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Enhancement of Aerodynamic Efficiency in a Commercial Propeller Through Bio-inspired Blade Design

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Abstract

Enhancing the aerodynamic efficiency of commercial multi-rotor propellers can be accomplished by implementing creative designs influenced by the wing structures of different insects. The present research is examining the feasibility of using insect-inspired propellers in missions, with a particular focus on studying their aerodynamic performance in four main areas: flight time, rotational speed, mechanical power, and propeller efficiency. The present study draws inspiration from the wing forms of six insect species: Hemiptera, Orthoptera, Neuroptera, Mantodea, Odonata, and Hymenoptera to enhance DJI Phantom-3 propeller performance requirements. Numerical simulations were performed to assess performance utilizing the moving reference frame approach (Multiple Reference Frame) and the SST $k-\omega$ turbulence model. The evaluations were focused on hover circumstances at rotational speeds between 4000 and 8000 rpm. There is a notable agreement between the numerical simulation and experimental findings. The results clearly showed that the propellers inspired by insects exhibit enhanced performance in specified missions. The Hemiptera propeller showed improved performance by decreasing the rotational speed at hovering condition. It demonstrated a 9.8% increase in flight time and rotated 13.36% slower than the DJI Phantom-3 propeller at hovering condition, with no additional weight. Ultimately, the wing planforms inspired by insects has significant potential to improve the aerodynamic performance of small multi-rotor rotors. This study's findings provide vital insights on how creative designs can surpass typical propeller configurations in terms of flight time and rotational speed.

Keywords: Bio-inspired, Insect, Propeller, Multi-rotor, Aerodynamic Performance, Numerical Simulations

1. Introduction

The wide array of commercial Unmanned Aerial Vehicles (UAVs) applications and their characteristics are evident nowadays. Multi-rotors, sometimes known as rotary-wings, are favored for their diverse maneuvering abilities, including hovering and vertical take-off and landing (VTOL) capabilities. Multi-rotors have many urban and civilian applications, such as environmental inspections, traffic monitoring, pollution inspection, delivery services, aerial photography, surveying, mining, rescue operations, and more [1]. Multi-rotor drones are considered a key platform for commercial UAVs, replacing and upgrading traditional technology to modern standards across several industries [2].

In the small commercial multi-rotor (0.2 to 1 kg with maximum payload of 0.3kg) propellers provide lift force known as multi-rotor thrust. These multi-rotors are modest in size, which results in them working at low Reynolds numbers, typically less than 100,000 [3]. Low Reynolds numbers complicate the assessment of small-scale propeller performance. The dense boundary layer forms on the propellers, compared to the modest propeller dimensions, leading to increased drag force and reduced lift-to-drag ratio. The efficiency of propellers is significantly influenced by Reynolds number, particularly at lower levels, due to the tight correlation between thrust and lift, as well as power and drag [4]. The constraints of small multi-rotors are mainly due to their small size, which results in reduced performance at low Reynolds numbers where viscous effects are significant [3]. These restrictions typically manifest in battery consumption, flight duration, and payload capacity. Small commercial multi-rotors rely on lithium batteries for their propulsion system due to their lightweight and efficiency. One of the main benefits of using these batteries is the decrease in noise levels, hence, focusing on enhancing the design of propellers is crucial for improving performance

and minimizing noise due to their significant role in generating push for upward movement, too [5,6,7].

UAVs can be categorized into three groups based on wing movement: fixed wing, flapping wing, and rotating wing. The paper focuses on the propellers of commercial small multi-rotor drones. In 2003, Bohorquez et al. [8] conducted an experimental investigation on the design, analysis, and performance of rotary wings in Micro Air Vehicles (MAVs). The results indicated that a key aerodynamic issue was the improper selection of propeller planform. In 2007, Ramasamy et al. [9] conducted an experimental study on the flow field of rotary wings in Micro Air Vehicles (MAVs). They demonstrated that increasing the boundary layer thickness and turbulence significantly reduces aerodynamic performance. Brandt and Selig [10] conducted an experimental study on how altering blade diameter impacts propeller performance for UAV constructions, highlighting the significant influence of selecting the appropriate propeller. Jordan et al. [11] conducted an experimental study to assess the performance of commercial drone propellers for development and validation purposes. The study demonstrated that the total sound pressure level rises as the rotating speed increases, particularly with low harmonics. Shams Uddin and Madzni's [12] numerically demonstrated that the appropriate design of propellers and rotor arrangement is crucial for enhancing the aerodynamic performance and efficiency of the propulsion system. In 2017, Deters et al. [13] conducted experimental research on the static performance of propellers and engines in small UAV configurations. They verified the flight duration stated by manufacturer and compiled a database of propeller performance data.

Aside from altering the geometry of propellers to enhance aerodynamic efficiency, utilizing bio-inspired techniques is another strategy that may be employed to increase propeller performance and several research studies have been carried out in this area. Gomez et al. [14] conducted one of

the initial studies on bio-inspired propellers in 2014, focusing on analyzing the cicada wing statistically. Their findings indicated that bio-inspired propellers produce less powerful vortices and are more suited for use in rotorcraft. In 2017, Ning and Hu [15] conducted experimental research on the aerodynamic and aeroacoustics properties of UAV propellers designed based on a combination of cicada wings and maple seeds. They demonstrated that, for the same input power, a conventional propeller may provide equivalent thrust at a lower RPM during hovering, perhaps leading to reduced noise levels. Hintz et al. [16] conducted an experimental study in 2018 to examine the impact of a propeller design based on cicada on thrust and energy consumption. Their findings indicated that this bio-inspired propeller demonstrated improved efficiency. In 2022, Masdari et al. [17] conducted an experimental study on the acoustic properties of propellers modeled after insect wings from five different species and a plant seed. Their bio-inspired propellers demonstrated superior thrust and rotation at lower speeds, while also producing less noise compared to the baseline propeller.

Due to the scarcity of studies in the area of bio-inspired and insect-inspired propellers, together with the interesting outcomes from prior research, it is clear that more in-depth investigation is required. Previous research has explored the bio-inspiration, particularly focusing on insect wings and propellers aerodynamic properties, as detailed in the references [14,15,16,17]. The current research is based on that developmental work in continuation of research conducted in this field. Specifically, we have developed further types of planform and new bio-inspired propellers that complement the existing designs and more insects' wings are investigated. Furthermore, the limited research conducted has primarily concentrated on the acoustic properties of the propellers, utilizing an experimental methodology for analysis. The goal of this study is to investigate the potential of more insect-inspired wings with the aim of enhancing the aerodynamic efficiency of

propellers by exploring the benefits of integrating bio-inspired concepts into their design using numerical simulation.

2. Methodology

This research aims to examine the effectiveness of insect-inspired propellers when compared to conventional propellers. The first step in achieving this goal is selecting a base propeller. At this stage, insect wings are chosen for modeling, and their shapes and structures are examined. The base propeller and insect-inspired propellers developed during modeling are numerically simulated and validated using experimental results [13]. A confirmed numerical simulation is used to model the flow field of all propellers and analyze their aerodynamic performance based on performance characteristics like thrust and torque coefficient, propeller efficiency, etc. In a practical study, several tasks are assigned to a conventional multirotor platform that is fitted with standard and insect-inspired propellers to lift and transport various loads, including commercial payloads.

The propeller of the DJI Phantom-3 has been chosen to validate the numerical simulation as the initial stage. The propeller, depicted schematically in figure 1, has a diameter of 0.24 meters [18]. Based on the experimental test conducted on this propeller in Reference [13] and the availability of the experimental data, it is a fitting selection as the base propeller for the present study.

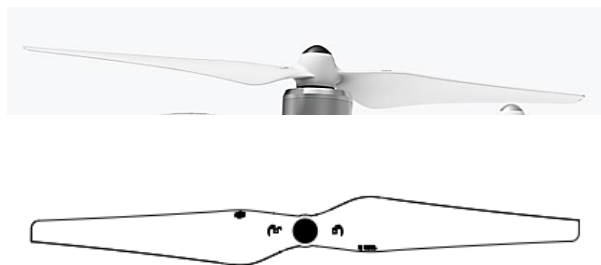


Figure 1. The Picture and a Schematic of the DJI Phantom-3 propellers considered as base propeller in this research [19,20].

The insect wings selection was a significant challenge during the present research. One of the key requirements is the availability of a perfectly captured wing planform. However, it is difficult due to various factors such as extremely small dimensions, rapid wing movement, and unique rest positions of some insects. These factors making it difficult to find high-quality images that showcase the planform characteristics and features. In the selection process of insect wings, one crucial factor is considering the simplicity of the border lines that define its shape. This holds particularly true when utilizing design software for 3D modeling and depends on the level of expertise involved. Despite the complexity mentioned and the consideration of these factors in insect wing selection, several species have been chosen for further studies. These selected species belong to the Hemiptera, Orthoptera, Neuroptera, Hymenoptera, Mantodea, and Odonata orders as are illustrated in figure. 3. Hemiptera, with more than 80,000 known species, are divided into 4 suborders, which they are vary in size, shape, and wing color. Cicadas are from of this order.

The DJI Phantom-3 multi-drone and its equipment requirements have been chosen as the base multi-rotor platform for this research. Three distinct missions have been outlined in order to achieve the main goal. Then, crucial parameters such as propeller efficiency, rotational speed, mechanical power, and flight time analyzed. Additionally, the information provided in previous studies, specifically calculations carried out in [13], have taken into account to enhance the accuracy of our findings. The primarily focus of this study is on investigating the thrust to weight ratio of 1:1. For the multicopter drone, in order to successfully take off and hover for its mission, the thrust required must be at least equal to its weight (thrust to weight ratio is 1:1). This thrust to weight ratio (1:1) is defined as the hovering condition and the propeller rotational speed related to the *hovering condition* is defined as the *hovering rotational speed* in the present study.

The mission specifications have been compiled and presented in Tab. 1. The m_t is defined as the total weight of the commercial multirotor platform including the multirotor structure, battery, and propellers. Considering the Phantom DJI-3 as a platform multi-rotor in the present study, total weight, m_t , is considered equal 1216 g based on the its data sheet. This multi-rotor is tailored for commercial tasks in photogrammetry and aerial video recording. Additionally, it is important to account for the camera and its gimbal as integral components of the multi-rotor platform. During various challenging missions which are defined in the present study, some payloads, m_p , are considered to transport using the multi-rotor equipped with the base and all insect-inspired propeller.

Table 1. Definition of some missions for a commercial multirotor equipped with the present insect-inspired propellers

Parameter	Condition	
m_t: Total Weight (Battery & Propellers Included)	1.216 kg	
Flight condition	Hover condition at thrust to weight ratio of 1:1	
payload		m_p: payload
	Mission 1	-
	Mission 2	First case: + 0.250 kg Second case: + 0.772 kg Third case: + 0.553 kg
Flight time target		Endurance
	Mission 1	25 minutes
	Mission 2	15 minutes

The performance parameters are essential for comparing and analyzing propellers in missions. One of the parameters that can be used for the performance of the propeller is the propeller efficiency

which can be calculated from the Eq. 1 and it is defined as the ratio of the output power (which is the driving power) to the input power (which is the mechanical power) [13].

$$\eta_P = \frac{TV_0}{P_m} = J \frac{C_T}{C_P} \quad (1)$$

Where T is the thrust, V_0 is the freestream velocity, and P_m is the required mechanical power which can be calculated from the following equation [13]:

$$P_m = 2\pi nQ \quad (2)$$

The parameter Q in Eq. 2 is the torque and n is the rotational speed (in rpm). In the propeller efficiency equation, C_P is the power coefficient and C_T is the thrust coefficient, which can be calculated from the following equations [13]:

$$C_T = \frac{T}{\rho n^2 D^4} \quad (3)$$

$$C_P = \frac{P_m}{\rho n^3 D^5} \quad (4)$$

Also, the torque coefficient, C_Q , can also be defined as the following equation [21].

$$C_Q = \frac{Q}{\rho n^2 D^5} \quad (5)$$

In the above equations, ρ is the flow density, D is the propeller diameter. The advance ratio (J) is calculated from the Eq. 6. Due to the low value of the speed, the advanced ration in this research is very close to zero [21].

$$J = \frac{V_0}{nD} \quad (6)$$

The flight duration of a multirotor-drone depends on several factors including its capacity, battery charge, and the average amount of electrical current it receives. This can be calculated using Eq. 7. The capacity is typically measured in mille ampere hours, which determines how much energy the battery can store. For optimal performance, it is recommended to charge the Lipo 4 flight batteries used in the multirotor-drone to around 80% of their capacity. The average electrical current required to determine the duration of the experimental research data, as provided by Deters [13], is calculated by considering the total weight of the multi-drone, including the battery, and then obtaining the interpolation.

$$Endurance = \frac{capacity \times Discharges}{total\ electrical\ current} \quad (7)$$

4. Geometry Modelling

Propellers are crafted from diverse materials and assembled by aligning multiple airfoil sections uniformly along the span wise direction, as illustrated in Figure 2a. The Drones typically utilize two blades for stability and to keep the overall weight of the structure manageable [22]. Additionally, propeller blades possess geometric characteristics akin to those of airfoils, including the trailing edge, leading edge, chord, thickness, and more, as depicted in figure 2b. [23 and 24]. The geometric pitch refers to the theoretical distance that the propeller must travel in a complete revolution. It is important to note that this distance is not constant along the span of the propeller. On the other hand, the effective pitch represents the actual distance covered by the propeller in one

complete revolution, as shown in figure. 2c. [24]. The advance ratio, which compares the distance covered by the propeller in one rotation and in one direction to the propeller diameter, is another significant parameter [24]. Furthermore, the twist angle, also known as the pitch angle, is the angle between the chord line and the rotation plane at a specific point along the length of the propeller. This angle changes progressively from the root to the tip due to the twisting of the propeller, as illustrated in figure 2a. [23 and 24].

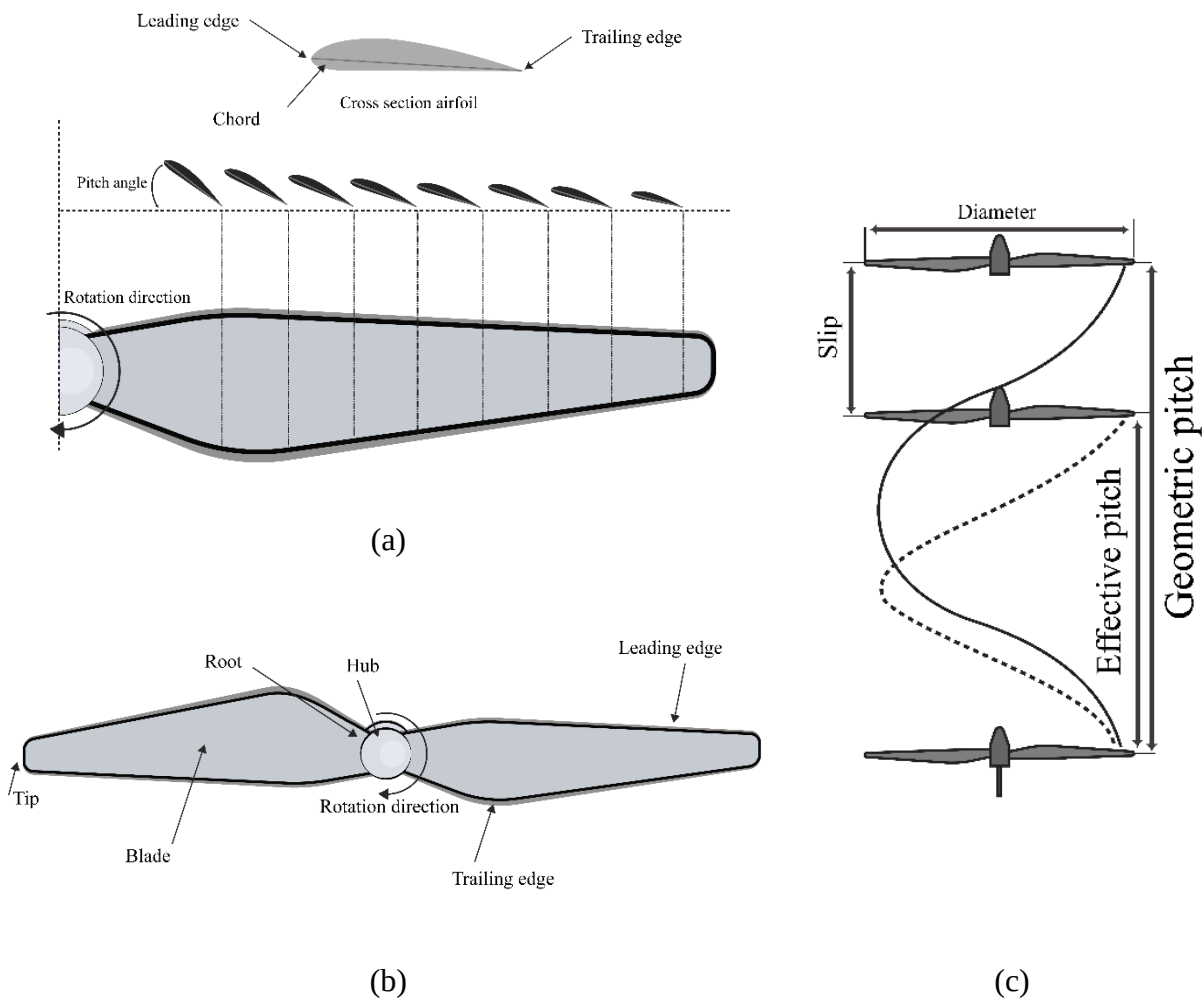


Figure 2. Propeller geometry and performance parameter; Propeller cross-section at different local radius and twist along the span (a), Propeller's geometry parameter (b), Geometric pitch, effective pitch, and advance ratio (c).

Figure 3 shows the images of the selected insects and the insect-inspired propellers created according the base propeller specifications and dimensions, as explained below. To create a precise three-dimensional propeller blade, it is crucial to determine three essential factors including the chord distribution (planform), twist distribution, and airfoil of the propeller section. The chord distribution is captured based on top-view images of the selected insect wings. All insect-inspired propellers are scaled and became dimensionless proportionately to the base propeller radius.

The three-dimensional geometry modeling of the propellers was executed using SolidWorks software, incorporating specific twist and chord values for each section's airfoil. After merging the sections, the final solid geometries of the propellers were obtained, as depicted in figures. 3a-f.

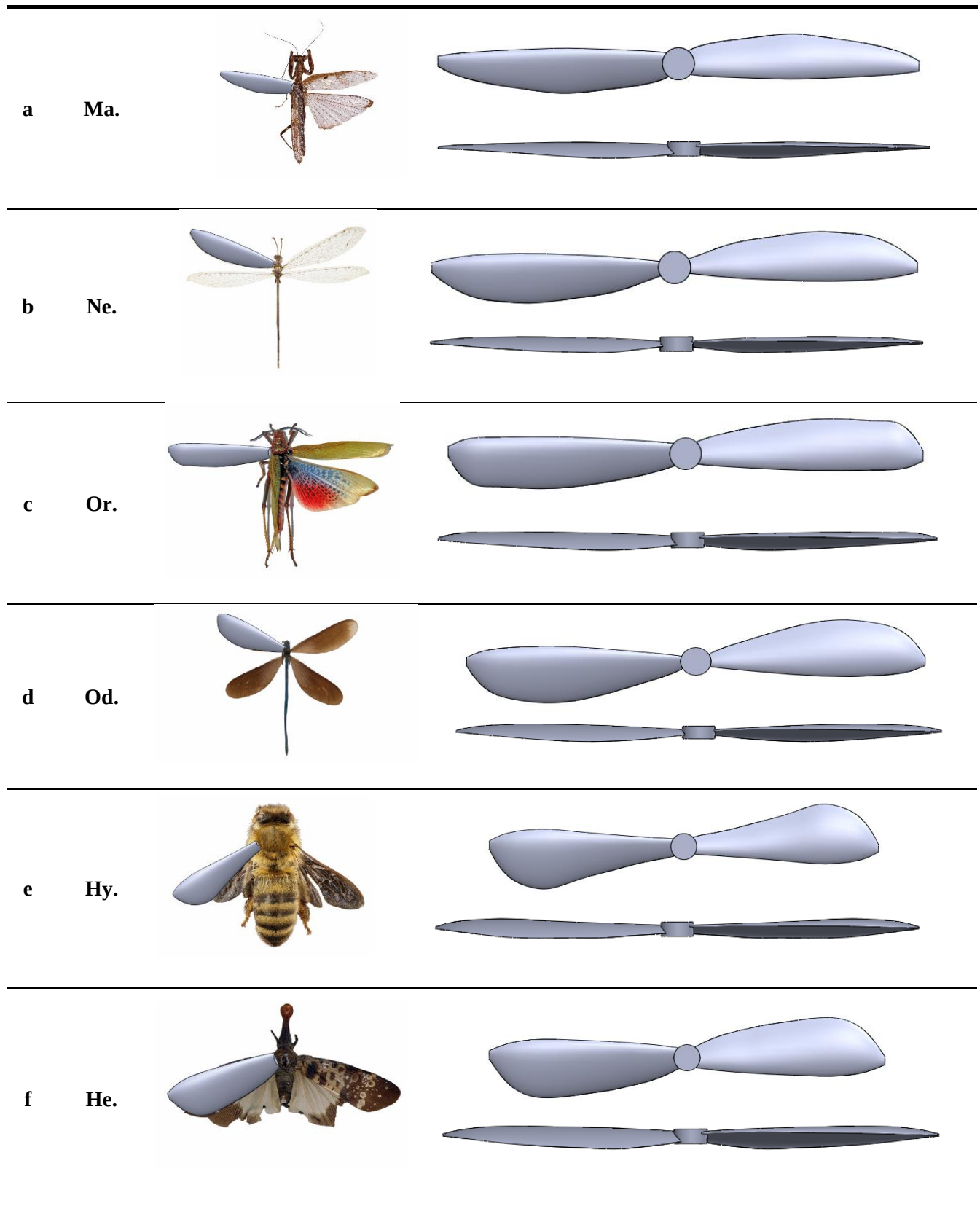


Figure 3. Three-dimensional models of bio-inspired propellers, Mantodea (a) [25], Neuroptera (b) [26], Orthoptera (c) [27], Odonata (d) [28], Hymenoptera (e), Hemiptera (f) [29].

It should be acknowledged that the mentioned three-dimensional modeling of the insect wings may contain some modeling errors. However, these would only yield a negligible margin of error. The twist distribution, taking into account previous studies [13, 17], starts at 17.72 degrees from the root to approximately 30% of the propeller radius. From that point to the tip, the twist decreases linearly to 4.7 degrees. Since there is a lack of information regarding the geometry and airfoil specifications of the DJI Phantom-3, we have considered the EPPLER E63 airfoil for all insect-inspired propellers. This airfoil is widely used in research on small-scale propellers and is known to be suitable for low Reynolds number flows [15, 17]. We have utilized this airfoil for all propellers sections in our study and the diameter is hold fixed, equal to base propeller.

5. Numerical Simulation

The focuses in this research is on the aerodynamic performance and mission analysis of the bio-inspired propellers. To achieve the objectives, the flow field around the propellers are simulated numerically using ANSYS FLUENT. The Multiple Reference Frame (MRF) feature is selected because this method is used in the cases where there are moving part, like propeller, and the flow around this part is desired to simulate [31]. Noting the recommendation of the MRF method in previous studies [32-35] and also considering the subject of this study, MRF method is considered.

Figure 4 illustrates the computational domain. The computational domain includes two parts: the rotating domain, which encompasses the propeller, and the larger stationary domain which includes both the rotating domain and an interface connecting the two. The propeller is fully enclosed within the rotating domain, causing the propeller tips to be slightly distanced from the

interface. Consequently, the diameter of the rotating domain is 1.08 times the propeller's diameter. On the other hand, the dimensions of the stationary domain cylinder must be sufficiently large to minimize its impact on the propeller. Therefore, its diameter is 4.14 times the propeller's diameter, while its height is 14 times the propeller's diameter [32,34,36].

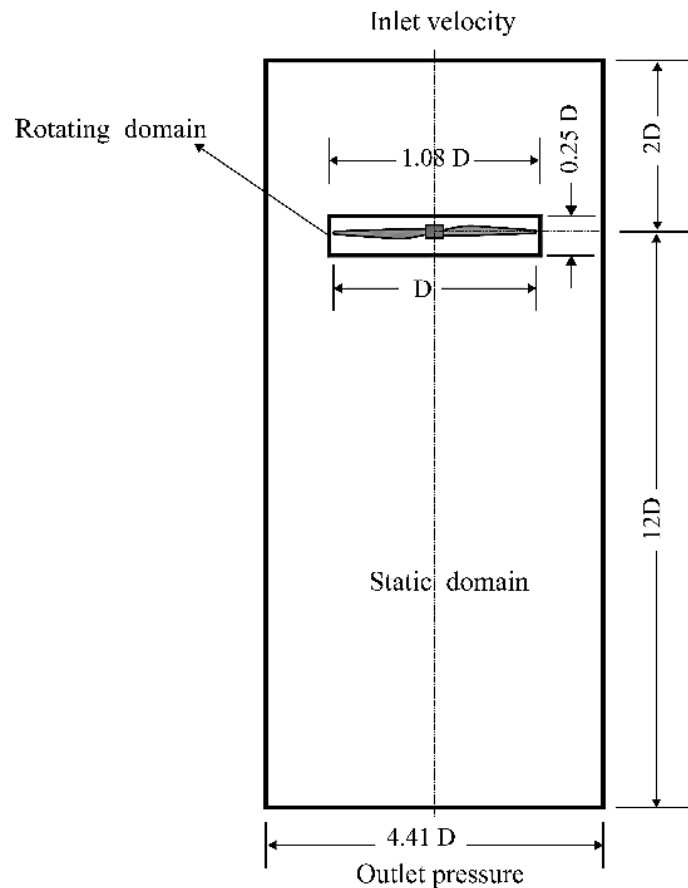


Figure 4. Computational domains along with dimensions and boundary conditions

The boundary conditions between the two parts of domains are defined as the interface and the wall boundary condition is considered for propellers surfaces. The velocity inlet and pressure outlet boundary conditions are considered for the upper and lower domain surfaces, respectively, considering the hover flight condition. In addition, the velocity at inlet is low and about 0.1 meter

per second and in y-direction which is demonstrated hover condition. The rotational speed is considered in the range of 4000 to 8000 rpm with a step of 1000 rpm.

Considering the relatively small dimensions of the propellers' geometries compared to the size of the computational domain, significant geometrical gradients of propellers, and the three-dimensional nature of the geometry, unstructured mesh and tetrahedral elements were utilized. This ensured that the mesh size would be compatible with the available computing resources. Additionally, as viscosity effects were found to be predominant, boundary layer meshing and prism elements were employed. The calculations were conducted based on the chord and tangential speed at 75% of the propeller radius, standard temperature, Reynolds number, and thickness of the turbulent boundary layer [3 and 37]. Figure 5 presents the propellers mesh.

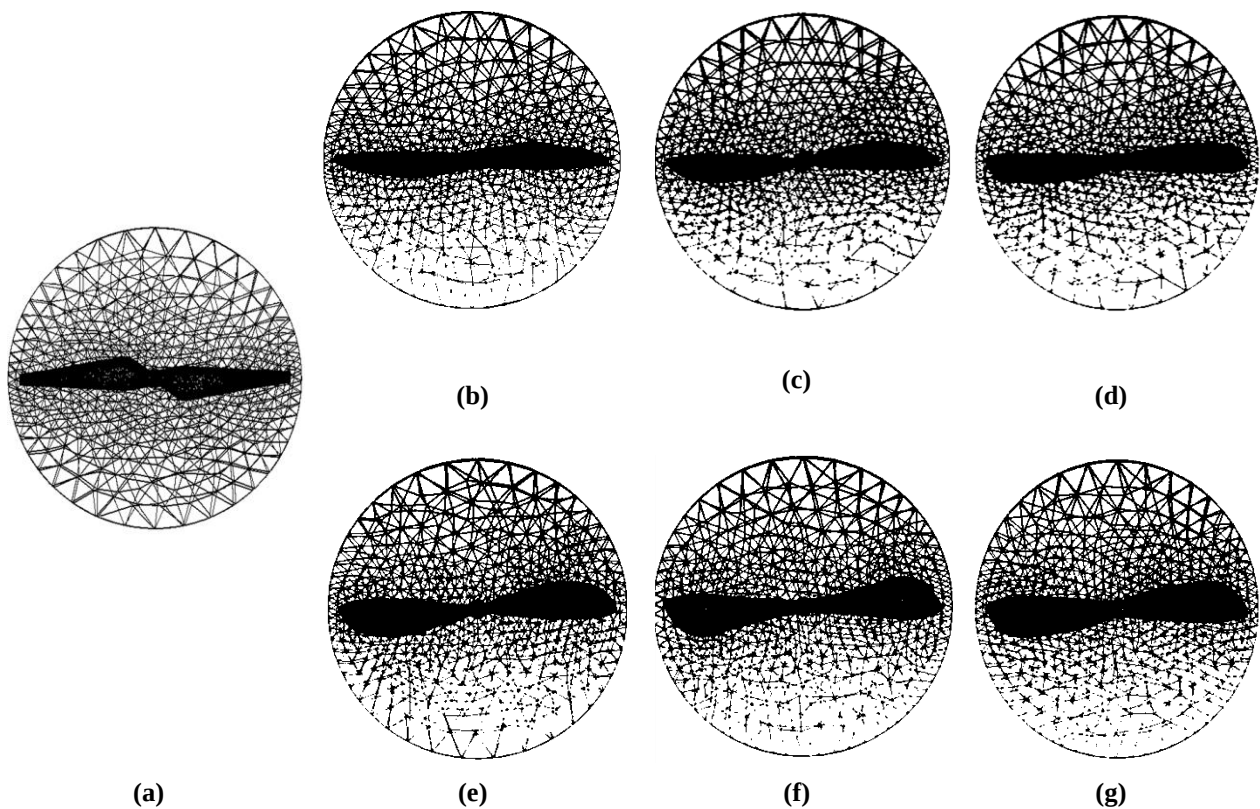


Figure 5. Propellers Unstructured Grids, Mesh of: base propeller (a), Mantodea (b), Neuroptera (c), Orthoptera (d), Odonata (e), Hymenoptera (f), Hemiptera (g).

The SST $K-\omega$ turbulence model is utilized for modeling flow turbulence in this study. This particular model has been recommended and employed by various researchers to analyze the aerodynamic performance of small propellers [5, 32, 36, and 38]. It consists of two equations: The K equation, which represents turbulent energy, and the ω equation, which represents dissipation [39 and 40]. Despite the higher computational costs associated with the need for boundary layer meshing, this turbulence model is suitable for accurately modeling propeller turbulence. Typically, the average Y^+ value is remained in the order of one. The solver for solution is pressure based with coupled algorithm and discretization of all equations are based on second upwind scheme with second-order accuracy for all equations. Also for gradients, Least Squares Cell-Based is used. The solution process is repeated until the residuals reach the selected convergence criterion of 10^{-5} . Moreover, a convergence criterion of 10^{-5} is also applied to the thrust and torque measurements. The number of iteration steps varies between 2000 and 3000, depending on the computing system. The numerical solution was stopped after the residuals reached the convergence criterion and the forces, thrust, and torque converged, and their graphs did not change significantly, and a low percentage of error between the thrust and torque values obtained from the numerical solution and the experimental solution.

5.1. grid and static domain independency

One of the important requirements for performing a correct numerical simulation is to check the grid independency, meaning that the results do not change much with the increase in the number of elements, or in other words, with the finer grid, and the percentage of error between each grid and the grid before it is within an acceptable range. In this study, three grids with different numbers of elements at the same rotational speed have been studied, and the percentage of error between each grid and the grid before has been calculated with respect to the aerodynamic parameters of

the propeller performance, which here are the thrust and torque, between each grid and is presented in below in table 2.

Table 2. Grid independency

Rotational speed	grid	Number of elements	Thrust (N)	Error between each grids
8000	1	666699	6.62	-
8000	2	777896	6.71	First and second grid=1.3%
8000	3	880745	6.77	second and third grid=0.26 %

To increase the accuracy for results, two cases of different static domain dimensions were considered and compared the results with experimental data conducted by Deters et al. [13], as presented in Table 3. As a final step, by considering a compromise between the available computing resources, the number of simulation cases, and the computational cost of each case by increasing $H=14D$ and $Dsd=4.41$, it was observed that the thrust is obtained with less than 0.005 difference compared with the previous case ($H=10D$ and $Dsd=4$).

Table 3- Static domain independency

	RPM	Number of elements	Dimensions	Thrust(N)-CFD	Thrust(N)-Deter's studies[13]	Differences with previous Num. case	Differences with Exp.
2	8000	880745	$H=10D$ $Dsd=4D$	6.78	6.93	-	0.0216
3	8000	949661	$H=14D$ $Dsd=4.41D$	6.81	6.93	0.0044	0.0173

Considering these two tables data, grid number 3 was selected from the table 3.

5.2. Validation

The numerical simulations of the base propeller and all bio-inspired propellers were conducted using the described solution method. Figure 6-a, demonstrate the comparison of the thrust trends at various rotational speeds between the base propeller's numerical results obtained in this study and the experimental measurements conducted by Deters et al. [13]. The findings reveal a strong agreement between the two sets of data, indicating the high accuracy of the present numerical simulation method. This result suggests that the selected solution methodology is suitable for other bio-inspired propellers as well. However, it is important to note that there are some small differences between the experimental and numerical results, which can be attributed to various factors. One of the main reasons is the unavailability of precise geometric information about the DJI phantom-3 propellers used in the experimental tests. This lack of accurate geometry, including the chord distribution, twist, and cross-section airfoil, may introduce errors in the analysis. In order to compensate for this, the chord distribution and twist were determined based on previous studies or by using scanning software, which may slightly differ from the original propeller geometry used in the experimental tests and the model employed in the computational fluid dynamics (CFD) simulations. This discrepancy in airfoil selection can also contribute to the disparity between the results obtained from the two methods.

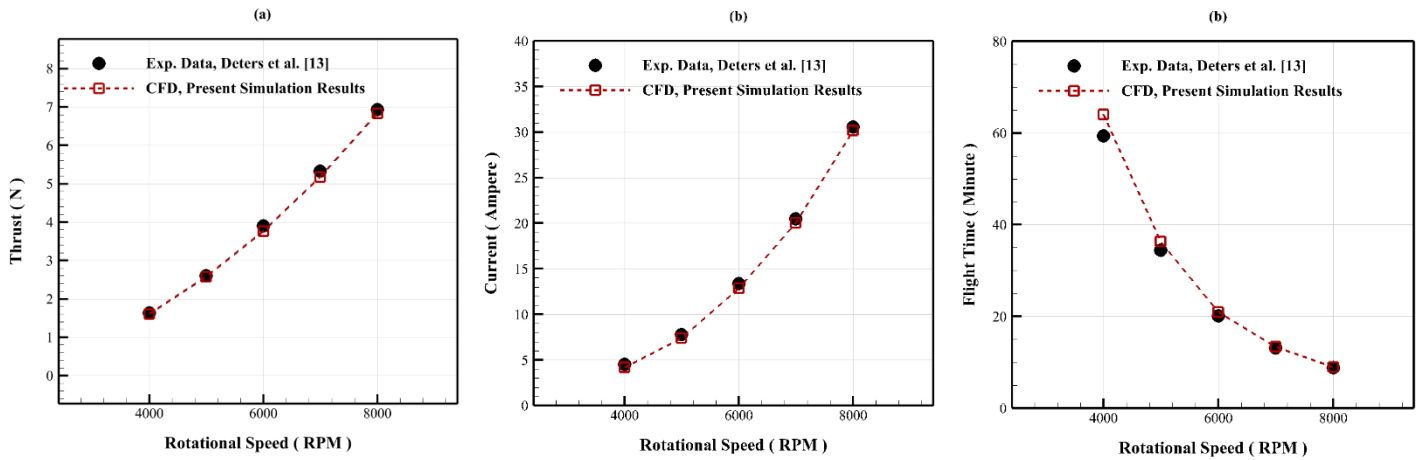


Figure 6. Validation of the present numerical method, Thrust versus RPM (a), electrical current versus RPM (b), flight time versus RPM (c).

According to Deter's findings [13], it is possible to calculate the electrical current-to-thrust ratio at any rotational speed. By equating the weight to the thrust generated by the multi-drone, the corresponding electrical current can be determined. Hence, based on these results and through calculations and interpolation, the total electrical current can be calculated. Figure 6-b, also, illustrates a significant agreement between the obtained results.

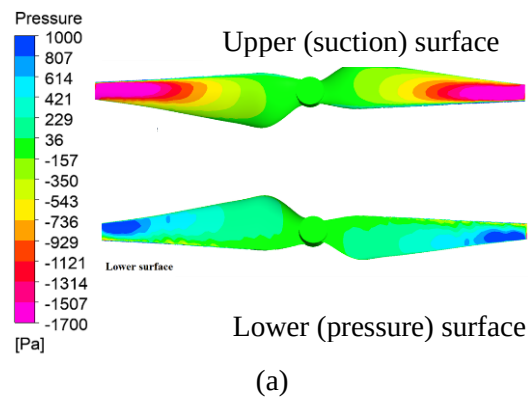
The focus in Deters' studies [13], was solely on the duration of the flight at a specific rotational speed, without addressing the discharge percentage of the flight battery. Consequently, assuming a discharge percentage of 100% and utilizing Eq. (7), the flight time was calculated for verification purposes. This time approach validation can be extended to calculate the time for all propellers. Figure 6-c, demonstrates a substantial degree of agreement among the results, with the discrepancy between the numerical and experimental methods attributed to the electrical current estimation technique at the low rotational speed ranges. Therefore, considering the validation results and the consistent geometric parameters such as pitch distribution and radius shared with the DJI Phantom-

3 propeller, it is reasonable to assume that the variations in the electrical current to thrust ratio reported in Daters' findings [13] for the DJI Phantom-3 propeller can be applied to other propellers as well. Consequently, an approximation of the flight time can be made.

6. Results and discussion

Performance analysis of propellers

Figure 7 depicts pressure distribution on the base and bio-inspired propellers' upper and lower surfaces at 6000 rpm. These contours show that the static pressure is higher on the pressure surface than the suction surface. This thrust is related to the pressure difference between these surfaces, which increases with propeller rotational speed. Thus, lift force rises with rotating speed and vice versa. Furthermore, a reduction in pressure is evident from the root to the tip of the blades, as evidenced by the spanwise pressure distribution in these contours. The rotational speed component and the expanding blade radius are the main causes of the spanwise increase in the speed vector's magnitude, which results in this spanwise pressure gradient.



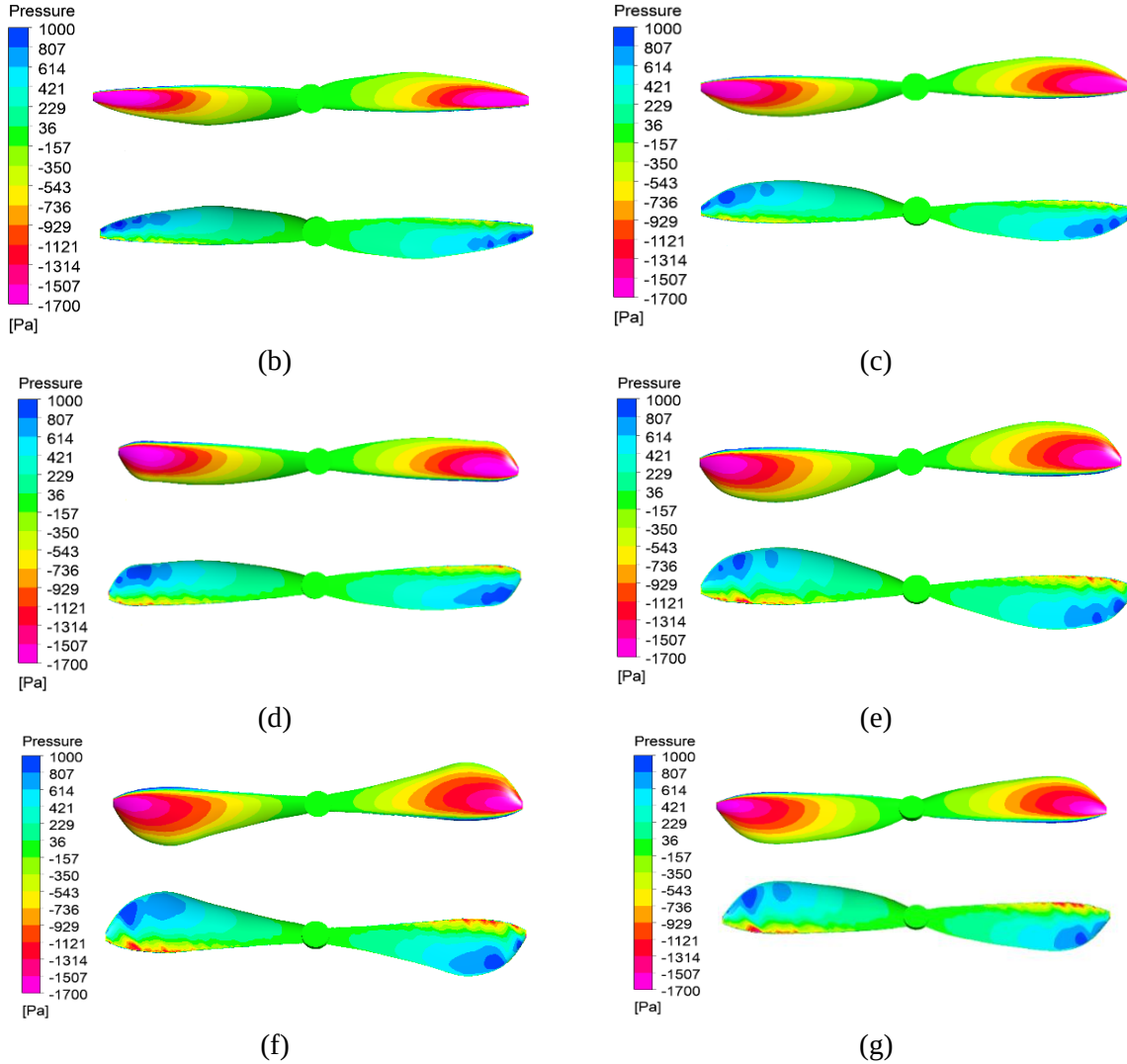


Figure 7. Pressure contour of: base propeller (a), Mantodea (b), Neuroptera (c), Orthoptera (d), Odonata (e), Hymenoptera (f), Hemiptera (g); in 6000 RPM.

In the hovering condition, when the thrust to weight ratio is 1:1, each multirotor drone propeller provides a specified amount of thrust, resulting in a total power equal to the drone's weight. The overall thrust is related to the multi-rotor weight at a specific propeller rotational speed. Thus, insect-inspired propellers' rotational speeds fluctuate for a certain thrust-to-weight ratio under constant thrust conditions. Figure 8 and 9 represent the variation of the rotational speed and propeller efficiency for all propellers studied in the present investigation, respectively. According

to the figure 8 and 9, with an increase in the thrust to weight ratio, propellers need to rotate at higher speeds demanding more mechanical power. Consequently, the propeller efficiency decreases at higher ratios. Additionally, wider propellers, such as Odonata, Hymenoptera, and Hemiptera, tend to have lower efficiency in higher thrust to weight ratios, ultimately reaching efficiencies of less than 1%. In a 1:1 thrust to weight ratio, Neuroptera and Mantodea propellers exhibit the highest efficiency, while Hymenoptera propellers have the lowest. At a 2:1 ratio, all propellers have similar efficiency, with Neuroptera and Mantodea propellers leading, and Hymenoptera propellers trailing in efficiency. In a 3:1 ratio, Neuroptera propellers demonstrate the highest efficiency, while Hymenoptera propellers lag behind.

According to figure 9, Increasing the ratio of thrust to weight results in a higher rotational speed, following a nearly linear trend with a positive and relatively steep slope. The slope of Mantodea propeller changes is the highest, surpassing DJI Phantom-3 and the base propeller. Conversely, Hemiptera and Hymenoptera propellers have the lowest slope. Despite lower efficiency at higher thrust to weight ratios, Hymenoptera propellers exhibit a lower rotational speed compared to other propellers, potentially reducing noise levels.

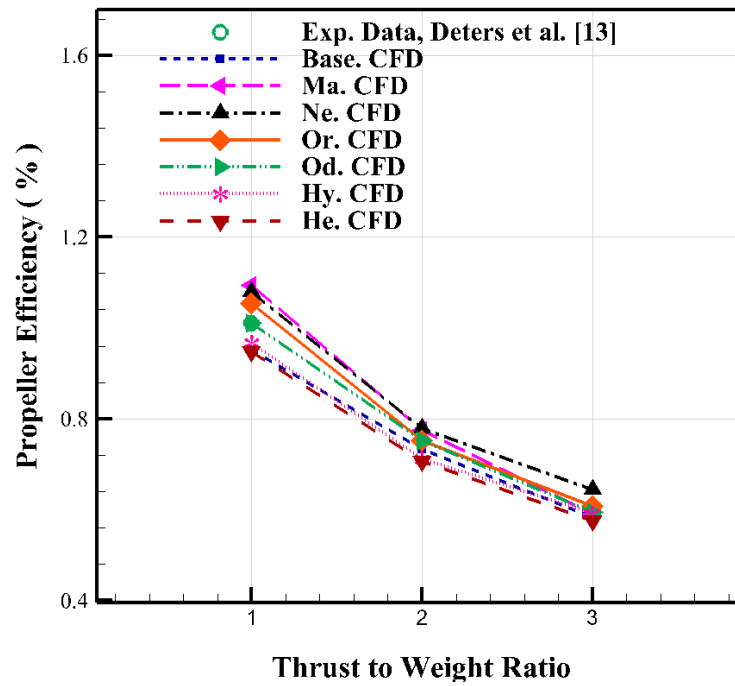


Figure 8. Propeller efficiency of base and insect-inspired propellers at various thrust to weight ratios

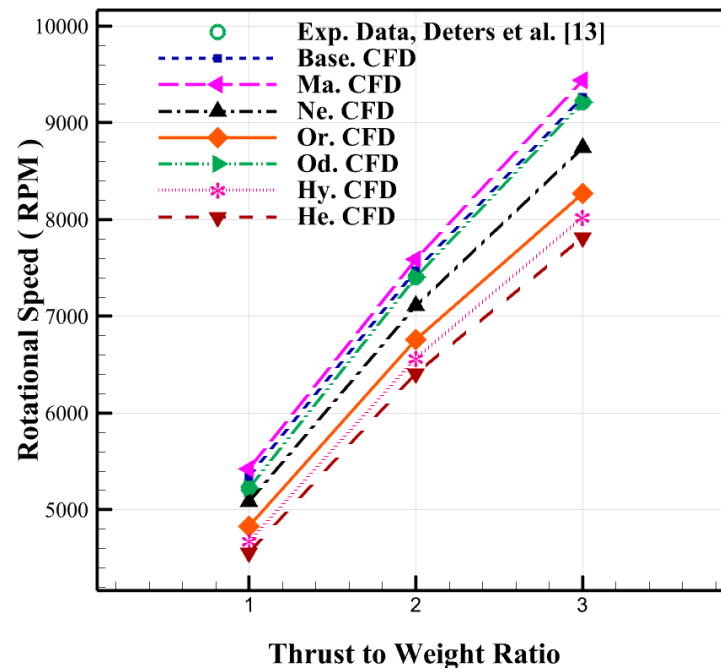


Figure 9. Rotational speed of base and insect-inspired propellers at various thrust to weight ratios

Figures 10 display the relationship between changes in electrical current and flight time at 80% flight battery discharge respect to rotational speed. As shown in Figure 10-a, an increase in rotational speed requires a higher electrical current. Furthermore, larger propellers such as Odonata, Hemiptera, and Hymenoptera necessitate a more electrical current for their rotation. The electrical current also increases as the rotating speed increases. The relationship between electrical current and rotational speed is consistent across all propellers, whether they are base or insect-inspired. Hemiptera and Hymenoptera propellers exhibit more pronounced differences than the standard propeller. Unlike the previous two examples, a minor variation trend is noticed in the Mantodea propeller, resembling the base propeller. Higher rotational speeds require more energy and power to generate increased thrust values. The Figure 10-b, illustrates that flight time decreases as rotational speed increases due to this trend. Based on these observations, the Mantodea propeller exhibits the longest flight duration across all rotational speeds. The Hemiptera has the shortest flight length time at all rotational speeds compared to other insects.

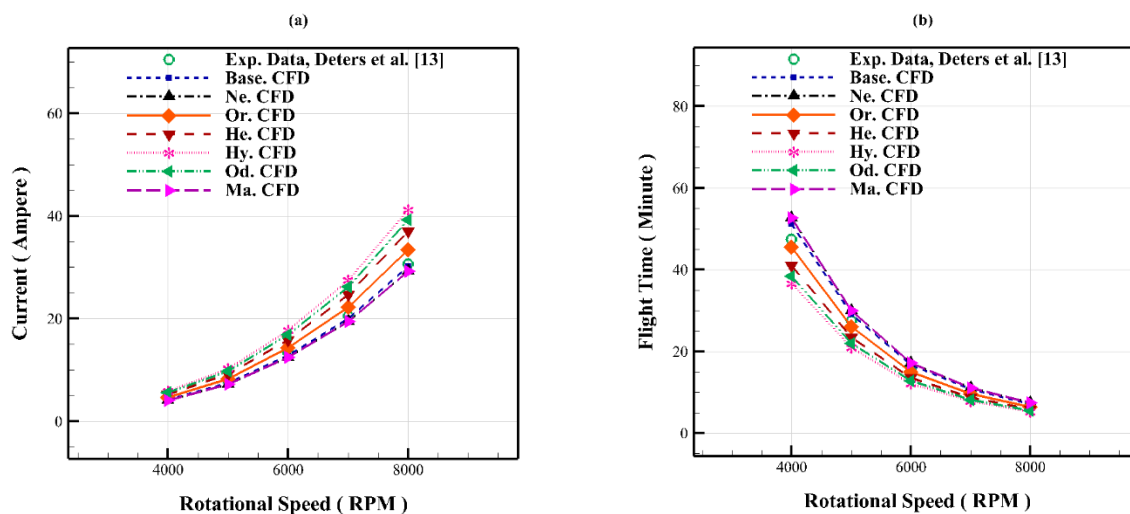


Figure 10. Electrical current versus RPM (a), flight time versus RPM (b), for the base and insect-inspired propellers

Despite the fact that these calculations can be done at all rotational speeds, all propellers can only hover at one speed, hence they should be compared under these conditions. Any propeller with a minimum thrust-to-weight ratio of 1:1 can hover. By calculating the flying time at this rotational speed for all propellers, the endurance performance of the base propeller and the insect-inspired propellers can be compared. Table. 4 illustrates the percentage of differences between insect-inspired propellers and DJI phantom-3 propeller flying time at 1:1 thrust-to-weight ratio and 80% flight battery discharge. This table shows that all insect-inspired propellers except Mantodea outperform the base propeller in endurance. Hymenoptera and Hemiptera improve flight time most at 1:1 thrust-to-weight ratio and 80% flight battery discharge.

Table 4. Flight (time) endurance performance at the thrust to weight ratio of 1:1 and 80% of flight battery discharged.

	$\frac{T}{W}$	Motor	Propeller	Flight time (minute)	Difference (%)
No Added Payload	1:1	DJI Phantom3	Exp. Data, Calculated	24.061	-
			Ma.	23.224	-3.478%
			Ne.	24.729	+2.777%
			Or.	25.517	+6.050%
			Od.	25.846	+7.419%
			Hy.	26.184	+8.823%
			He.	26.27	+9.18%

6.1. Mission analysis

Some commercial missions are outlined in this part to compare the practicality of the multi-rotor with insect-inspired propellers to the base one. Table. 1 describes these missions. The performance

characteristics (flight time, mechanical power, propeller efficiency, and hovering rotational speed) throughout these missions are calculated and compared to quantify the multi-rotor capability.

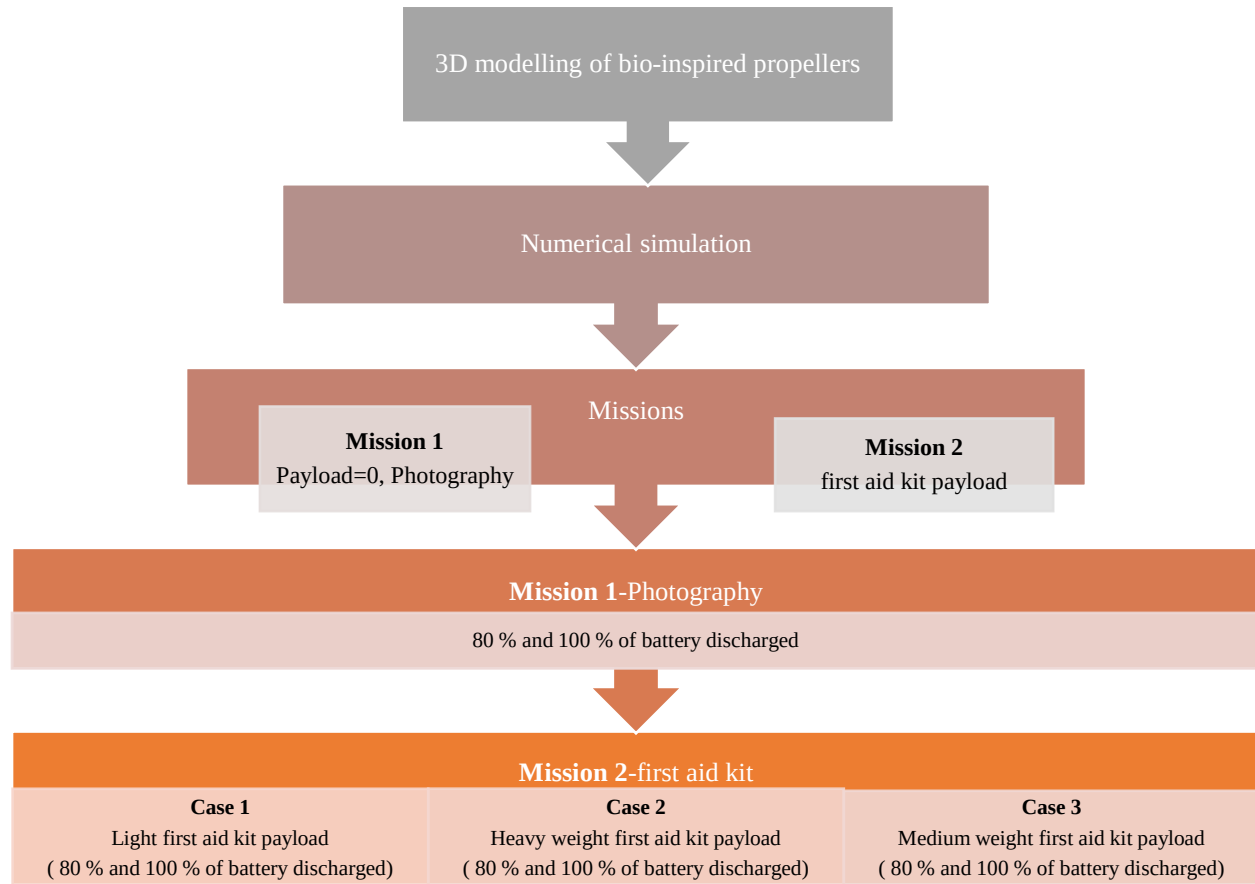


Figure 11. Framework of missions considered for performance study.

First Mission

The main application of the DJI Phantom-3 is for aerial photography and videography, which is the initial focus of the present research. During this mission, the multi-rotor is assumed to have no payload ($m_p = 0$). The official website of this multi-rotor states that the flight duration is around 25 minutes, as per the data-sheet information. The mission and its target are determined according to the flight endurance. The mission specifications in Table.1 provide two flight battery charge

conditions: 80% as optimal charge and 100% as fully charged. During the initial mission, there is no payload in either condition.

Based on figure 12 for the initial mission, all insect-inspired propellers, with the exception of the Mantodea propeller, enable multi-drones to achieve a longer flight duration. The DJI Phantom-3 propeller, with the flight battery at 80% discharge, allows for multi-rotor flight for under 25 minutes. Insect-inspired propellers can fly for 23 to 26 minutes, demonstrating the amazing powers of Orthoptera, Odonata, Hymenoptera, and Hemiptera rotors. The propellers enable drones to operate within specified time constraints. The mechanical power of Odonata, Hymenoptera, and Hemiptera propellers is high because of the significant width of their blades. This results in a decrease in propeller efficiency, as shown in the diagram. Odonata, Hymenoptera, and Hemiptera propellers experience reduced efficiency because of their size. When examining the hovering rotational speed, all propellers show a diminishing trend except for the Mantodea propeller. The Hemiptera propeller has the lowest rotating speed in the group. The findings provide valuable information on the flight time and characteristics of different propellers, offering crucial insights into their performance capabilities.

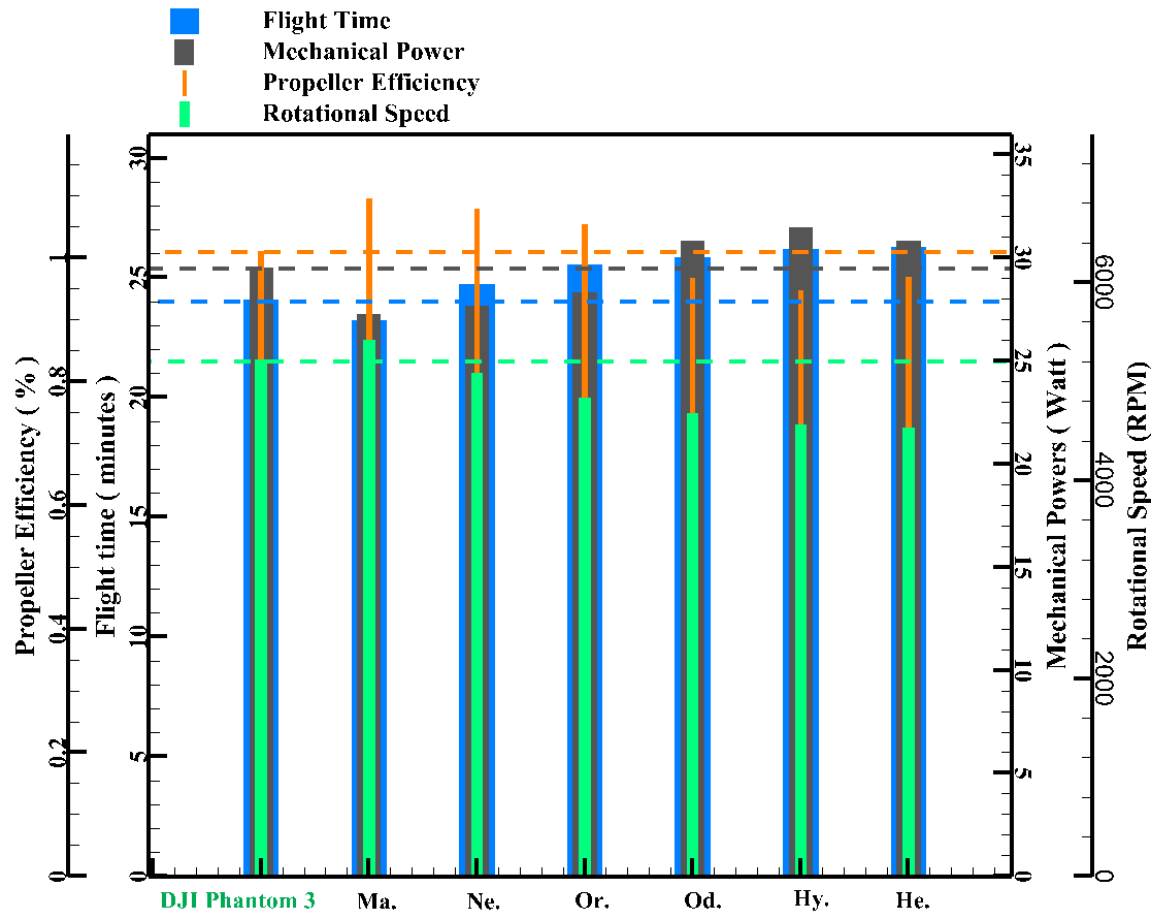


Figure 12. Comparison of parameters-first mission-80% discharged

Charging the flight battery to 100% solely affects the flight time, as per the given relation. As shown in figure. 13, the flight range of these insect-inspired propellers varies between 30 and about 32 minutes. The Hemiptera propeller has the longest flight time.

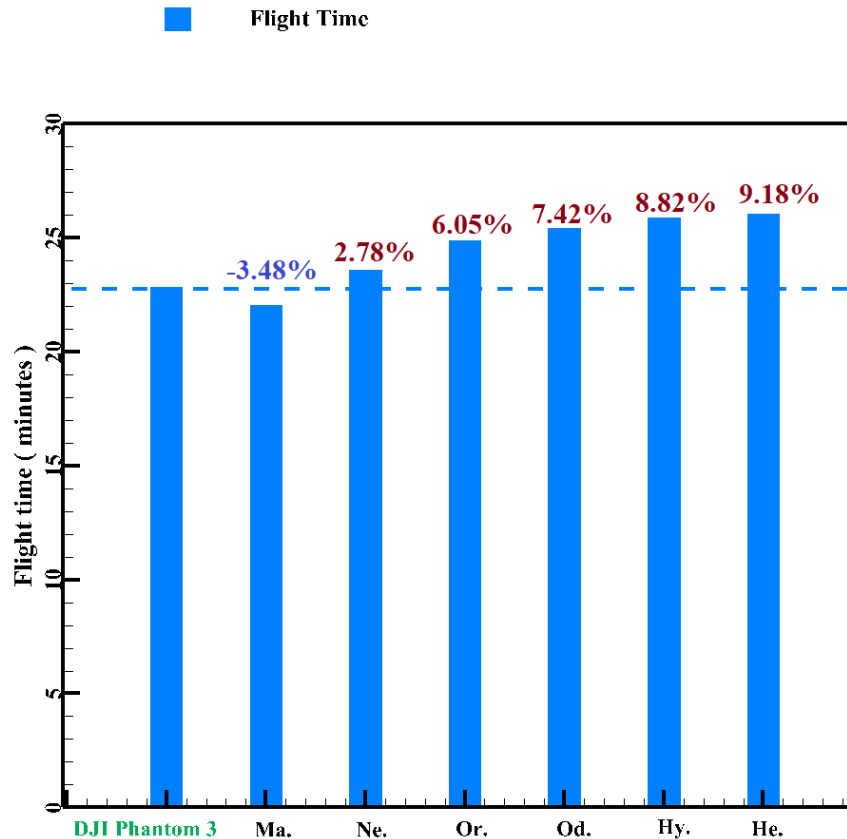


Figure 13. Comparison of flight time-second mission-third case- 100% discharged.

Second Mission

One significant mission involves delivering medical equipment and packages to places affected by accidents, natural catastrophes, or excessive traffic congestion. The packages may contain essential supplies like first aid kits, medicine, equipment, antidotes, and related stuff. Regarding the second mission, three distinct possibilities (Cases) may be identified:

1. Light first aid kit payload (Case 1)
2. Heavy weight first aid kit payload (Case 2)
3. Medium weight first aid kit payload (Case 3)

Case 1: Light first aid kit payload

A small first aid kit with 113 pieces, it weighs 0.158 kg [41]. This assumes that a 0.092 kg gadget released the package [42]. The mission is for the required multi-rotor drone with the defined package to execute a 1:1 thrust-to-weight ratio and discharge the flight battery at 80% and 100% hover for 15 minutes. These conditions are separate and assume a 1:1 thrust-to-weight ratio to hover. Hover with flight battery discharged of 80 %.

Figure 14 shows how the payload changed multi-rotor performance metrics on this trip. In particular, flying time and efficiency have dropped while rotational speed and mechanical power have increased. This flight takes 17–22 minutes, allowing for mission completion and several minutes of hovering. Orthoptera, Odonata, Hymenoptera, and Hemiptera propellers fly longer than DJI Phantom-3 propellers. Payload addition increases hovering rotating speed. All propellers except Neuroptera and Mantodea rotate slower than the DJI Phantom-3. Due to increasing mechanical power, propeller efficiency is lower than in the first mission. The DJI Phantom-3 propeller is less efficient than Odonata and Neuroptera propellers. The Orthoptera propeller matches the efficiency of DJI Phantom-3.

Figure 15 shows that increasing the discharge percentage of the flight battery to 100% extends the flight duration from 22 to 26 minutes, as anticipated. This signifies a notable improvement in flight endurance when compared to the situation where the battery is depleted by only 80%. All propellers have successfully achieved their mission objectives, resulting in an increased flight duration. The Hemiptera model stands out among the propellers for having the longest flight time, lasting an amazing 26 minutes.

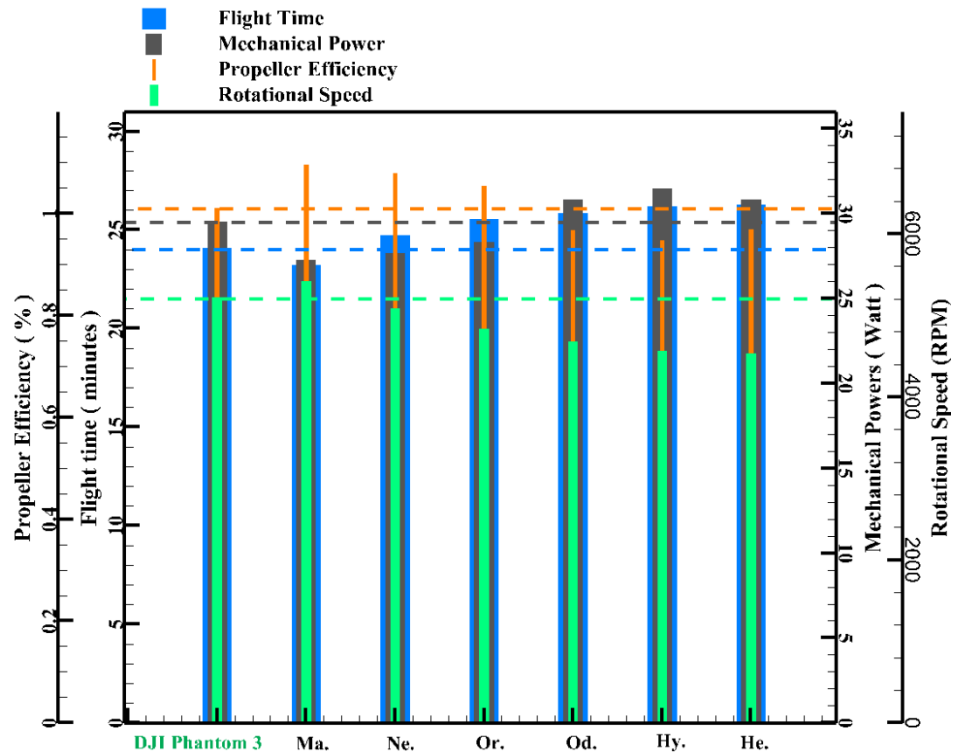


Figure 14. Comparison of flight time-second mission-first case-80% discharged

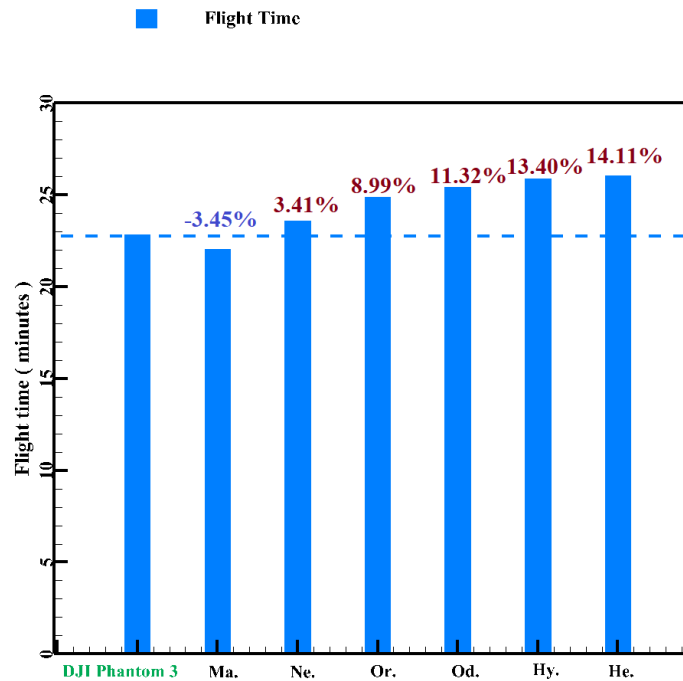


Figure 15. Comparison of flight time-second mission-third case-100% discharged.

Case 2: Heavy weight first aid kit payload

In the second case of the second mission, a new practical challenge has arisen involving insect-inspired propellers. The payload weight has increased to 0.772kg, consisting of a first aid medical kit with 230 items and a releasing device. This increase has affected the investigation of performance parameters of the multirotor equipped with the base and insect-inspired propellers. The increased payload has led to a higher rotating speed compared to the preceding scenario, as shown in Figure 16, Orthoptera, Odonata, Hymenoptera, and Hemiptera propellers rotate at a slower speed compared to the DJI Phantom-3 propeller. Moreover, the necessary mechanical power has increased compared to the previous scenario. This issue is responsible for the decrease in propeller efficiency. The Hemiptera propeller is the least efficient propeller when compared to the DJI Phantom-3 propeller. The Hymenoptera propeller is equally efficient as the DJI Phantom-3 propeller, but the Neuroptera propeller is the most efficient. The flight time range recorded in Figure 16 spans from 11.5 to 13.5 minutes. Therefore, it is clear that both the DJI Phantom-3 propeller and the insect-inspired propellers are unable to maintain a hover for 15 minutes. The Hemiptera propeller extends the flight time to 13.5 minutes, resulting in a beneficial outcome.

When the flight battery is entirely depleted, the flying time typically ranges from 14 to 16 minutes for hovering, as shown in figure 17. Nevertheless, no propeller can accomplish this objective. An exceptional case is the Hemiptera propeller, recognized for its prolonged flying endurance. The drone can fly for just over 16 minutes due to the modified propeller, which is ideal for this mission specification with an additional payload of +0.772 kg.

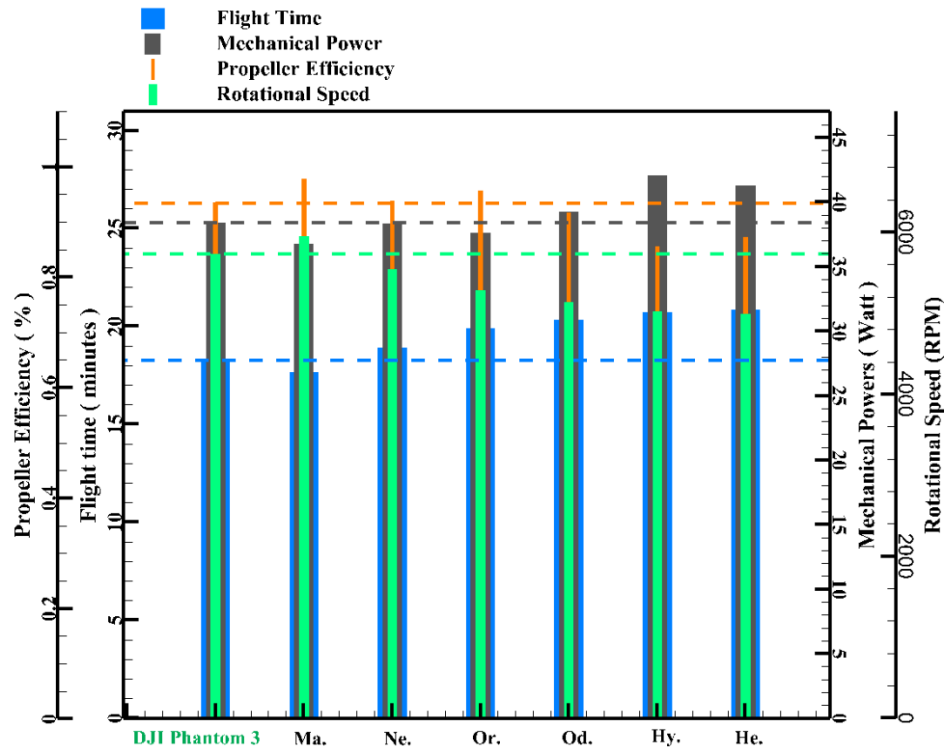


Figure 16. Comparison of flight time-second mission-second case-100% discharged

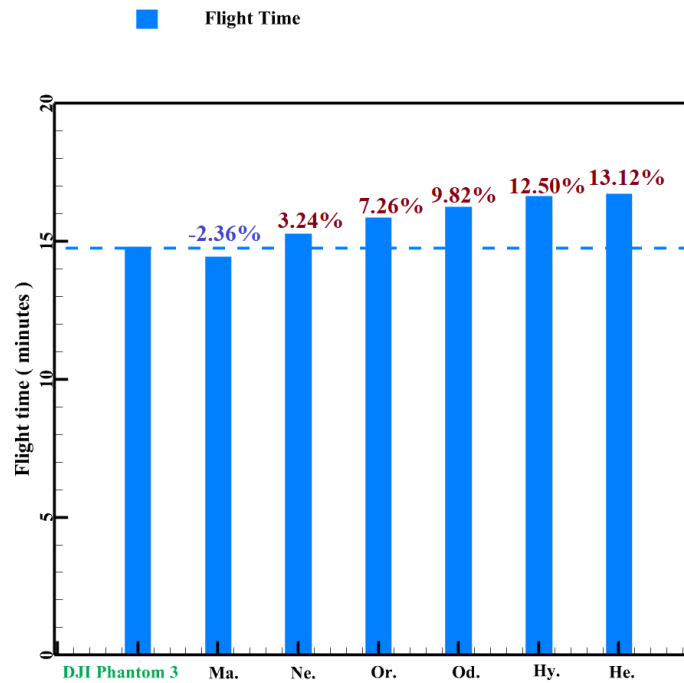


Figure 17. Comparison of flight time-second mission-third case- 100% discharged.

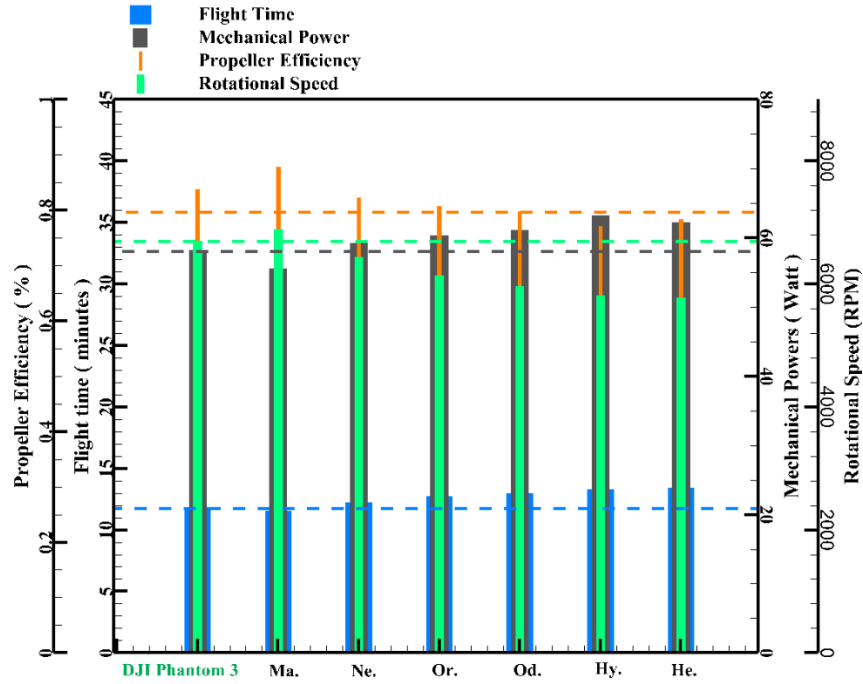


Figure 18. Comparison of flight time-second mission-third case-80% discharged

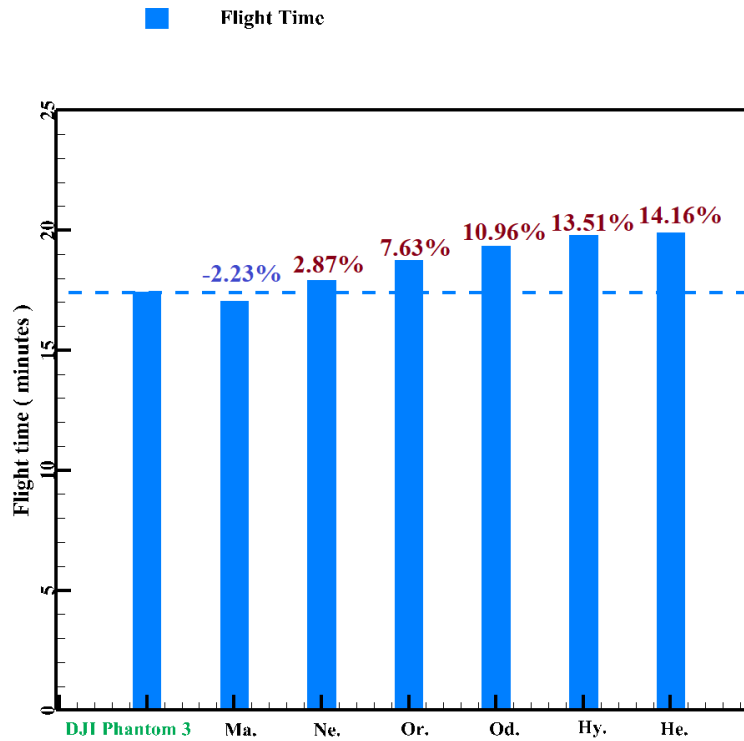


Figure 19. Comparison of flight time-second mission-third case- 100% discharged

Case 3: Medium weight first aid kit payload

The payload weight has been decreased to 0.553 kg, consisting of a first aid bag with 160 items and a lighter release device weighing 0.055 kg [44].

As depicted in Figure 18, the rotational speed during hovering is slightly lower than in the second mission scenario but still higher than in the first example. Additionally, the efficiency of propellers for Hymenoptera, Mantodea, and Orthoptera are very similar to each other, however the Odonata propeller is comparable in efficiency to the DJI Phantom-3 propeller. The flight duration ranges from 13.5 to 16 minutes when the flight battery is at 80% capacity. The Odonata, Hymenoptera, and Hemiptera propellers provide a 15-minute flight duration, which differs from the DJI Phantom-3 propeller. Extending the aircraft battery's discharge to 100% increases the flying time range to around 17 to 19 minutes. Furthermore, all propellers completed the mission successfully, with the Hemiptera propeller achieving the greatest flying time of 19.89 minutes, Figure 19.

Table.6 displays the performance results of the multi-rotor using the insect-inspired propeller compared to the DJI Phantom-3 propeller in the two specified missions. The Hemiptera propeller excels over the DJI Phantom-3 propeller in all missions by prioritizing the "flight time" metric. In the second mission's second case, with a payload weight of roughly 0.772 kg, the Hemiptera propeller has a flying time of around 15 minutes and a flight duration of about 13.39 minutes. In the second mission, the third case shows a notable difference, with the Hemiptera propeller having a 14.16% edge over the DJI Phantom-3 propeller.

If the "required mechanical power" criteria are prioritized, the Mantodea propeller outperforms its narrow equivalents in all missions. The Mantodea propeller requires less mechanical power than the DJI Phantom-3 propeller in the first mission and the first case of the second mission, with a

percentage difference of 7.76% in both circumstances. The Mantodea propeller demonstrates more efficiency than the DJI Phantom-3 propeller when considering "propeller efficiency" in conjunction with the necessary mechanical power parameter. This is accomplished by demanding the minimal mechanical power needed to turn the propellers. During the initial voyage without any payload, the efficiency parameter differential between the Mantodea and DJI Phantom-3 propellers is significantly more significant.

Table. 6. Conclusion remarks for the performance results of the multirotor equipped with the present insect-inspired propeller with DJI Phantom-3 propeller during various practical missions.

Mission Definitions			Best Improvements Compared to DJI Phantom-3 Propeller (%)			
Mission	Endurance (minutes)	Payload	Flight Time	Mechanical Power	Propeller Efficiency	Hovering Rotational Speed
First Mission	25	-	Hemiptera (+ 9.18 %)	Mantodea (- 7.76 %)	Mantodea (+ 9.40 %)	Hemiptera (- 13.36 %)
Second Mission	15	First case: + 0.250 kg	Hemiptera (+ 14.11 %)	Mantodea (- 7.76 %)	Mantodea (+ 4.60 %)	Hemiptera (- 13.03 %)
		Second case: + 0.772 kg	Hemiptera (+ 13.12 %)	Mantodea (- 4.57 %)	Mantodea (+ 4.90 %)	Hemiptera (- 13.79 %)
		Third case: + 0.553 kg	Hemiptera (+ 14.16%)	Mantodea (- 6.45 %)	Mantodea (+ 6.94 %)	Hemiptera (- 13.68 %)

Finally, while prioritizing "rotational speed" over other factors, the Hemiptera propeller shows exceptional performance. During all missions, it turns at a slower pace than the DJI Phantom-3 propeller. In the second and third cases of the second mission, the percentage difference with the DJI Phantom-3 propeller is significantly greater. The Mantodea propeller demonstrates superior performance in propeller efficiency and required mechanical power, although the Hemipteran propeller shines in rotational speed and flight time. For best outcomes, a propeller should achieve a balance among these factors. The ideal propeller should prioritize a balance between all parameters by combining their average scores.

The Orthoptera propeller consistently achieves balance across all mission situations. The propeller has higher efficiency, longer flight time, and lower rotational speed than the DJI Phantom-3 propeller. The Orthoptera propeller is a solid candidate for the best choice. Alternatively, the Odonata propeller could be an acceptable choice after the Orthoptera propeller. While its propeller efficiency may be marginally inferior to that of the DJI Phantom-3 propeller, it excels in other performance aspects.

It needs to mention that the proposed method represents a novel approach in this field, and the authors believe that practical implementation will require extensive and comprehensive studies. It is essential to assess the method's applicability with regard to structural, aero-acoustic, and aerodynamic considerations. As the first step, in this research, the authors have taken an initial step by investigating the method from an aerodynamic perspective, with a primary focus on aerodynamic potential. The authors hope these findings contribute valuable insights into the field and encourage further exploration of this promising method. However, in order to achieve this idea proposed in this paper into a practical product, more detailed and comprehensive investigations are needed, and this investigation will be very useful and fruitful if it is carried out in a multi-

objective and multi-physics manner, taking into account aerodynamic, structural and aero-acoustic considerations.

7. Conclusion

In this research, insect-inspired propellers are tested for their aerodynamic performance in four major areas: flying time, rotational speed, mechanical power, and propeller efficiency. To increase DJI Phantom-3 propeller performance, it is inspired by Hemiptera, Orthoptera, Neuroptera, Mantodea, Odonata, and Hymenoptera wing forms. This study employed numerical simulation and MRF to calculate propeller thrust and torque under stable conditions at rotational speeds from 4000 to 8000 rpm. Based on numerical simulation findings, performance parameters were derived. Additionally, a series of missions with different conditions were created to test these propellers.

Here is a summary of the results obtained from this research:

- Increasing thrust-to-weight ratio from 1:1 to 3:1 increased rotational speed.
- Increasing thrust to weight ratio led to higher mechanical power and rotational speed for propellers. However, this ratio reduced propeller efficiency.
- Increased rotational speed increased electrical current consumption in the 1:1 thrust-to-weight ratio. The electrical current rose with each rotational speed increment.
- Increasing rotating speed and electrical current reduced flying time overall.
- Flight time increases for all missions when the battery charge reaches 100%.

- Flight time is at least 15 minutes with a zero-to-0.250-kg payload and an 80% flight battery. This period can reach 20 minutes, making payload hovering possible.
- As payload weight grows from 0.250 to 0.550 kg and flight battery is 80%, flying time reduces. Maximum duration is 15 minutes at 550 grams.
- Flight time is drastically shortened with a payload weight of 0.550-0.770 kg and an 80% flight battery compared to earlier examples. Duration is 11–13 minutes at 0.770 grams, depending on propellers. Flight periods are longer for insect-inspired propellers.
- The Mantodea propeller outperforms the DJI Phantom-3 propeller in mechanical power and efficiency, while the Hemiptera propeller outperforms in rotational speed and flight duration. The Orthoptera propeller consistently outperforms in all missions, making it a viable alternative. Odonata propellers are another decent option, but they are less efficient than DJI Phantom-3 propellers.

The insect-inspired propellers outperform the DJI Phantom-3 propeller. By further examining and adjusting the geometry of these propellers, it is feasible to create an enhanced propeller design that outperforms conventional propellers. This research has the potential to replace the primary propeller of the vehicle. Additional research can be carried out on these propellers to explore their suitability for application in various traditional and commercial unmanned vehicles of varying weights but identical size.

8. Competing interests

I declare that I have no significant competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

9. Data Availability

The data that support the findings of this study are available on reasonable request from the corresponding author.

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