Celal Bayar University Journal of Science

Propeller Modification with Groove Structure on Thrust Performance

Duygu Özyurt[1], Hürrem Akbıyık[2*]

[1,2] Adana Alparslan Türkeş Science and Technology University, Aerospace and Aeronautical Engineering Department, 01250, Türkiye
* hakbiyik@atu.edu.tr
* Orcid No: 0000-0002-1880-052X

Received: 9 August 2024
Accepted: 25 November 2024
DOI: 10.18466/cbayarfbe.1531094

Abstract

This study includes an investigation into the application of grooves in drone propellers that inspired from the structure of a bird's wing. The designed propeller involves the application of grooves at angles of 30, 45 and 60 degrees. Main purpose of using biomimetic design is to determine whether it is effective in improving thrust performance by directing the flow to the propeller blade through the grooves. Experimental investigation of the effects of these grooves on the propeller-engine thrust and the underlying causes of these effects were tried to be presented experimentally with TiO_2 based surface oil visualization technique. From the experimental results, the highest thrust value was obtained for the modified prop-60º model compared to the base propeller. Thrust measurements were measured at various RPM/V values. The maximum increase in thrust improvement is reached when the engine driven by 25% nominal power.

Keywords: Biomimetics, Propeller modification, Thrust measurement, TiO_2 surface oil visualization

1. Introduction

The expectation of continuous development based on human needs plays a leading role in prioritizing inspiration from nature. For this reason, the field of biomimetics aroused interest from researchers and development in areas such as aerospace, robotics, transport, military and art. So far, many innovations and technological developments have been achieved in the field of aviation by using biomimetic. The steps taken in the past just to fly have evolved into today's technology, and designs that prioritize efficiency in aircraft systems continue to be developed. In Table 1, the inspired livings in nature and the distribution of the examples of these livings that have found application in the field of aviation according to years are presented. Moreover, findings affecting aerodynamic efficiency obtained in the field of aviation due to these applications are presented.

Table 1. Biomimetic studies in the field of aerospace.

Date	Ref.	Animal	Anatomical Structures	Engineering Application	Aerodynamic Efficiency
2000-2005	[1]	Dragonfly	Flapping wings and legs	Entomopter	• Controlled vortex separation points
	[2]	Birds	Hyper-Elliptic Cambered Span	UAV	• Higher lift with less drag, • Higher maneuverability.
	[3]	Aphids	Thin and flexible wing	Flying Insect Robot	• The ability to determine the wing area and flapping frequency.
	[4]	Insects	Flapping flight mechanisms	MAV	• Improving maneuverability • Increasing thrust force
2006-2010	[5]	Insects	Flapping wings	FW-MAV	• Improving flapping behavior, • Increase in thrust force
	[6]	Dragonfly	Wing	UAV	• Increase in lift force

Celal Bayar University Journal of Science
Volume 21, Issue 1, 2025, p 27-34
Doi: 10.18466/cbayarfbe.1531094

	[7]	Beetles	Wing	UAV	• An efficient design of flapping wing mechanism
2011-2016	[8]	Owl	Fully structure	MAVs	• Increase in aerodynamic performance • Improvement perching capability
	[9]	Locust	Wing	MAV	• Providing improvement in lift for large range of angles of attack
	[10]	Humpback whale	Tubercles	Airplane	• Delaying stall • Enhancement in energy efficiency
	[11]	Birds	Flexible wing	UAV	• Decrease the power requirement at maximum speed
2017-2022	[12]	Bees	Fully strucutre	MAV	• Reduction in power consumption
	[13]	Dove	Wing	UAV	• Lateral stability improvement • Rolling maneuver improvement • Wing-tip vortex strength reduction
	[14]	Owl	Wing	FUAV	• Better control facing gust
	[15]	Birds	Wing	sUAV	• Minimizing energy consumption • Energy recovery
	[16]	Flying squirrels	Wing	UAV	• Improve maneuverability
	[17]	Organic molecules (CH4)	Bond structure	BioTetra	• Improve flight efficiency • Improve stability.
	[18]	Humpback whale	Tubercles	UAV	• Increasing lift • Delaying stall • Extended flight time • Carry heavier payloads
2023-Present	[19]	Birds	Wing	Propeller	• Reduced acoustic power level
	[20]	Owls	Feathers	Propeller	• Reduction in noise
	[21]	Birds	Wing	Propeller	• Generate more torque • Reduction of noise-inducing tip speed ratio
	[22]	Birds	Wing	Propeller	• Reduction in noise level
	[23]	Birds	Fold ability the wing	Monocopter	• Stable flight • Position control
	[24]	Butterfly	Wing	UST Butterfly	• Improving control in all lateral, longitudinal, and vertical directions
	[25]	Humming birds	Wing	MAV	• Increase in lift • Increase in drag.
	[26]	Eagle	Claw	Quadrotor	• Dynamically grasp various unknown objects • Enhanced perching ability.
	[27]	Birds	Primary feathers	UAV	• Improvement in aerodynamic forces • Increase in rolling coefficient

Biomimetic inspirations not only bring innovation to the literature, but they also provide many different perspectives to the engineering field as a result of using nature efficiently. In the design development phase, studies are carried out for the determined purpose. These objectives include issues such as making the design more durable, making it lighter, increasing energy efficiency, reducing sound or noise, increasing aerodynamic efficiency. In addition to many advantages, biomimetic also has some disadvantages. If it is considered briefly, we can first say the limitations of existing production technologies, especially for nanomaterials in surface structures, and then the lack of techniques for researching and determining the functioning and biomimetic concepts within the biological system [28]. Some studies in the aviation sector have been inspired by the profiles of bird wings in UAVs to increase aerodynamic performance [29]. Studies on dragonfly models to reduce drag force [30], utilization of the alula of peregrine falcon in the field of flow separation control [31], observation of owls in the reduction of sound noise [32] are among the important topics studied in this field.

Biomimetic is also a field that contributes to increasing thrust generation in aircraft. In a study, Xue et al. (2024) focused on improving the design of ornithopter aircraft in order to increase the cruising speed of the vehicle by considering the flapping performance of birds. In the experimental phase of their design, it was observed that increasing the lift force and increasing the flapping frequency significantly enhanced the thrust force, as it is the main determining factor in the speed increase of the aircraft [33]. Considering the studies carried out in this field, various configurations inspired by nature are aimed to increase the thrust by transferring them to the propeller blades. Propellers are one of the parts that are open to development with biomimetic designs. The shape, number, width, size and material of the propeller blades may vary according to the vehicle used. These can be listed as aircraft, unmanned aerial vehicles, marine vehicles and wind turbines. Further improvements in the performance of the blades have led to the general use of customized blade types for each vehicle, in addition to the traditional propeller blade. In particular, to obtain maximum thrust, the wing's chord length, bending angle and shape are among the important parameters. Consideration of these parameters provides many alternative, non-traditional designs [34]. Seeni et al. (2018) investigated a biomimetic method to improve the aerodynamic performance of a propeller. The progress of the study was about adding tubercles to the propeller blades. It has been previously tested on blades and wind turbines has provided the researchers with the prediction that it will provide improvements in performance when applied to the propeller blade. In the experiments, the increase in thrust force was calculated as 1.5% and supported the previous studies [35]. Butt and Talha (2019), observed that although the new design created by the addition of tubercles increased the propeller efficiency [36]. The study of Bui et al. (2023) is an alternative example of a developed biomimetic propeller blade. In this design, which is considered suitable for drone propellers, the flexible structure of the dragonfly wing is taken into account. It is generally aimed to adapt to collisions and complete the flight with minimal damage in these situations [37]. In terms of reducing risk and ensuring safety when using the Tombo propeller, it was found that the drone suffered two-thirds less damage during collision with an obstacle than with conventional propellers. The Tombo propeller was found to be particularly suitable for use in gliders and flapping wings. Ksiazek et al. (2023) investigated the noise reduction methods of UAV propellers inspired by the feathers on owl wings. In the experiments, the propellers varied with creating grooves engraved in 3 different positions with the base propeller. These positions were determined as inlet surface, outlet surface or both sides of the blade. The results were evaluated only on the outputs obtained with a rotational speed of 700 RPM. It is reported that using this technique provides noise reduction. As a result of the biomimetic approach, the propeller with grooves at both inlet and outlet showed a 6.2 dB reduction compared to the reference propeller [20]. Noda et al. (2022) proposed a new biomimetic design to reduce propeller noise by various methods. By adding a Gurney design to the airfoil shape, the blade area was enlarged. As a result of their application, the lift force of the propeller was increased, and the noise generated was significantly reduced as the propeller rotation speed decreased [38]. In another study on noise reduction, Rao et al. (2017) tried a new design, and this design was successful in noise reduction and the measured efficiency was close to the reference propeller [39]. Since the efficiency was low in previous studies, a new design was tried. This innovation was realized by adding a plate to the trailing edge of the propeller. The optimum position of the plate was found empirically. One of the most important studies on noise reduction was carried out by Wei et al. (2020). In this study, different designs were compared, and the best performance was determined. In the rotational tests, it was found that the sawtooth propeller showed the best result in terms of thrust increase (3.53%) and noise reduction (max. 4.18 dB). It was observed that the previous design, which was created by cutting grooves in the propeller blade, was more successful in noise reduction. The saw-toothed propeller is extra good in that aerodynamic performance is also improved [40].

Kudo et. al. (2001) have been studied groove modification under supercavity condition on the propeller blade for obtain higher thrust values maximum efficiency [41]. Another study of the groove modification in the literature has done by Shengwang et. al. (2022). In their experimental research on four blades propeller the achieved noise reduction was %35 [42]. Additionally, a design on pump jet propeller duct surface done by Zhang et. al. (2024), for suppressing of the tip vortex cavitation and to prevented from radiative noise [43]. On the propeller’s optimization in the field of UAV’s endurance and operational range provides improvement in thrust force and reduced torque. According to this subject, Seeni (2020) studied a passive flow control technique which is groove design on the propeller surface. Findings show that, at low Reynolds Number (Re) when angle of attack increased, the wake structures progressed from trailing edge to leading edge [44]. It is concluded, biomimetic design has made a great contribution to the development of more effective designs today.

In this present study, the surface geometry of the propeller modified with an inspired geometry which is including groove structures as in the bird feather surface. In this context, thrust experiments of the base model and modified models with 3 different groove placement angles were carried out. In addition, TiO_2 based surface oil flow visualization technique, which is an important method to reveal the effects of these geometries on thrust changes and to explain the flow structures on the models containing groove structures, is used. It is aimed to reveal both the changes in thrust values of the relevant models and to explain the flow structures on the surface.

2. Materials and Methods

KingKong 6040R model propeller was chosen for modification and tests. The reason for this is that the modification process is easier on this propeller, which has two blades in design. Another reason is that it is a widely used propeller for drones. It is a self-tightening propeller and is made of ABS plastic [45]. Another part to be used in the test system is the motor to be connected to the propeller. One of the first parameters to be considered when choosing the motor is whether it is compatible with the propeller and the other is whether it is compatible with the battery. Brushless motors are generally preferred in experiments with drone propellers. For this reason, EMAX XA2212 brushless motor was used in the experimental setup due to its compatibility with the selected propeller and being cost-effective [46]. Some of the propulsion test equipments were designed specifically for the experiments. The designed parts were produced by using a 3D printer. The system includes motor holder, load cell, carbon rib and support elements. The motor holder part holds the motor and stabilizes it. It also helps to provide connection control of the motor and propeller system. As shown in Figure 1, the motor-propeller pair is integrated on a single axis Honeywell brand loadcell by the help of a connection rod. The loadcell amplifies the signals with the help of a Smowo brand amplifier. Each thrust measurement is repeated 3 times and averaged.

Figure 1. Experimental setup and devices.

This system is connected to the NI-DAQ card and provides the data acquisition process with the use of computer. This DAQ card shown in Figure 2 is a National Instruments brand and is NI-USB-6009 model. Also shown in Figure 2, two power supplies were used for driving the motor-propeller pair and for the use of the amplifier which is connected to loadcell. These power supplies are AA-Tech brand and ADC-3050DD model. A servo tester was used to adjust the speed of the motor and an ESC with a value of 30A was used in the motor version.

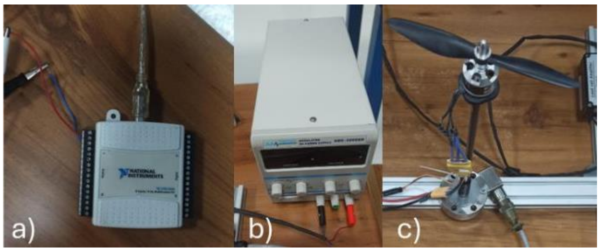

Figure 2. a) DAQ card (left), b) power supply (mid) and c) motor-propeller-ESC (right) equipments.

Figure 3 represents the base model and modified test models. In order to increase the flow control and thrust performance, modifications were made with grooves in the chordwise direction. In this context, these grooves are designed to be 30º, 45º e 60º in the flow direction of the rotary wing. In this study, groove structures inspired by bird wings are in the direction of flow, as in the feathers on bird wings in nature, and are known to contribute to the control of flow [47]. For this purpose, it is desired to contribute to the study of thrust change in rotary wing systems by controlling the flow with these modifications. Figure 3 shows the direction of rotation of the propellers and the modifications of the grooves in the direction of rotation. The number of these flow control surfaces is proportional to the placement angle.

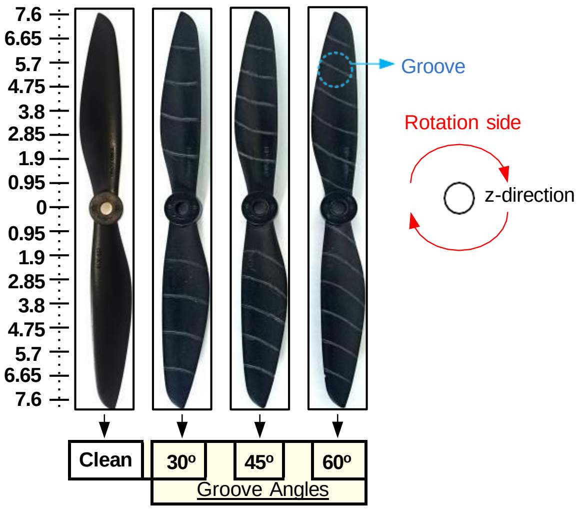

Figure 3. Base propeller and modified propellers.

Although it is aimed to increase the thrust performance with the modified propeller, TiO_2 based surface oil flow visualization experiments shown in Figure 4 were carried out to understand the reasons for this thrust change. These flow visualization experiments are an effective technique used to reveal the flow structures on the model surface. In this study, titanium powder, oleic acid and SAE30 gas oil were mixed in a 1:5:7 ratio. Seyhan and Akbıyık (2024) successfully revealed the flow topologies on the surface using this mixture ratio in their study [48].

In this study, the number of revolutions, which is one of the parameters affecting the thrust level in examining these flow structures and observing the thrust change, was set as 25%, 50%, 75% and 100%.

Figure 4. Test setup used for surface flow visualization.

3. Result and Discussion

In this section, the thrust test results and TiO_2 based surface oil visualization test results for the base model and the modified test models are presented. Previously, KK6040 propeller's thrust have been measured in gram unit by Abhishek et. al. (2017). Present study's base propeller average thrust data and data from in literature measured thrust values are coincided [49]. Figure 5 shows the thrust-KV values for different models. At the minimum value of 280 RPM/V, the thrust value of the base propeller-motor is 72 g, while the thrust values of all modified propeller-engine pairs are higher than this value. Compared to the base model, the highest thrust increase value is obtained for the Modified-Prop-60º model at around 26.5% for 280 RPM/V. It is revealed that the modified-prop-60º model has the highest thrust value according to the direction of rotation at all speeds. The main reason for this is thought to be that the modified micro grooves effectively control the flow in the rotational direction of the propeller. However, it is revealed that the improvement in thrust value decreases as the number of revolutions increases. As a result of the numerical study by Oktay and Erarslan (2020), for the effect of rotational speed and airspeed on thrust coefficient based on UAV propeller, it is concluded that as the rotational speed increases, higher turbulent flow is effective at blade tip region. Moreover, it is found that the turbulence intensity is effective in transform the laminar flow structure on the propeller blade to turbulent, leading to a decrease in thrust coefficient [50]. It is observed from the results of the study that the effectiveness of this modification will be higher in flights at low RPM/V. At 1120 RPM/V, the improvement in thrust value was again obtained as 3.2% in the Modified-Prop-60º model.

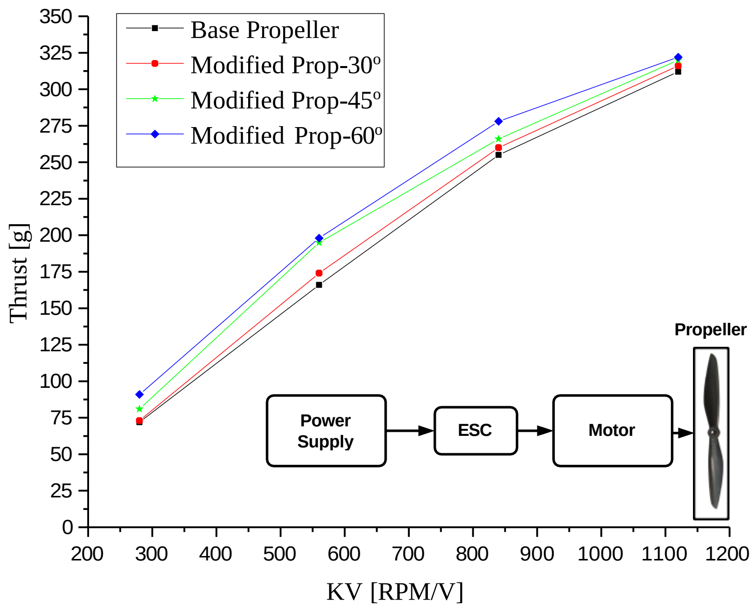

Figure 5. Thrust values of base and modified models for various RPM/V values.

As seen in Table 2, TiO_2 based surface oil flow visualization results were made for all models. It is clearly seen that the flow structures on all experimental models were revealed. In the base model, the rotational direction of the propeller drives the TiO_2 based flow visualization mixture. It is clearly seen that the flow separation line and reattachment line are formed on the surface of all experimental models. Montagner (2024) demonstrated the flow separation line and reattachment line on the propeller surface with surface oil flow visualization experiments. In addition to, it is reported that LSB occurred between the flow separation line and the reattachment line [51]. Considering the region near the center where the base propeller is connected to the motor (propeller root), transition zones and regions where the flow is at low speeds are obvious. Svorcan (2023) reported that the velocity values are high towards the ends of the propeller and there is a low velocity profile around the propeller root [52]. When propellers are modified with groove geometry, these transition zones become narrower towards to central region. In this case, it can be said that more fluid plays an active role on the propeller surface and as a result of this situation, the thrust value increases.

Table 2. TiO_2 surface oil flow visualization result at 280 RPM/V value

Model Name	TiO_2 Surface Oil Flow Visualization Results
Base Model	
Modified Prop-30º	
Modified Prop-45º	
Modified Prop-60º	

4. Conclusion

In this study, a modification method is proposed to improve the thrust produced by the propeller-motor pair used in drones. This modification method includes inspiration of the structure of bird feathers in the biomimetic field. Also, this groove structure was applied on the propeller at various angles in the direction of rotation of the propeller.

In the data obtained, thrust increase was observed in each of the propellers to which modifications were applied, and the best thrust increase was observed in the Modified Prop-60º propeller. When the propeller-motor pair was operating at 280 RPM/V, 26.5% improvement in thrust was observed when comparing the base propeller with Modified Prop-60º. When the propeller-motor pair was operating at 1120 RPM/V, the improvement in thrust was 3.2%. As a result of the experimental process, it is seen that the modifications provide more improvement in thrust production at low speeds. TiO_2 based flow visualization experiments revealed the flow structures on the propeller surface. Moreover, TiO_2 based flow visualization experiment results showed that the laminar separation line and reattachment line formed on the propeller blades. Furthermore, the region of very low velocity flow at the propeller root was clearly defined and it was demonstrated that this region was narrowed towards the propeller root by means of flow control grooves.

Author's Contributions

Duygu Özyurt: Writing-review and editing, Writing-original draft, Visualization, Validation, Methodology, Investigation, Conceptualization

Hürrem Akbıyık: Writing-review and editing, Writing-original draft, Visualization, Validation, Methodology, Investigation, Conceptualization

Ethics

There are no ethical issues after the publication of this manuscript.

References

[1]. Colozza, A. 2000. Planetary Exploration Using Biomimetics, GN:07600-051.

[2]. Davidson, J., Chwalowski, P., Lazos, B. 2003. Flight dynamic simulation assessment of a morphable hyper-elliptic cambered span winged configuration, AIAA Atmospheric Flight Mechanics Conference and Exhibit, Austin, Texas, AIAA 2003-5301.

[3]. Chan, H. Y., Lam, J. H., Li, W. J. 2004. A biomimetic flying silicon microchip: Feasibility study, IEEE International Conference on Robotics and Biomimetics, Shenyang, China, 447- 451.

[4]. Jones, K. D., Bradshaw, C. J., Papadopoulos, J., Platzer, M. F. 2005. Bio-inspired design of flapping-wing micro air vehicles. *The Aeronautical Journal*; *109*(1098): 385-393.

[5]. Nguyen, Q. V., Truong, Q. T., Park, H. C., Goo, N. S., Byun, D. 2010. Measurement of force produced by an insect-mimicking flapping-wing system. *Journal of Bionic Engineering*; *7*, S94-S102.

[6]. Kim, S. H., Chang, J. W., Sohn, M. H. 2008. Flow visualization and aerodynamic-force measurement of a dragonfly-type model. *Journal of visualization*; *11*, 37-44.

[7]. Nguyen, T. T., Byun, D. 2008. Two-dimensional aerodynamic models of insect flight for robotic flapping wing mechanisms of maximum efficiency. *Journal of Bionic Engineering*; *5*(1), 1-11.

[8]. Nelson, D., Keating, F., Leonard, J., Jacob, J. 2013. Design of a Biomimetic Unmanned Aircraft System, 51th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine (Dallas/Ft. Worth Region), Texas, AIAA 2013-0761.

[9]. Laliberté, J. F., Kraemer, K. L., Dawson, J. W., Miyata, D. 2013. Design and manufacturing of biologically inspired micro aerial vehicle wings using rapid prototyping. *International journal of micro air vehicles*; *5*(1), 15-38.

[10]. Fish, F. E., Weber, P. W., Murray, M. M., Howle, L. E. 2011. The tubercles on humpback whales' flippers: application of bio-inspired technology. *Integrative and Comparative Biology; 51(1), 203-213.*

[11]. Galantai, V. P., Sofla, A. Y. N., Meguid, S. A., Tan, K. T., Yeo, W. K. 2011. Bio-inspired wing morphing for unmanned aerial vehicles using intelligent materials. *International Journal of Mechanics and Materials in Design*; *8*, 71-79.

[12]. Bluman, J. E., Pohly, J. A., Sridhar, M. K., Kang, C. K., Landrum, D. B., Fahimi, F., Aono, H. 2018. Achieving bioinspired flapping wing hovering flight solutions on Mars via wing scaling. *Bioinspiration & Biomimetics*; *13*(4), 046010.

[13]. Hui, Z., Zhang, Y., Chen, G. 2019. Aerodynamic performance investigation on a morphing unmanned aerial vehicle with bio-inspired discrete wing structures. *Aerospace Science and Technology*; *95*, 105419.

[14]. Abbasi, S. H., Mahmood, A. 2019. Modeling, simulation and control of a bio-inspired electromechanical feather for gust mitigation in flapping wing UAV, 2nd International Conference on Communication, Computing and Digital systems (C-CODE), Islamabad, Pakistan, 195-200.

[15]. Gudmundsson, S., Golubev, V. V., Drakunov, S., Reinholtz, C. A. 2017. Biomimemic Energy-Conserving/Harvesting Trajectory Planning for a sUAV, AIAA Atmospheric Flight Mechanics Conference, Denver, Colorado, 3889.

[16]. Pons, A., Cirak, F. 2022. Pitch-axis supermanoeuvrability in a biomimetic morphing-wing aircraft. *arXiv preprint arXiv:2205.09431*.

[17]. Li, B., Wang, D., Ma, L. 2019. BioTetra: a bioinspired multi-rotor aerial vehicle, IEEE International Conference on Robotics and Biomimetics (ROBIO), Dali, China, 114-119.

[18]. ElGhazali, A. F., Dol, S. S. 2020. Aerodynamic optimization of unmanned aerial vehicle through propeller improvements. *Journal of Applied Fluid Mechanics*, *13*(3), 793-803.

[19]. 손창호, 김상현, 송지훈, 이동렬. 2023. A Study on Aerodynamic and Acoustic Characteristics of Blades by Biomimetic Design for UAM. *Journal of the Korean Society for Precision Engineering*, *40*(7), 571-580.

[20]. Książek, P., Lalik, K., Pasławski, P., Pietrzak, M., Przejczowski, P., Przepióra, J. 2023. A preliminary measurement verification of sound power level emitted by biomimetic drone propellers inspired by an owl's feather, *International Carpathian Control Conference (ICCC)*, Miskolc-Szilvásvárad, Hungary, 225-229.

[21]. Rajendran, P., Jayaprakash, A. 2023. Numerical performance analysis of a twin blade drone rotor propeller. *Materials Today: Proceedings*; *80(2)*, 492-498.

[22]. Hasegawa, M., Sakaue, H. 2024. Propeller-noise reduction by microfiber coating on a blade surface. *Sensors and Actuators A: Physical*; *371*, 115273.

[23]. Bhardwaj, H., Cai, X., Win, L. S. T., Foong, S. 2023. Nature-inspired in-flight foldable rotorcraft. *Bioinspiration & Biomimetics*; *18*(4), 046012.

[24]. Huang, H., He, W., Zou, Y., Fu, Q. 2024. USTButterfly: a servo-driven biomimetic robotic butterfly. *IEEE Transactions on Industrial Electronics; 71*(2), 1758-1767.

[25]. Min, Y., Zhao, G., Pan, D., Shao, X. 2023. Aspect ratio effects on the aerodynamic performance of a biomimetic hummingbird wing in flapping. *Biomimetics*, *8*(2), 216.

[26]. Xu, M., De, Q., Yu, D., Hu, A., Liu, Z., Wang, H. 2024. Biomimetic Morphing Quadrotor Inspired by Eagle Claw for Dynamic Grasping. *IEEE Transactions on Robotics*; 40, 2513-2528.

[27]. Bardera, R., Rodríguez-Sevillano, Á. A., Barroso, E., Matías, J. C. 2023. Numerical analysis of a biomimetic UAV with variable length grids wingtips. *Results in Engineering*; *18*, 101087.

[28]. Banken, E., Oeffner, J. 2023. Biomimetics for innovative and future-oriented space applications-A review. *Frontiers in Space Technologies*; *3*, 1000788.

[29]. Rao, C., Liu, H. 2020. Effects of Reynolds number and distribution on passive flow control in owl-inspired leading-edge serrations. *Integrative and Comparative Biology*; *60*(5), 1135-1146.

[30]. Mulligan, R. 2020. Bio-inspired aerofoils for small wind turbines, International Conference on Renewable Energies and Power Quality (ICREPQ'20), Granada, Spain, 753-758.

[31]. Ito, M. R., Duan, C., Wissa, A. A. 2019. The function of the alula on engineered wings: a detailed experimental investigation of a bioinspired leading-edge device. *Bioinspiration & biomimetics*; *14*(5), 056015.

[32]. Gu, Y., Song, F., Bai, H., Wu, J., Liu, K., Nie, B., Lu, Z. 2024. Numerical and experimental studies on the owl-inspired propellers with various serrated trailing edges. *Applied Acoustics*, *220*, 109948.

[33]. Xue, D., Li, R., Liu, J. 2024. Research on Improvement Methods for Driven System of Bio-Inspired Aircraft to Increase Flight Speed. *Drones*; *8*(4), 133.

[34]. Kutty, H. A., Rajendran, P. 2017. Review on numerical and experimental research on conventional and unconventional propeller blade design. *Int. Rev. Aerosp. Eng*; *10(2)*, 61-73.

[35]. Seeni, A., Rajendran, P., Kutty, H. A. 2018. A critical review on tubercles design for propellers. In *IOP Conference Series: Materials Science and Engineering*, 370(1), 012015.

[36]. Butt, F. R., Talha, T. 2019. Numerical investigation of the effect of leading-edge tubercles on propeller performance. *Journal of Aircraft*, *56*(3), 1014-1028.

[37]. Bui, S. T., Luu, Q. K., Nguyen, D. Q., Le, N. D. M., Loianno, G. 2023. Tombo propeller: bioinspired deformable structure toward collision-accommodated control for drones. *IEEE Transactions on Robotics, 39*(1), 521-538.

[38]. Noda, R., Ikeda, T., Nakata, T., Liu, H. 2022. Characterization of the low-noise drone propeller with serrated Gurney flap. *Frontiers in Aerospace Engineering, 1*, 1004828.

[39]. Rao, C., Ikeda, T., Nakata, T., Liu, H. 2017. Owl-inspired leading-edge serrations play a crucial role in aerodynamic force production and sound suppression. *Bioinspiration & Biomimetics, 12*(4), 046008.

[40]. Wei, Y., Xu, F., Bian, S., Kong, D. 2020. Noise reduction of UAV using biomimetic propellers with varied morphologies leading-edge serration. *Journal of Bionic Engineering*; 17, 767-779.

[41]. Kudo, T., Ukon, Y., Sumino, Y. 2001. Proposal of a Groove Cavitator on a Supercavitation Propeller, http://resolver. caltech. edu/cav2001: sessionB9. 003.

[42]. Shengwang, Z. H. U., Guijian, X. I. A. O., Yi, H. E., Gang, L. I. U., Shayu, S. O. N. G., JIAHUA, S. 2022. Tip vortex cavitation of propeller bionic noise reduction surface based on precision abrasive belt grinding. *Journal of Advanced Manufacturing Science and Technology* 2(1), 2022003.

[43]. Zhang, K., Ye, J., Zhong, H., Fu, B., Zhang, Y. 2024. Study on the tip flow control effect of pump jet propeller with groove structure. In Fourth International Conference on Mechanical, Electronics, and Electrical and Automation Control, Xi'an, China, 13163, 1771-1777.

[44]. Seeni, A. S. 2020. Effect of grooves on aerodynamic performance of a low reynolds number propeller, (Doctoral dissertation).

[45]. de Oliveira, T. L., de Carvalho, J. 2021. Design and numerical evaluation of quadrotor drone frame suitable for fabrication using fused filament fabrication with consumer-grade ABS. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 43(9), 436 (1-19).

[46]. Nikhil, N., Shreyas, S. M., Vyshnavi, G., Yadav, S. 2020. Unmanned aerial vehicles (UAV) in disaster management applications, In 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), Tirunelveli, India, 140-148.

[47]. Feng, B., Chen, D., Wang, J., Yang, X. 2015. Bionic research on bird feather for drag reduction. *Advances in Mechanical Engineering*; 7(2), 849294.

[48]. Seyhan, M., Akbıyık, H. 2024. An experimental investigation on the flow control of the partially stepped NACA0012 airfoil at low Reynolds numbers. *Ocean Engineering*; 306, 118068.

[49]. Abhishek, A., Krishna, M., Sinha, S., Bhowmik, J., Das, D. 2017. Design, development and flight testing of a novel quadrotor convertiplane unmanned air vehicle. In 73rd Annual Forum of the American Helicopter Society. Fairfax, VA: *AHS International, Inc.*

[50]. Tuğrul Oktay, Yüksel Eraslan, 2020. Numerical investigation of effects of airspeed and rotational speed on quadrotor UAV propeller thrust coefficient. *Journal of Aviation,* 5(1), 9-15.

[51]. Montagner, S. 2024. On the effects of freestream turbulence on a small drone propeller aerodynamics and aeroacoustics, (Doctoral dissertation, Politecnico di Torino).

[52]. Svorcan, J. 2023. WMLES of flows around small-scale propellers-estimating aerodynamic performance and wake visualization. *Theoretical and Applied Mechanics, 50*(2), 133-144.