh, where both medium and fine mesh had thrust value of 1.112N which is also the same as the experimental value of 1.11N as shown in Table 4. To further support the validation, comparison between the coefficients of torque values were made using the formula below. Figure of Merit (FOM) shows how effectively each propeller converts input power into useful thrust, which allows to directly compare which design performs better aerodynamically. To be able to calculate the FOM both thrust and torque of propellers received by running simulation using medium mesh were induced into the FOM formula below.

Formula for Figure of Merit (FOM):

$$FM = \frac{T^{3/2}}{P \cdot \sqrt{2} \cdot \rho \cdot A} \quad (1)$$

where:

$T$  = Thrust (in Newtons)

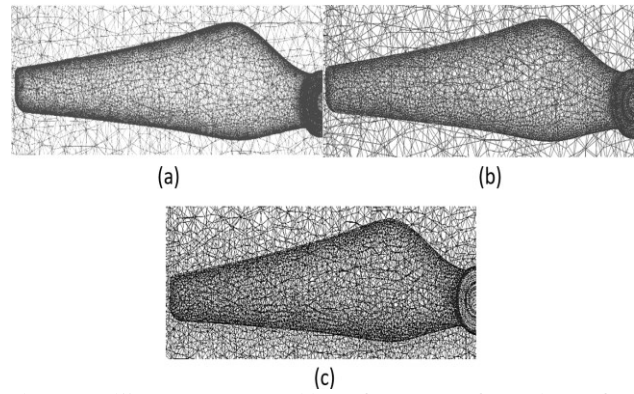
$\rho$  = Air density (at sea level,  $\rho \approx 1.225 \text{ kg/m}^3$ )

$A$  = Rotor disk area =  $\pi \left(\frac{D}{2}\right)^2$  (in square meters)

$D$  = Diameter of rotor (in meters)

$P = 2\pi \cdot n \cdot \tau$  (for rotational power)

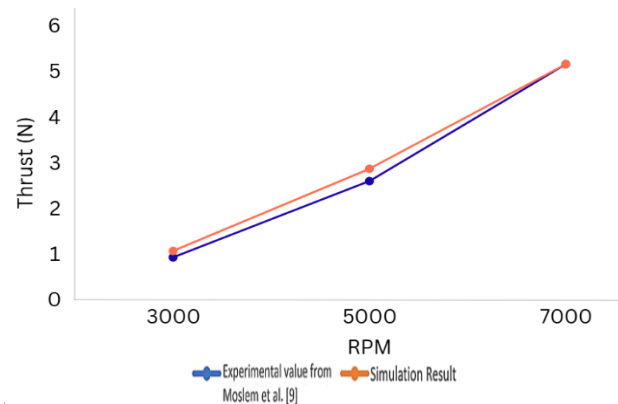
The FOM received for this simulation and the experimental value provided by Moslem *et al.* [9] were the same which was 4.06. Hence, the medium mesh is validated to be enough to predict the aerodynamic loads for the current study. Figure 7 shows the different mesh qualities obtained from the validation.



**Figure 7** Different mesh qualities: a) Coarse; b) Medium; c) Fine

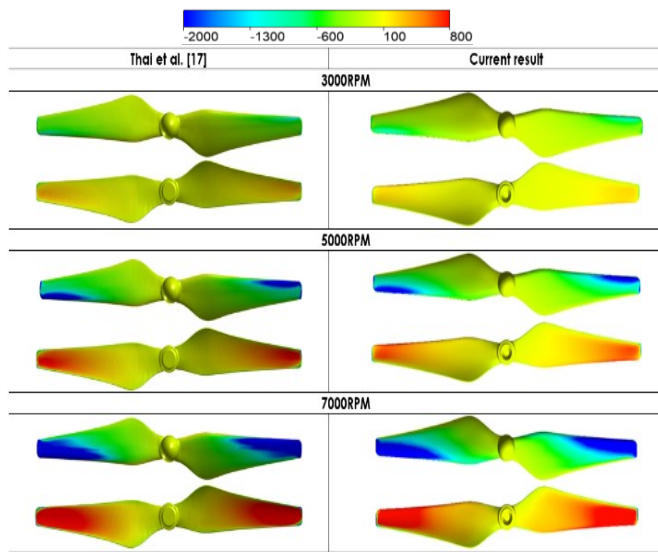
The validated medium meshing is then used for all the propeller rotational speeds (RPM). Figure 8 shows the comparison between the obtained thrust values for simulation and experimental values from Moslem *et al.* [9]. The values obtained were almost the same across all RPMs involved which are 3000RPM, 5000RPM and 7000RPM.

In addition, Table 5 shows the qualitative results comparison between these, where the pressure contour provided in the article was compared with current simulated output.



**Figure 8** Thrust comparison between experimental and simulation values

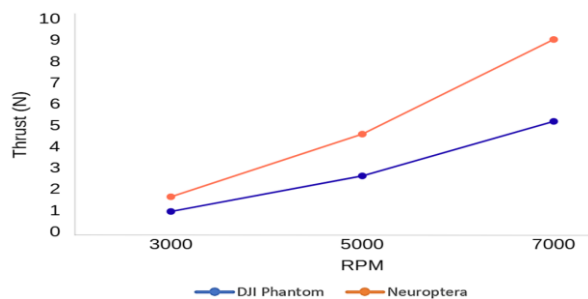
**Table 5** Surface pressure contour comparison between Thai et al. [20] and current simulated result on propeller



The contours reveal almost the same results across different RPMs as well. Hence, it is proved that the validation is genuine. Apart from the quantitative data, the qualitative comparison, between Thai et al. [20] and current pressure contours for the propeller at 3000, 5000, and 7000 RPM show overall similar trends in pressure distribution. The pressure contour obtained from simulations shows that the distribution at high and low pressure areas on propeller surface is almost similar with the experimental data. These similarities further prove that the simulation validation is a success and the mesh used is sufficient to run this study.

**2.4 Neuroptera Simulation Results**

The validated simulation configurations and setup were used to run the simulation on newly created Neuroptera design. The simulation for all RPMs were run on medium type mesh with 1000 iterations. Figure 9 shows the comparison of simulated thrust values between DJI Phantom propeller and Neuroptera propeller.



**Figure 9** Thrust between DJI Phantom Neuroptera simulation values

Based on the simulation performed as comparison between conventional DJI Phantom Pro and Neuroptera shows that the bio-inspired design has better thrust generation across all RPM levels. When rotating at 3000RPM, the Phantom generates 0.93N of thrust while the Neuroptera produces 1.62N which is 74% more when compared. A similar trend can be seen in the case of 5000RPM as the Phantom stands at 2.60N while Neuroptera with a significantly higher thrust of 4.56N. Meanwhile it was 5.16N for Phantom and 9.01N for Neuroptera when simulated at 7000RPM. This improvement on thrust will benefit the propeller's control and stability which is important in harsh weather conditions such as heavy crosswinds. It also makes the drone work on heavier loads compared to the conventional type [20].

In addition to thrust, another key aspect that needs to be focused for a drone propeller is its aerodynamic efficiency. To evaluate the level of maximum efficiency the propeller can achieve in its ideal circumstances, the FOM was calculated. Since FOM is known as the amount of useful power required to achieve a certain thrust to the torque power provided by the motor, both thrust and torque values obtained from the simulation [20]. These parameters then integrated in the formula stated to calculate the FOM of the propeller at different RPM of 3000, 5000 and 7000. A higher FOM indicates a more efficient propeller that converts a greater portion of the input energy into thrust, minimizing energy losses due to drag, tip or vortices [21][22]. Table 6 shows the FOM comparison between both conventional and bio-inspired propellers.

**Table 6** FOM between DJI Phantom and Neuroptera

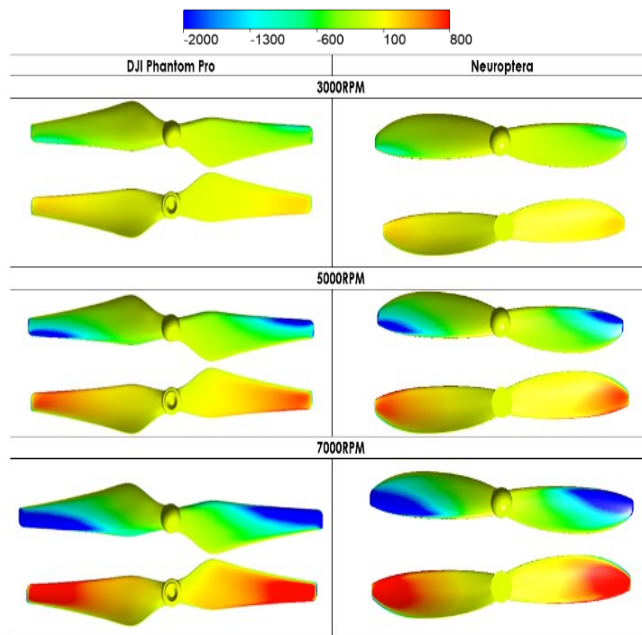
Propeller/ RPM	DJI Phantom Pro	Neuroptera
3000	0.536	0.616
5000	0.534	0.628
7000	0.552	0.633

The calculations reveal that the Neuroptera designed propeller managed to outperform Phantom propeller across all three different RPM levels. This can be seen as at 3000RPM, the Neuroptera achieves 15% higher FOM of 0.62 compared to Phantom which was 0.54. The improvement was significant when rotating at 5000RPM as the Neuroptera scored 0.63 which is 17.6% better compared to Phantom's FOM of 0.52. The trend was similar when calculated for 7000RPM as Neuroptera was 14% better with the merit of 0.63 to 0.55 on conventional. These results suggest that the bio-inspired design is more efficient across both low and high rotational speeds.

The FOM reveals that the Neuroptera propeller design is more aerodynamically efficient when compared to Phantom in various operational speed conditions. The design difference between both propellers, especially at the tip area, leads to this better efficiency for Neuroptera by having an improved overall flow and lesser vortex generation. The positive trend towards energy efficiency states that a lesser

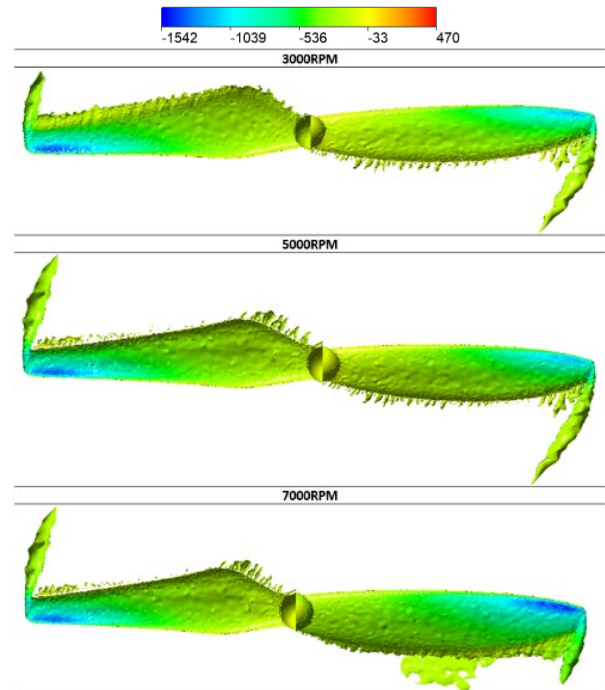
amount of energy from the motor is lost while converting into thrust, which makes the design a better option when it comes to a drone with need for higher endurance and performance such as rescue drones [23]. Apart from these quantitative results, the qualitative results from simulation also show the improvement on pressure contour of Neuroptera as shown in Table 7 and vortex core in Table 8.

**Table 7** Pressure Contour between DJI Phantom and Neuroptera



At all RPM levels, the Neuroptera exhibits a smoother and more uniform pressure distribution across the blade surface, indicating optimized aerodynamic performance. The Phantom Pro, on the other hand, exhibits greater pressure gradients and localised pressure changes, particularly in the vicinity of the blade tips and edges, indicating less effective airflow control [24][25]. The Neuroptera's design reduces sudden pressure changes at higher RPMs (5000 and 7000) where the difference on pressure contour is subtler and more lesser compared to DJI Phantom Pro. The high pressure region (red) at the backside of Neuroptera propeller can be seen covering lesser area compared to the DJI Phantom propeller which helps explain its increased thrust and possibly decreased drag. The notable variations highlight the Neuroptera's sophisticated blade design, which probably makes use of enhanced geometry and aerodynamics for enhanced performance and energy efficiency. The Neuroptera's greater thrust generation and efficiency over the Phantom Pro may be attributed to its smoother pressure contours, which indicate less turbulence and energy losses [26].

**Table 8** Vortex Core between DJI Phantom and Neuroptera



Across all RPM settings, the Neuroptera propeller consistently demonstrates smoother and more organized vortex structures, particularly noticeable in reduced turbulence and more streamlined wake patterns. In contrast, the DJI Phantom propeller exhibits more chaotic vortex shedding and stronger low-pressure cores, especially at higher RPMs. This suggests that the Neuroptera propeller design may lead to improved aerodynamic efficiency, reduced noise generation, and lower energy losses due to less intense vortex formation. These advantages point to the Neuroptera propeller as a more aerodynamically optimized solution, particularly beneficial in applications requiring stable and efficient flight performance.

Moreover, the mechanical power of the propeller was calculated at different RPM to ensure the operating RPMs are well within structural and motor limits. Operating within structural and motor limits ensures that the Neuroptera propeller can safely withstand centrifugal and bending forces without failure. It also guarantees that the motor can deliver the required thrust efficiently, allowing the study to focus on aerodynamic performance and UAV applicability rather than structural or motor safety concerns. Table 9 shows the calculated tip speed and thrust-to-torque ratio using the thrust and torque data from simulation which is used to calculate the mechanical power of the propeller.

**Table 9** Mechanical power of Neuroptera at different RPMs

RPM	Thrust (N)	Torque (Nm)	Tip speed (m/s)	T/Q (N/N·m)	Power (W)
3000	1.62	0.031	31.42	52.26	09.74
5000	4.562	0.088	52.36	51.84	46.05
7000	9.006	0.174	73.30	51.76	127.50

Based on measured thrust and torque, the Neuroptera propeller shows high thrust-to-torque efficiency which is around 52 N/N·m, tip speeds of 31–73 m/s, and mechanical power ranging from 9.7 W to 127.5 W. Since these power values are well below the continuous rated power of typical small UAV brushless motors around 150–250 W by (Beard and McClain, 2012), this confirms that the propeller operates safely and efficiently, supporting the statement that the operating RPMs are well within structural and motor limits. Maintaining operation within these limits is critical to prevent structural failure or excessive vibrations that could compromise UAV performance. It also allows the study to focus on aerodynamic optimization and practical UAV applicability rather than structural or motor safety concerns [27].

Hence this study, Neuroptera design is proven to outperform other bio-inspired designs. Previous study have shown that owl-inspired leading-edge serrations caused about a 3.2% drop in aerodynamic performance compared to smooth wings (Liu et al., 2020), and tubercle-modified propellers reported by Stark et al (2015) exhibited reduced thrust efficiency at certain advance ratios [28][29]. Liu et al. (2020), found that owl-inspired leading-edge serrations reduced aerodynamic performance at low angles of attack while Neuroptera propeller achieved a consistent 14–17% improvement in FOM across RPMs, highlighting its superior aerodynamic efficiency even under conditions where traditional serrations underperform. Moreover, Stark et al. (2021) found that introducing leading-edge tubercles on a ducted marine propeller increased thrust coefficient by up to 10% and improved propulsive efficiency by up to 6.5%, while Neuroptera design consistently boosted the FOM by 14–17% across 3000–7000 rpm, demonstrating significantly stronger aerodynamic gains [28]. In addition, Foad Moslem et al. (2022) conducted experimental investigation into the aerodynamic and aeroacoustic performance of bioinspired small-scale propeller planforms which include a Neuroptera planform. At 3000 RPM, Neuroptera-inspired propeller by Foad Moslem produced 1.11 N thrust with 0.037 Nm torque, whereas the Neuroptera propeller in this study produces 1.62 N thrust with 0.031 Nm torque. This demonstrates that this design achieves higher lift with lower torque, combined with smoother pressure distribution [9]. The improvement in thrust values are due to the minor adjustment made on chord length and blade shape to match motor torque limits and operational constraints, ensuring manufacturability and energy efficient. Moreover, studying forward flight is important because

it reflects real operational conditions for UAVs, where efficiency, thrust, and energy consumption determine performance, whereas hover-only studies do not capture the aerodynamic challenges encountered during cruising or maneuvering. Other than the design and setup differences, this study is simulation-based rather than experiment based which is more cost efficient in long run. The Neuroptera is appropriate for a variety of applications because of its improved aerodynamic performance, which not only allows increased payload capabilities but also suggests possible noise reduction advantages.

### 3.0 CONCLUSION

The comparison between the DJI Phantom 9450 propeller and Neuroptera propeller shows that the Neuroptera outperforms the Phantom in both thrust and efficiency. At all tested RPMs, the Neuroptera generates significantly higher thrust, with a 74% increase at 3000 RPM, and continues to surpass the Phantom at higher speeds. This result suggests potential for longer flight durations. Additionally, the Neuroptera achieves a higher FOM, indicating superior aerodynamic efficiency, with improvements ranging from 14.7% to 17.6% over the Phantom. These advantages point to the Neuroptera's optimized design, likely reducing drag and improving overall performance, making it more suitable for applications requiring better endurance and stability.

The research presents a novel bio-inspired propeller design, combining Neuroptera wing shape with a DJI blade twist, and leverages high-fidelity SST k- $\omega$  and LES simulations to capture detailed aerodynamic and aeroacoustic behavior. It provides hover efficiency and FoM metrics, offering useful insight into UAV propeller performance. While the study focuses on aerodynamic characterization using a steady-state approach and a simplified blade twist, these choices still allow for accurate and meaningful assessment of propeller efficiency and flow features relevant to practical UAV applications. The Neuroptera propeller is optimized for practical UAV operation, achieving high thrust-to-torque efficiency and mechanical power well within motor limits, ensuring safe and efficient performance. It demonstrates smoother pressure distribution and stable hover compared to typical insect-inspired designs, translating bioinspired insights into a functional, application-ready propeller. The study also integrates forward-flight considerations, providing relevant aerodynamic data for real-world UAV endurance and efficiency optimization. The study does not include a formal frequency or resonance analysis, so potential vibration modes under extreme operating conditions are not yet fully characterized; however, the operating RPMs were carefully selected and mechanical power was calculated to ensure safe operation within motor and structural limits. Additionally, aerodynamic loads were estimated from measured thrust rather than detailed blade-resolved CFD, but careful scaling and

comparison with bioinspired planforms were used to minimize uncertainties and approximate realistic flow behavior. Future studies could explore full transient simulations, blade twist optimization, and translation of aerodynamic metrics into mission-specific performance, such as energy consumption and hover endurance.

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## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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