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Design and Development of Unmanned Aerial Vehicles' Propellers based on Biomimetic Design

Saundarya Saran[1], Rosalam Che Me[1]*, Mohamed Thariq Hameed Sultan [2,3,4]*, and Navaneetha Krishna Chandran[2]

[1]*Department of Industrial Design, Faculty of Design and Architecture, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[2]*Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3]*Aerospace Malaysia Innovation Centre (944751-A), Prime Minister's Department, MIGHT Partnership Hub, Jalan Impact, 63000 Cyberjaya, Selangor, Malaysia*
[4]*Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*

ABSTRACT

This study aims to enhance UAV propeller performance by addressing aerodynamic inefficiencies caused by shock waves at high rotational speeds, which are also known as vortex formation. These shock waves, occurring at the propeller tips, increase drag, vibration, noise, and potentially can reduce flight time. The research focuses on optimising propeller design to minimise these effects and improve overall efficiency. The methodology involved a comprehensive review of existing propeller designs and the application of aerodynamic principles to develop a propeller approximately 9 inches in length. The background study also focuses on the application of biomimicry in the design of propellers. Simulation tests were conducted to evaluate its performance, with measurements taken at various rotational speeds, including a maximum rotational speed of 6000 rpm. The results demonstrated that the newly designed propeller achieved better efficiency compared to existing models, producing a thrust of 0.0016 N at maximum speed. The design also exhibited reduced noise and vibration, contributing to a more stable and efficient flight performance. The findings underscore the potential for improved UAV propeller designs to increase the efficiency of performance and enhance operational capabilities, particularly in applications like agriculture, inspection, and surveillance. Future research may explore additional modifications to further optimise aerodynamic performance and noise reduction.

Keywords: Computational fluid dynamics, efficiency, propeller, Shock Waves, unmanned aerial vehicles, vortex

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E-mail addresses:
saundaryasaran28@gmail.com (Saundarya Saran)
rosalam@upm.edu.my (Rosalam Che Me)
thariq@upm.edu.my (Mohamed Thariq Hameed Sultan)
navaneetha@upm.edu.my (Navaneetha Krishna Chandran)
* Corresponding author

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INTRODUCTION

Unmanned aerial vehicles (UAVs) have made it possible to revolutionise different areas by offering flexible, cost-effective and efficient remedies to various tasks. UAVs have become invaluable instruments that enhance the area of operation and have advantages over the conventional methods, including precision agriculture as well as environmental management, surveillance, logistics and disaster management. Some advancements made on various parts have also led to the rapid adoption of the UAV technology (Du et al.,2024), and one of the fundamental parts is the propeller that directly influences the overall performance, stability and efficiency of the aircraft (Vijayanandh et al., 2022). The efficiency of UAV propellers is of the essence, considering that they generate the force that is required to lift off and remain airborne. However, the propeller performance at fast rotational speeds remains inefficient, which is a continuing problem with the design of UAVs (Xu et al., 2024). This inefficiency is mainly caused by the shock waves that are produced at the ends of the propeller blades (Perikleous et al., 2024). The aerodynamic inefficiencies generated by the shock waves deteriorate the overall performance of the UAV because they augment the levels of drag, vibration, and noise (Lin et al., 2023). These issues are particularly problematic for applications that are required to be very quick, precise, or discrete (Ciliberti et al., 2023). Although the technology of UAVs has undergone massive research and development, there are still aspects of propeller tip vortex designs that need to be improved and optimised to achieve induced drag reduction and noise reduction (Park et al., 2018). The available studies often neglect the complex interactions at the ends of the propellers, and experimental validation should be more thoroughly incorporated to enhance the design and test these designs (Zhang et al., 2024). Consequently, several UAVs can and do work below their capacity, and this limits their utility and effectiveness in performing various tasks (Zhang et al., 2024). Assessment of such properties using propeller bench tests, comparing the performance datum of trading-off designs to the conventional propellers to determine the gains made in thrust and efficiency (Fish & Beneski, 2014; Panagiotopoulos et al., 2024).

Bio-mimicry practice presents human beings with a chance to learn and imitate methods of nature to come up with viable solutions to human technology. The image reveals the nature of the design of drone propellers, which is adopted to resemble the structures of eagle wings, hence the principles of biomimicry. The performance and agility of the eagles in the air, plus the quietness of the manoeuvre, have been made possible by their wing structure and the arrangement of their feathers. Natural attributes incorporated in the UAV propellers result in significant gains in aerodynamic performance. The fusion of adaptation blades in eagle propellers offers efficiency in airflow, such as eagle feathers, that reduces drag to produce less energy consumption and flight duration (Abdulrahim & Lind, 2006).

The bio-mimetic design is effective in controlling the airflow along the propeller tips by its enhanced aerodynamics, which decreases drag and avoids the formation of turbulence and vortices (Liu & Aono, 2009).

Propeller tip shock waves are created as blades pass through supersonic velocity, which significantly decreases aerodynamic efficiency and creates performance issues in UAVs. Besides creating excessive noise, the shock waves cause massive drag forces and high vibration in addition to creating elevated stability problems whilst amplifying structural tension and minimal performance (Carlson & Hassan, 2002; Platzer & Sargent, 2012). The propellers that are biomimetic eagles have a specialised shape of the blade that slows down the formation of shock waves or minimises their occurrence, allowing the propellers to operate steadily and silently. The eagle feathers depict favourable aerodynamics that correct airflow issues to reduce the shock waves as well as promote propeller efficiency and extend the operation span (Choi & Hassan, 2002).

The biomimicry used in UAV propeller development develops a transformative process that combines millions of years of evolution optimisation with the current technology. Eagle wings have aerodynamic characteristics such as feather serrations and flexible designs that reduce turbulent air velocity and allow a sharp acoustic signature of reducing and improving aerodynamic efficiency (Carruthers & Thomas, 2007; Mueller & DeLaurier, 2003). This is because the introduction of biomimicry in the development of the UAV propeller provides enhanced operational performance when operating at very high speeds and reduces the detectability and operational signatures since it enhances speed whilst maintaining low detectability. The criticism of the biomimetic designs is that it is difficult since scientists have problems in closely recreating the complex environmental scenarios and aerodynamic designs or measurements accurately under controlled laboratory conditions (Stanford et al., 2008; Webb & Aono, 2008). The further development of computational fluid dynamics (CFD) and the enhancement of the testing methods should be further developed to overcome current challenges to advance the development of the bio-mimetic unmanned aerial vehicles technology (Zheng et al., 2013).

METHODOLOGY

Research Flow

The methodology of the research is structured and multi-phase to develop and verify optimised UAV propeller designs to increase aerodynamic efficiency and performance. The literature review and analysis of the current UAV propeller designs are the initial step in the process. Through this study, the comprehension regarding bio-mimicry design and how it is applied in industrial products and aerospace products has been gained. It has analysed previous research and determined the gap in it. The review of academic papers, technical reports, and other books related to the topic is done to reveal the lack of knowledge in the field and which parameters are critical to be known: the pitch of the blade, the blade length, the blade curvature, and the shape of the tip. Descriptive and comparative analyses are conducted to evaluate key metrics such as thrust, torque, acoustic, lift, watt and efficiency. Figure 1 shows the flow chart of the methodology of this study.

Design constraints and standards were established to ensure consistency and comparability across all propeller configurations. The propeller diameter was fixed at 9 inches with a pitch of 4 inches (9x4E), which is commonly used in small UAV applications. The material selection for simulation was assumed to be a standard lightweight polymer suitable for 3D printing. Rotational speeds were limited to 2000, 4000, and 6000 RPM to represent typical UAV operating conditions. Additionally, aerodynamic performance evaluation was conducted under steady-state conditions with uniform airflow, and structural deformation effects were neglected to simplify the analysis.

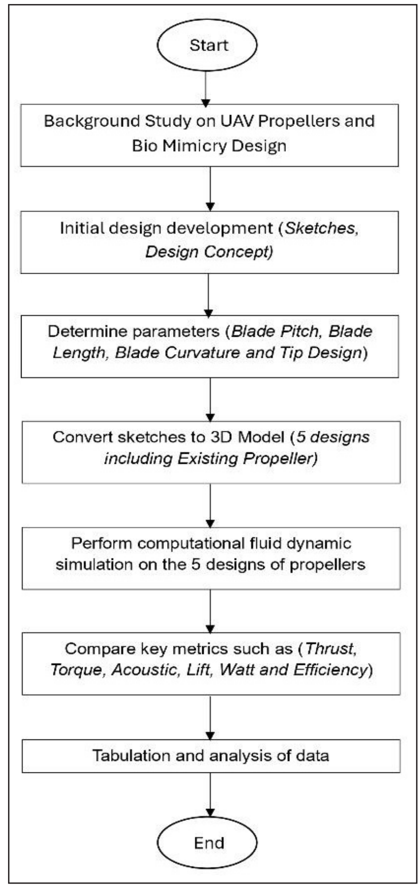


Figure 1. Flowchart of numerical research

In the research, a background study was initiated, in which the working principle of a propeller was learned. The knowledge of the principle of working of the propeller to know the intention of each part of the propeller, which possesses various curves and shapes. The propellers have been sketched in several designs, keeping the basic shape of a propeller and the illustration of the biomimicry of an eagle wing feather. The parameters of propellers were adhered to in the circumstance of controlled designing of 9x4E propellers. The propeller diameter remained 9 inches, and the pitch of the propeller remained at 40. After the drawings of the propellers were sketched, they were converted into SolidWorks computer-aided drawing (CAD) software 3D models.

After completion of the 3D CAD models, the next stage is the computational modelling, validation of the simulation and development of a prototype. Analysis of the dynamics of airflow and optimisation of propeller design was done by means of SolidWorks computational fluid dynamics (CFD) simulations. Several assumptions were made during the CFD analysis.

The airflow was considered incompressible and steady-state, and the effects of turbulence were modelled using standard turbulence models available in SolidWorks CFD. The propeller rotation was simulated under constant angular velocity without transient effects. Environmental conditions such as temperature and air density were assumed constant at standard atmospheric conditions. Structural deformation and material flexibility were not considered, and the propeller was treated as a rigid body. The optimal designs are fabricated into tangible prototypes with the help of 3D printing and evaluated in controlled tests in technical laboratories to evaluate their functionality. To accommodate accuracy and reliability, statistical, comparative, and parametric analyses are used at all points. This combined methodology will bring together the virtual testing and the physical testing by working towards providing innovative UAV propeller designs, which will be as efficient and operative as possible.

Design Concept Development

Propeller designs with high performance and efficient design of propellers have continuously been influenced by nature, especially the anatomy of birds, which is admired for its aerodynamic excellence. In Figure 2, the eagle feather has been designed as the propeller in the tip of the propeller. The propeller has a better shape at the tip that provides better thrust. Moreover, the upper shape of the propeller is inspired by the shape of the eagle when it flies. The biomimetic design was translated into engineering geometry through specific transformations. Feather serrations were mimicked by introducing segmented edges along the propeller tips to reduce vortex intensity. The curvature of eagle wings was translated into varying blade curvature profiles to improve airflow attachment. Additionally, flexibility concepts were incorporated by designing looped and curved structures that simulate adaptive deformation under aerodynamic loading. These transformations were implemented using parametric modelling in SolidWorks.

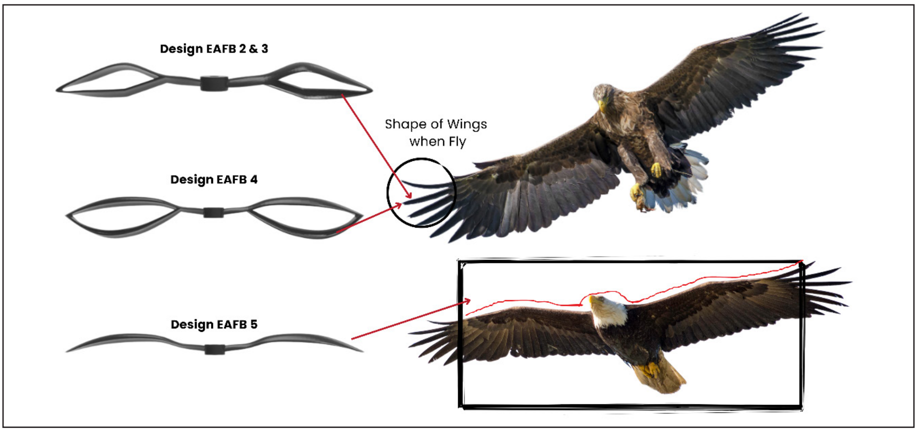


Figure 2. Design inspired by the eagle feather

The design is identified as Eagle Feather Biomimicry (EAFB), which is an approach that moves beyond traditional, functional forms and explores loop-shaped and segmented structures that emulate the aerodynamic behaviour of bird wings. The progression of designs reflects a deliberate shift towards improving lift, reducing drag, and enhancing overall flow efficiency by mimicking the natural adaptability and smooth airflow seen in eagle feathers. This fusion of biological inspiration and aerodynamic engineering showcases an innovative direction in propeller development, one that emphasises not only technical performance but also harmony with natural flight mechanics. Figure 3 illustrates the design concept development of four design propellers inspired by aerodynamic principles and bird anatomy, particularly the wings and feathers of eagles.

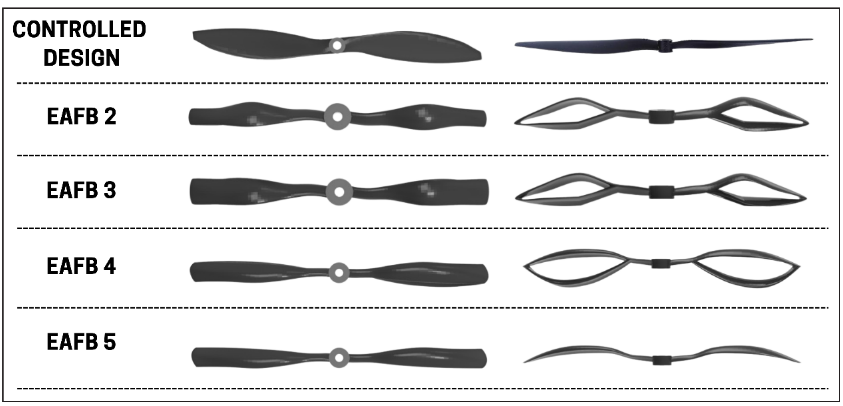


Figure 3. Design development of 9inch propeller

The design is in the form of a changing propeller design beginning with the traditional, functional forms through the bio-mimetic eagle feather forms. The loop designs are aimed at emphasising the shift of traditional blades to designs based on nature to replicate the effectiveness of movement and lift by bird wings. The adopted segmented designs and refined loops imply the struggle to recreate the dynamic adaptability of feathers, which, during movement, vary to provide the best performance. This progressive growth is an indicator of a concern with drag reduction, lift acceleration, and efficiency. Equally, the sharp curves and angles of the designs are influenced by the streamlined shape of the wing to provide an improved circulation of the air. This engineering-meets-nature approach focuses on efficiency, flexibility and environmental compatibility when developing a propeller.

The design of drone propellers also uses biomimicry and willingly takes ideas on how to become better at flying, using the example of birds of prey, such as eagles. The four propeller designs based on eagle-inspired designs illustrated in Figure 4 demonstrate that the various designs have distinct biomimetic characteristics that have been inspired by eagle feathers to increase the performance of the drone.

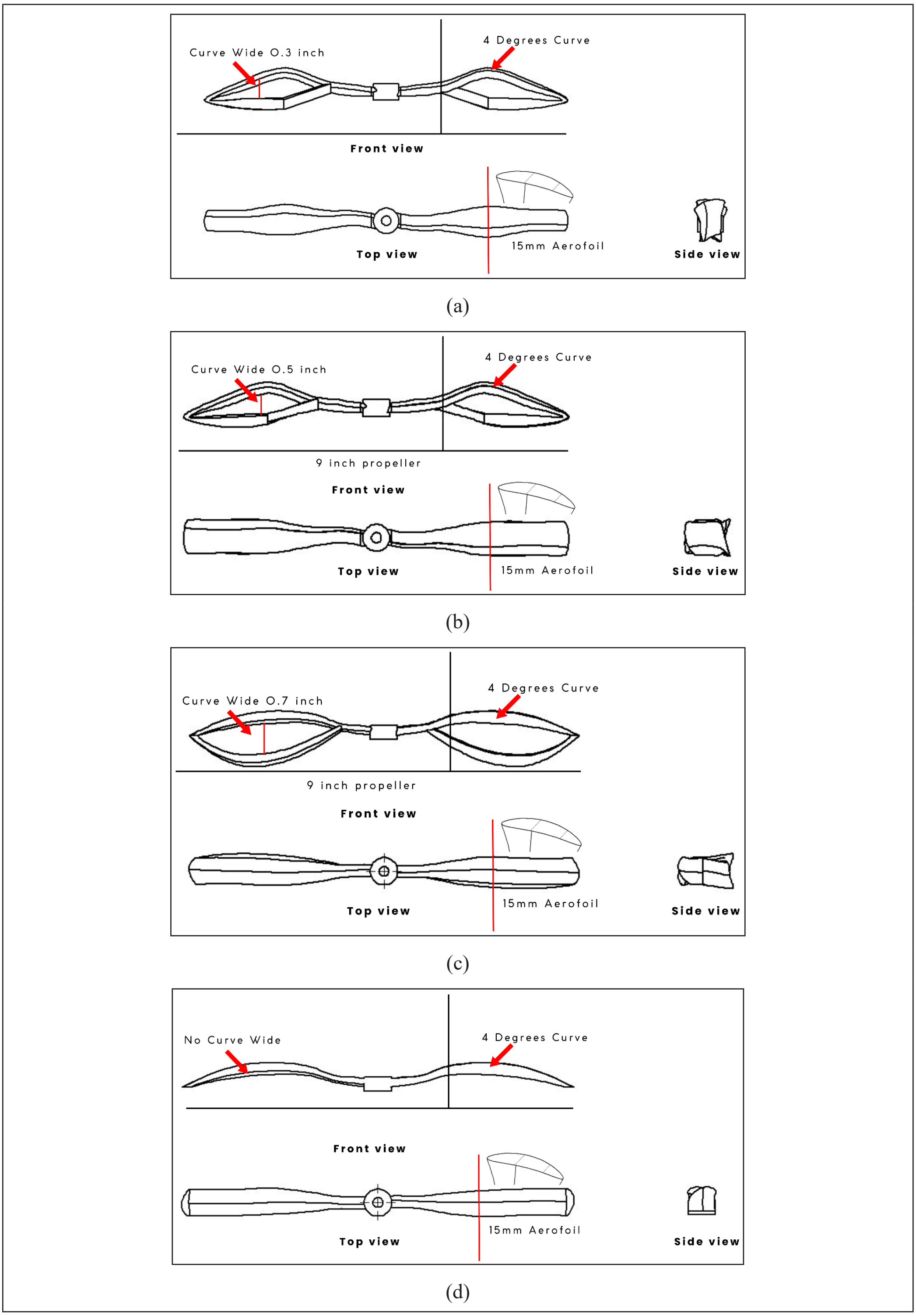


Figure 4. Four eagle-inspired propeller designs: (a) Curve wide 0.3-inch; (b) Curve wide 0.5-inch; (c) Curve wide 0.7-inch; (d) No curve

These designs are designed to improve the functionality of the drones by raising their aerodynamic efficiency, lowering noise levels, and raising the flight flexibility. The use of loop-shaped curves and streamlined shapes in every propeller model reflects a deliberate transition of traditional blade geometry to a geometry based on nature and its inherent adaptation to different conditions in flight operations, including maximising airflow, reducing drag, and changing the geometry under different conditions of flight. Such a design not only improves the modern drone technology's energy efficiency and flight stability, but it also makes it more adaptable and adjusted to the sensitive or mission-critical applications like wildlife observation, aerial photography, and surveillance. Through this nature-based innovation, these propeller designs offer a new level of performance, reliability, and environmental compatibility.

The primary distinction between the controlled design and the EAFB propellers lies in the overall blade morphology, particularly the incorporation of biomimetic features such as modified blade curvature, tip configuration, and surface profile derived from eagle feather structures. By maintaining a constant airfoil profile across all designs, the study ensures that any observed differences in aerodynamic performance, such as thrust generation, lift characteristics, vortex behaviour, and efficiency, can be directly attributed to the biomimetic geometric adaptations rather than confounding variables.

This approach enhances the validity and replicability of the comparative analysis, as it establishes a controlled experimental framework where the influence of a single design variable, the biomimetic modification, is systematically evaluated. Consequently, the controlled design functions as a reliable benchmark, enabling a clear and meaningful assessment of the performance improvements introduced by the EAFB propeller configurations.

The loop shapes of EAFB-2, EAFB-3 and EAFB-4 are of growing widths (0.3, 0.5, and 0.7 inches, respectively) which emulate the natural curve and shape of eagle feathers. The curves facilitate steering the air around the blades in a smooth manner, generating a lot less turbulence as well as noise in flight. EAFB-3 is one of them, and it is particularly due to its hollow-frame design, which also reduces vibrations and the level of noise. It ensures that the EAFB-3 model is particularly useful in those operations that require almost undisturbed operation, like wildlife research, nature photography or surveillance, where noise and vibration-free operation is paramount.

EAFB-4 (best curve is 0.7 inches) design is flexible, and the concept promotes flexibility like the eagle feathers. The propeller blades have the flexibility that enables them to automatically and effectively adapt to various aerodynamic pressures when flying. Consequently, the use of EAFB-4 propeller enables drones to be predictable even during long-range flights and respond to alterations in the concept or impromptu environment, which offers improved durability and reliability. The EAFB-5 model is different and has a lean design without loops.

Rather, it focuses on low drag by ensuring a smooth, sleek profile based on the aerodynamic features of eagle feathers. This reduced wind drag makes the shape streamline and thus consumes less energy, hence increasing flight duration. It is especially beneficial to specialised missions in which propulsion efficiency and the length of time high are critical. All in all, biomimetic forms inspired by the eagles are a tremendous advancement over conventional propeller designs, which can take advantage of the known principles of aerodynamics in nature, which lead to more efficient, quieter, and reliable drone technology.

RESULTS AND DISCUSSION

The propeller performance study is an important feature of creating an effective and efficient propulsion engine for unmanned aerial vehicles (UAVs). This paper assesses five propeller designs: Controlled Design, the standard propeller and four new ones (EAFB 2, 3, 4 and 5) obtained through computational fluid dynamics (CFD) calculations. It is evaluated based on thrust, torque, acoustic noise, lift, power consumption and efficiency at three rotational speeds (2000 RPM, 4000 RPM and 6000 RPM). The aim is to determine the positive and negative aspects of each design and give recommendations on how the UAV can be optimised to improve its performance.

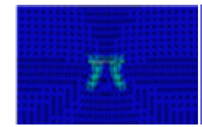
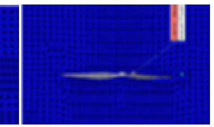
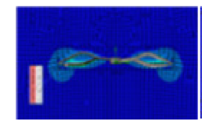
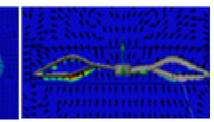
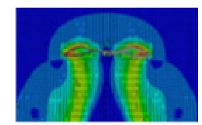
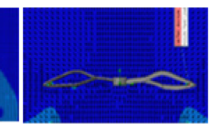
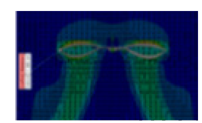
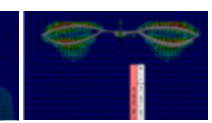
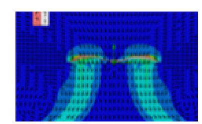
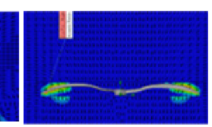
Propellers Performance at 2000 RPM

At 2000 RPM, the Controlled Design (Standard Propeller) has a thrust of 0.114 N with a torque of 0.004 N -m and consumes 0.0003 W of power. Its performance, measured to be 0.0052 N.m/W, is the best amongst all the designs at this RPM. Its lifting force of 6.15 N is, however, much less than the other design alternatives. Table 1 shows the CFD analysis of the propellers at 200 rpm.

EAFB 2 demonstrates a strong advantage in lift production, generating 48.53 N of lift while maintaining low power consumption of 0.0000775 W. This design sacrifices some efficiency, with a value of 0.00478 N·m/W. EAFB 3 achieves the highest thrust of 0.434 N, which is nearly four times greater than the standard propeller, but this improvement comes at the cost of higher power consumption of 0.000242 W. EAFB 4 delivers a balance of moderate thrust of 0.382 N and lift of 33.26 N, while consuming the most power of 0.000542 W at this speed. EAFB 5 exhibits a well-rounded performance, generating a moderate thrust of 0.229 N, lift of 35.47 N, and efficiency of 0.004826 N·m/W.

In the aspect of torque, the existing design of the propeller has the lowest torque compared to the other designs, which is 0.004 N · m. Although the other designs have higher torque compared to the existing design, the difference in torque between design 2 and the existing propeller is slight. The factor can be compensated for by using a higher torque brushless motor. At 2000 RPM, EAFB 3 and 4 are ideal for applications requiring higher thrust, while EAFB 2 is more suitable for lift-focused applications. The standard propeller maintains its edge in efficiency but is less effective in thrust and lift generation compared to the alternative designs.

Table 1
CFD results for 2000 rpm of each propeller design

2000 RPM	Thrust	Torque	Acoustic	Lift	Watt	Efficiency (Torque/Watt)	Percentage Difference %	Lift and Drag	Noise
Controlled Design 	0.114	0.004	**6.15**	0.0003	0.765	**0.00522875**	N/A	 (i)	 (ii)
EAFB 2 	0.015	0.009	48.53	0.0000775	1.88	0.00478	8.58	 (i)	 (ii)
EAFB 3 	**0.434**	0.013	42.7	0.000242	2.657	0.00489	6.48	 (i)	 (ii)
EAFB 4 	0.382	0.017	33.26	**0.000542**	3.638	0.004672	10.65	 (i)	 (ii)
EAFB 5 	0.229	0.009	35.47	0.0002308	1.865	0.004826	7.70	 (i)	 (ii)

Note. Highlighted the best performance of the designs

Performance of the Propellers at 4000 RPM

As the rotational speed increases to 4000 RPM, the performance differences between the designs become more pronounced. The standard propeller produces 0.469 N of thrust and 3.67 N of lift, consuming 0.001 W of power. Although it retains low acoustic noise levels of 0.014, its efficiency decreases to 0.00232 N·m/W. Table 2 shows the CFD analysis for the propellers at 4000 rpm.

EAFB 2 continues to excel in lift generation, producing 69.06 N while maintaining the lowest power consumption of 0.0008 W. However, its thrust remains minimal of 0.003 N, and efficiency remains relatively low of 0.00236 N·m/W. EAFB 3 delivers the highest thrust of 1.751 N at the cost of the highest power consumption of 0.002 W and significant acoustic noise of 0.049. EAFB 4 matches EAFB 3 in lift production of ~57 N but achieves slightly lower thrust of 1.56 N and consumes equal power. EAFB 5 strikes a balance between thrust of 0.843 N, lift of 57.26 N, and power consumption of 0.006 W, with improved acoustic performance compared to Designs 3 and 4.

EAFB 2, 3, 4 and 5 exhibit higher torque compared to the existing design propeller. This is because the cross-sectional area at the tip of the propeller is higher compared to the existing design. If the tip of the propeller is designed to be thin, it will reduce the load at the tip of the propeller, which eventually will reduce the propeller torque. Still, the higher torque can be compensated for by using a higher torque brushless motor. Although propeller design 3 exhibits higher torque, it produces the highest thrust.

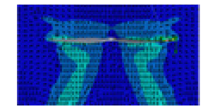
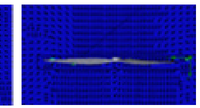
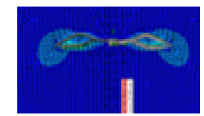
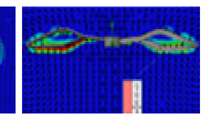
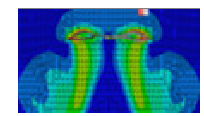
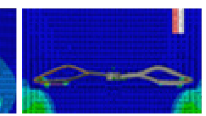
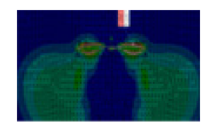
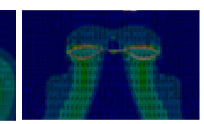
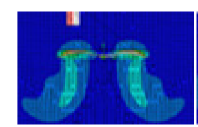
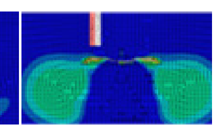
At 4000 rpm, EAFB 3 and 4 demonstrate superior thrust and lift capabilities, making them suitable for high-performance UAV applications. However, EAFB 2 remains an efficient choice for scenarios prioritising lift with minimal power requirements.

Performance of the Propellers at 6000 RPM

At 6000 rpm, the standard propeller generates 0.984 N of thrust and 32.77 N of lift, consuming 0.003 W of power. While its efficiency decreases further of 0.00158 N·m/W, it retains the lowest acoustic noise levels of 0.03. Table 3 shows the CFD analysis of propellers at 6000 rpm.

EAFB 2 continues to dominate in lift production, reaching 83.86 N, while maintaining moderate power consumption of 0.006 W. Its efficiency, however, is 0.00158 N-m/W, which is equal to normal propeller. EAFB 3 produces the second-highest thrust of 3.21 N and significant lift of 66.34 N but consumes 0.006 W of power, with notable acoustic noise of 0.098. EAFB 4 outperforms all designs in thrust of 3.447 N and lift of 69.6 N, achieving the best efficiency at this speed of 0.0016 N·m/W. EAFB 5 provides a compelling trade-off, generating a moderate thrust of 1.932 N and the highest lift of 71.56 N while consuming the least power of 0.000693 W.

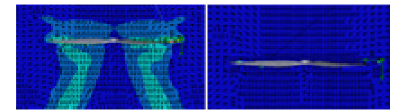
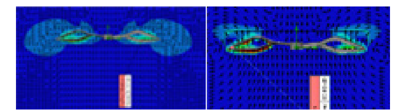
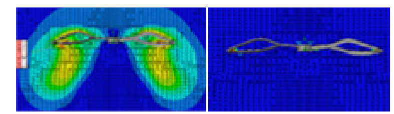
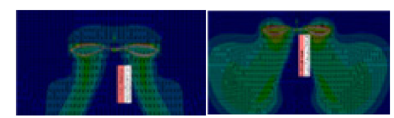
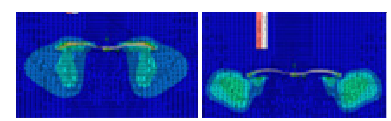
Table 2
CFD analysis for 4000 rpm of each propeller design

4000 RPM	Thrust	Torque	Acoustic	Lift	Watt	Efficiency (Torque/Watt)	Percentage Efficiency %	Lift and Drag	Noise
Controlled Design 	0.469	0.014	**3.67**	0.001	6.03	0.00232	N/A	 (i)	 (ii)
EAFB 2 	0.003	0.032	69.06	0.0008	13.52	0.00236	1.72	 (i)	 (ii)
EAFB 3 	**1.751**	0.049	57.22	0.002	20.728	0.00236	1.72	 (i)	 (ii)
EAFB 4 	1.56	0.069	57.46	0.002	28.852	0.00267	15.09	 (i)	 (ii)
EAFB 5 	0.843	0.035	57.26	**0.006**	14.64	**0.00239**	3.02	 (i)	 (ii)

Note. Highlighted the best performance of the design

Table 3

CFD images for 6000 rpm of each propeller design

6000 RPM	Thrust	Torque	Acoustic	Lift	Watt	Efficiency (Torque/Watt)	Percentage Efficiency %	Lift and Drag / Noise
Controlled Design 	0.984	0.03	**32.77**	0.003	18.969	0.00158	N/A	 (i) (ii)
EAFB 2 	0.261	0.085	83.86	**0.006**	53.641	0.00158	0	 (i) (ii)
EAFB 3 	3.21	0.098	66.34	**0.006**	61.644	0.00159	0.63291139	 (i) (ii)
EAFB 4 	**3.447**	0.156	69.6	0.004	97.749	**0.0016**	1.26582278	 (i) (ii)
EAFB 5 	1.932	0.075	71.56	0.000693	47.201	0.00159	0.63291139	 (i) (ii)

Note. Highlighted the best performance of the design

In high rotational speeds, EAFB 4 is the most effective and the most powerful propeller, hence it is best suited for a UAV that needs as much thrust as possible. The energy-consuming nature of EAFB 5 places it well-suited for handling energy-constrained applications because of the high level of power efficiency and lift performance. Each UAVs possesses its optimal RPM during the propeller in the process of hovering, as the majority of UAVs flight time is devoted to the hover. Therefore, a 6000-rpm propeller 5 is the most efficient design of the propeller.

Nevertheless, the acoustic of EAFB 2,3,4 and 5 is increased compared to the acoustic of the present design propeller due to the inefficiency of the present design in relation to aerodynamic ensure the design of the propellers is not aerodynamic compared to the currently existing design. The vibration on the tip of the propellers is caused by the non-aerodynamic flow over the propellers. The result of this is the acoustical noise produced by the propellers.

With the findings realised after the simulation result, it can be concluded that the efficiency of each propeller is highest at a certain rotation speed. Placing the mass in another geometry of the propeller, out of the centre, causes an imbalance, and this makes the mass eccentric. With the rotation of the rod, centrifugal force increases with the further distance of the mass. The cycle of bending and transverse vibrations occurs on the rod due to this force. The more distant the mass is from the centre, the lower the critical speed becomes, making the system prone to vibrations at lower speeds.

According to Figure 3, the position of the curve, where the maximum mass is applied, is furthest in EAFB 5, followed by EAFB 4, EAFB 3 and EAFB 2. At the lowest speed that had been tested, 2000 rpm, the controlled design was the most efficient. At 4000 rpm and 6000rpm, the EAFB 4 will have the highest efficiency, as at 2000 rpm and 4000 rpm, the rotating frequency is closest to its natural frequency. Hence, the vibration lessens. We can make a conclusion, therefore, that the natural frequency of the propeller matters to ensure that the propeller vibration during the rotation is minimised, which ultimately maximises the propeller performance.

The manufacturing considerations for the Eagle Feather Biomimicry (EAFB) propellers are centred on achieving a balance between structural rigidity, lightweight characteristics, and material uniformity to ensure reliable aerodynamic performance. In this study, injection moulding is proposed as the primary fabrication method due to its ability to produce high-precision components with consistent quality, smooth surface finish, and scalability for mass production.

The propeller structure is required to be sufficiently rigid to withstand aerodynamic loads and vibrations induced by high rotational speeds, particularly those associated with flutter phenomena. Any excessive flexibility may lead to deformation of the blade geometry, thereby negatively affecting aerodynamic efficiency and stability during operation.

At the same time, the propeller must remain lightweight to minimise energy consumption and enhance overall UAV performance.

Material selection is equally critical, with preference given to materials exhibiting isotropic properties, ensuring uniform mechanical behaviour in all directions. This is important for maintaining predictable structural integrity and avoiding uneven stress distribution during rotation. In contrast, additive manufacturing techniques such as 3D printing are not recommended for this application, as many commonly used printing materials exhibit anisotropic characteristics due to layer-by-layer fabrication. This anisotropy can result in weaker interlayer bonding, reduced fatigue resistance, and increased susceptibility to failure under cyclic loading conditions.

Furthermore, while biomimetic designs may introduce geometric complexity, injection moulding remains advantageous in producing such intricate features with high repeatability once the mould is developed. However, challenges may arise in terms of initial tooling cost, mould design complexity, and ensuring accurate replication of fine biomimetic structures, particularly at the blade tips. Overall, the selection of injection moulding and isotropic materials supports the practical feasibility, durability, and performance consistency of the EAFB propellers, while addressing the limitations associated with alternative fabrication methods.

CONCLUSION

The key findings of this study are summarised as follows: The conventional propeller (controlled design) demonstrated stable performance with low acoustic noise and high efficiency at low RPM; however, it exhibited lower thrust and lift compared to the biomimetic designs. EAFB 4 achieved the highest thrust across all tested RPM levels, making it the most suitable design for high-performance UAV applications such as high-speed flight and heavy payload operations. EAFB 2 produced the highest lift with minimal power consumption, particularly at lower RPM, indicating strong suitability for hovering, stability, and endurance-based UAV missions. EAFB 5 demonstrated the lowest power consumption at high RPM, making it highly effective for energy-constrained applications such as long-endurance and solar-powered UAV systems. EAFB 3 exhibited high thrust generation but with increased power consumption and acoustic noise, making it more suitable for applications where maximum thrust is prioritised over energy efficiency. The biomimetic designs inspired by eagle feathers significantly improved aerodynamic performance by reducing vortex formation, drag, and vibration effects at the propeller tips. The performance of each propeller is dependent on operating RPM, highlighting the importance of selecting appropriate propeller designs based on specific UAV mission requirements. The study also confirms that natural frequency and vibration behaviour play a critical role in propeller efficiency, where matching rotational frequency with natural frequency reduces vibration and enhances performance. Overall, biomimetic propeller designs (particularly EAFB 2, EAFB 4, and EAFB 5) demonstrate significant improvements in thrust, lift, and energy efficiency compared to the conventional propeller, indicating strong potential for enhancing UAV performance across a wide range of applications.

FUTURE RECOMMENDATION

To further strengthen the practical applicability of the proposed Eagle Feather Biomimicry (EAFB) propeller designs, future work should focus on comprehensive experimental validation to complement the current simulation-based findings. While the present study demonstrates promising aerodynamic improvements through computational analysis, physical testing is essential to verify real-world performance and reliability.

Firstly, wind tunnel testing is recommended to evaluate the airflow characteristics around the EAFB propellers. This method will enable detailed observation of aerodynamic behaviour, including vortex formation, flow separation, and turbulence intensity at varying rotational speeds. Such analysis is crucial in validating whether the biomimetic design effectively reduces tip vortices and improves aerodynamic efficiency under controlled conditions.

Secondly, thrust measurement testing using a calibrated thrust stand or thrust meter should be conducted to quantify the actual thrust generated by each propeller design. This will provide empirical data on thrust-to-power ratio, efficiency, and performance consistency across different RPM ranges. The results can then be compared directly with simulation outputs to assess the accuracy and reliability of the computational models.

In addition, flight testing on a prototype UAV platform is highly recommended to evaluate the real-world operational performance of the EAFB propellers. Parameters such as flight stability, power consumption, payload capacity, noise levels, and endurance can be assessed under practical conditions. This step is essential to determine the suitability of the proposed designs for various UAV applications, including surveillance, delivery, and agricultural monitoring.

However, several challenges may arise during experimental validation. These include manufacturing limitations, particularly in accurately fabricating complex biomimetic geometries; scaling effects, where performance observed in controlled environments may differ in real flight conditions; and measurement uncertainties due to sensor limitations or environmental variability. Additionally, ensuring consistency in testing conditions, such as airflow uniformity in wind tunnels and battery performance during flight tests, may present further difficulties.

Future research may also explore the integration of advanced materials, such as natural fibre-reinforced composites (e.g., pineapple leaf fibre or kenaf), to enhance sustainability while maintaining structural integrity. Furthermore, optimisation techniques, including machine learning or parametric design approaches, could be applied to refine the biomimetic features for improved aerodynamic performance. Overall, the incorporation of systematic experimental validation and material innovation will significantly enhance the credibility, applicability, and scalability of biomimetic UAV propeller designs.

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