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Biomimetic-based propeller design for electric-powered drone systems

Elektrikle çalışan drone sistemleri için biomimetik tabanlı pervane

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Biomimetic-Based Propeller Design for Electric-Powered Drone

Highlights

- *Biomimetic propellers can reduce the noise caused by electric propulsion systems.*
- *The results were compared with the values of a commercial product in a similar class, and it was observed that the biomimetic design was able to achieve the same thrust at lower speeds.*
- *Although both propellers were compared at equal speeds, it was observed that the biomimetic propeller produced 1080 grams of thrust, and the commercial propeller produced 959 grams of thrust for consumption of 80W, corresponding to equal propeller work*

Graphical Abstract

A biomimetic-based propeller specialized for uncrewed aerial vehicles was designed. The designed propeller is customized for UAV systems with electric motors. This propeller was developed in light of the biomimetics discipline with the goals of high efficiency and low noise trail. propeller blade vet distribution, propeller torsion angle distribution, and airfoil designs were realized using the rear wings of a dragonfly, and numerical analyses were performed using computational fluid dynamics.

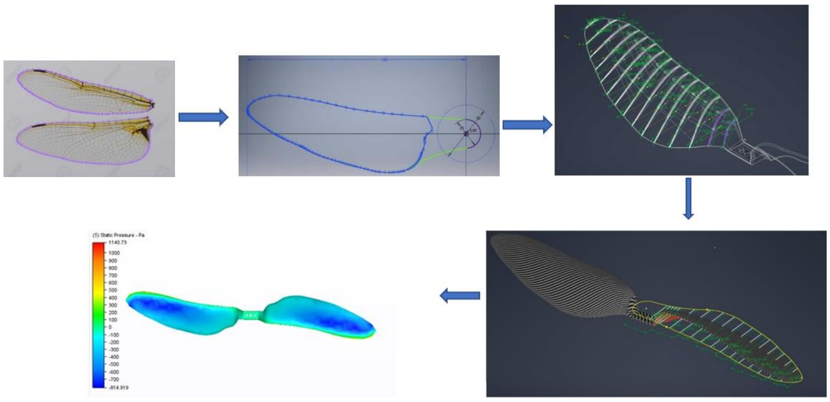

Figure. Graphical Abstract

Aim

Reducing noise caused by electric propulsion systems using biomimetic-based propellers.

Design & Methodology

Within the scope of this study, propeller blade vet distribution, propeller torsion angle distribution, and airfoil designs were realized using the rear wings of a dragonfly, and numerical analyses were performed using Computational Fluid Dynamics.

Originality

Although both propellers were compared at equal speeds, it was observed that the biomimetic propeller produced 1080 grams of thrust, and the commercial propeller produced 959 grams of thrust for a consumption of 80W, corresponding to equal propeller work

Bulgular

The results were similar to those of other biomimetically designed propellers in the literature. The high speed obtained at lower speeds is a common point with previous studies.

Conclusion

In light of this study, it is predicted that biomimetic propellers can reduce the noise caused by electric propulsion systems.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Biomimetic-Based Propeller Design For Electric-Powered Drone Systems

Araştırma Makalesi / Research Article

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ABSTRACT

In this study, a biomimetic-based propeller specialized for uncrewed aerial vehicles was designed. The designed propeller is customized for UAV systems with electric motors. This propeller was developed in light of the biomimetics discipline with the goals of high efficiency and low noise trail. Today, commercially used electric air vehicles still use scaled versions of propellers developed for high-speed internal combustion engines. A propeller capable of generating equal thrust at low speeds, where electric motors operate efficiently, is needed to achieve the required thrust at low speeds. Within the scope of this study, propeller blade vet distribution, propeller torsion angle distribution, and airfoil designs were realized using the rear wings of a dragonfly, and numerical analyses were performed using computational fluid dynamics. The results were compared with a commercial propeller of similar size and pitch. It was concluded that the designed biomimetic propeller could produce equal thrust at low speeds without losing efficiency.

Keywords: uncrewed aerial vehicles, biomimetic-based propeller, propeller efficiency.

Elektrikle Çalışan Drone Sistemleri İçin Biomimetik Tabanlı Pervane

ÖZ

Bu çalışmada, mürettebatsız hava araçları için özelleşmiş biyomimetik tabanlı bir pervane tasarlanmıştır. Tasarlanan pervane, elektrik motorlu İHA sistemleri için özelleştirilmiştir. Bu pervane, yüksek verimlilik ve düşük gürültü izi hedefleri ile biyomimetik disiplini ışığında geliştirilmiştir. Günümüzde ticari olarak kullanılan elektrikli hava araçları hala yüksek hızlı içten yanmalı motorlar için geliştirilmiş pervanelerin ölçeklendirilmiş versiyonlarını kullanmaktadır. Elektrik motorlarının verimli çalıştığı düşük hızlarda gerekli itkiyi elde etmek için düşük hızlarda eşit itki üretebilen bir pervaneye ihtiyaç duyulmaktadır. Bu çalışma kapsamında, bir yusufçuğun arka kanatları kullanılarak pervane kanat veter dağılımı, pervane burulma açısı dağılımı ve kanat tasarımları gerçekleştirilmiş ve hesaplamalı akışkanlar dinamiği kullanılarak sayısal analizler yapılmıştır. Sonuçlar, benzer boyut ve hatveye sahip ticari bir pervane ile karşılaştırılmıştır. Tasarlanan biyomimetik pervanenin düşük hızlarda verimlilik kaybı olmadan eşit itme gücü üretebildiği sonucuna varılmıştır.

Anahtar Kelimeler: insansız hava araçları, biyomimetik tabanlı pervane, pervane verimliliği

1. INTRODUCTION

Biomimetics was first coined by Janine M. Benyus, a writer and scientist. The central theme of biomimicry is that we have much to learn from nature as a model, measure, and wisdom. What researchers have in common is that they respect the design in nature and use this approach to inspire people to solve the problems they face (1,2). The use of biomimetics as a design guide is categorized under two headings; the first is "looking at biology," which is defined as defining a human need and looking for a solution to this need in nature, and the second is "biology influencing design," which is explained as developing a new design by looking for a function in a living thing (3).

In recent years, the concept of electric aircraft has garnered significant attention within the aviation industry, primarily due to its environmental and economic advantages. According to recent studies, the implementation of More Electric Aircraft (MEA) technologies can result in approximately a 20% reduction in CO_2 and NO_x emissions, a 50% decrease in noise levels, and a 20% decrease in fuel consumption when compared to the conventional models produced by the same manufacturer (4). Also, there have been many studies on the design of propellers aiming to increase aerodynamic efficiency. When the studies are examined, it is seen that almost all of them are designs or inventions inspired by nature. Although it is impossible to make this generalization for aircraft flying at supersonic speeds, the designs can be explained in light of the biomimetic discipline in aviation in general. Therefore, while examining past studies, we first examined the research on the flight of living things in nature and examined them in terms of aerodynamics. In the light of the analyzed research, a database of biomimetic design ideas was created to be used in the propeller design obtained as a result of this study.

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The explanation of aerodynamic lift has been studied using various theories. The theorem defined by Daniel Bernoulli in 1738 is a principle of the fluidity of air. The curved upper surface of the airfoil creates a faster airflow in the upper part, creating a low-pressure zone that generates lift. Another theory is based on Newton's Third Law of Motion. According to this theory, the lift is generated when the wing pushes the air downwards, and the air pushes the wing upwards in an equal and opposite way. This concept is considered one of the basic aerodynamic principles (5). McLean's complex explanation explains lift through the interaction of air movement, pressure differentials, and the wing. McLean's theory considers the complexity of the airflow around the wing and the relationship of the pressure fields. This approach provides a more comprehensive understanding of buoyancy (6,7).

Experimental and numerical studies on propeller design show that various methods have been investigated to improve the performance and design of propellers (8). Rossow (9) studied the effect of floor and ceiling planes on thrust, and Brandt (10) investigated the performance of small-scale propellers at low Reynolds numbers. Lee (11) visualized the effect of ground proximity of propellers in equilibrium flight. Deters (12) experimentally evaluated the performance of propellers at low Reynolds numbers, and Gamble and Arena (13) investigated the effect of Reynolds numbers on the performance of propellers. Heinzen (14) developed a variable angle propeller system, Tracy (15) analyzed a propeller design for a UAV, and Bettinger (16) fabricated and tested Mini UAV propellers. Merchant and Miller (17) tested propellers using an integrated propulsion test system. These studies contribute to understanding and improving propeller design and performance.

Numerical studies are performed using computational fluid dynamics (CFD). These studies provide an essential tool for evaluating and improving propeller performance. Most studies are based on the Reynolds-averaged Navier-Stokes (RANS) equations. Using uncertainty analysis, Moffitt (2008) validated the Vortex Propeller Theory for UAV design. Stajuda (18) stated that BET and BEMT (Blade Element Momentum Theory) methods can be used to evaluate the aerodynamic performance of propellers. Rumsey and Ying (19) predicted the aerodynamic properties of airfoils and three-dimensional blades using various CFD tools. However, it was found that the Stall state needed to be predicted correctly, and Reynolds number effects needed to be more consistent in three-dimensional configurations. Zeune (20) compared propeller numerical analyses with wind tunnel test results and noted that the BEMT results were sensitive to several variables of the propeller. These studies are significant contributions to the research and development of different approaches and methods for propeller design.

Some studies have been carried out that can serve as examples for understanding the wing structures of living things in nature. The maple seed is an autorotating seed that generates lift by rotating and creating a vortex. This property helps the seed achieve aerodynamic stability to control the fall rate (21). Javan cucumber seeds can reach long distances in a stable flight. This ability is based on their ability to maintain their angle of descent by utilizing thermal currents (22). Nomadic dragonflies are insects that can glide using thermals in their long-distance migrations. The unique structure of their wings provides high aerodynamic efficiency (23). Honeybees fly by visual interactions, and this interaction is called "optomotor reaction" (24). Owls can get a panoramic view by turning their necks 270 degrees. They achieve silent flight through feathers and flapping techniques (25). The aerodynamic optimization of humpback whales is associated with the "tubercle effect." This phenomenon increases the aerodynamic efficiency of the ridges on the whale's wing leading edge (26). Evolutionary processes of adaptation and adaptation to environmental requirements have shaped these animals' aerodynamic characteristics and flight strategies.

Biomimetic design offers innovative solutions in engineering applications by taking inspiration from the structure and function of natural organisms. Some studies conducted in this context are as follows: Wei (27) investigated propellers' aerodynamic performance and noise level with different blade notches inspired by owl wings. The study found that notched propellers have a higher thrust-generating capacity than a standard propeller, and the sawtooth design significantly reduces noise. Zhang (28) surveyed delta blades inspired by the lumpy fins of humpback whales. It was found that lumpy edges of attack increased lift and delayed stall, and it was observed that small-sized lumps provided a higher lift/drag ratio at low angles of attack. Tay (29) investigated the noise reduction effect of the teeth on the propellers used for quadrotor UAVs. It was determined that serrated propellers have a lower noise level and higher thrust generation. Ning and Hu (30) evaluated the performance of a propeller inspired by maple seeds and cicada wings. The biomimetic-inspired propeller was found to have a quieter operation and the ability to produce an equal amount of thrust at low speeds compared to a standard propeller.

Unlike the studies in the literature, the wing bends of the dragonfly's wing flap were also imitated to maximize the aerodynamic capabilities.

2. BIOMIMETIC PROPELLER DESIGN

Uncrewed Aerial Vehicles (UAVs) are increasing with the decreasing cost of electronic devices (31,32). Rally-wing UAV systems are especially preferred due to their vertical take-off and landing features (32). Along with these developments, many studies have been conducted on rotary-wing UAV systems; however, most have focused on control systems, sensor technologies, mechanical-function improvements, and software developments (33).

Rotary-wing UAV systems have been used in many fields, such as cargo transportation, aerial photography, inspection, analysis, and military applications (34). However, these systems are disadvantageous compared to fuel-powered or hybrid rotary wing systems as they generally have low flight times. Moreover, they can operate inefficiently when carrying heavy loads, causing noise pollution in cities (35). Therefore, there is a need for innovations in the propeller design of rotary-wing UAV systems.

Propeller designs using biomimetic inspirations are thought to operate more efficiently and quietly at low speeds (28). Studies in the literature show that propellers with low sound signatures have been developed by taking inspiration from maple wings and cicada wings (30, 36). These biomimetic designs can increase efficiency at low speeds and reduce noise pollution.

However, studies in the literature have generally focused on propellers designed with a fixed blade angle by mimicking blade projections. Therefore, more research is needed on mimicking the wing angle as part of biomimetic design (36 Hintz, 2018). In some studies, aerodynamic wing shapes often include manufactured or designed propellers. Evolutionarily, creatures that feed or migrate by flying have saved energy by improving their aerodynamics.

In studies in the literature, some propellers have been produced and tested by imitating the shape of cicada wings (30). The wing of the cicada has a structure similar to the winglets. A wing structure is seen expanding from the wing root to the center of the wing and then narrowing towards the wing tip. This is because the velocity of the wing tip is greater than that of the wing root during flapping. Therefore, for the pressure and structural deformation on the wing to be homogeneous, the wing has to narrow towards the tip, and less air has to be displaced. However, the wings of cicadas or bees are not the most suitable mimic for the most efficient design. This is because dragonflies are more active fliers and migrate long distances. The differences in the wings of dragonflies are indicative of this. These insects can also glide using airflow without flapping their wings. Therefore, dragonflies' wing shape and flight behavior may have optimal aerodynamic properties that can be used in propeller design. In this study, a propeller that mimics the wing shape of dragonflies is developed and analyzed.

2.1.Wing Profile Development

Both the fluid efficiency and the structural design of the dragonfly have the potential to make it a lightweight and efficient rotary wing UAV component. It was decided that if we rotate one of the wings and add them to each other end-to-end at the wing roots, we can have a propeller to obtain sufficient lift at low speeds. This blade feature, which narrows as you go from the blade roots to the tip, can be observed in wind turbines rotating at low speeds. These wind turbine blades, produced at high angles and with large blade surfaces to capture low-speed winds, are similar to the wings of dragonflies, cicadas, or maple seeds.

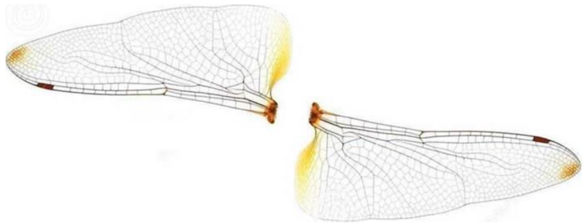


Figure 1. Dragonfly hind wings

A biomimetic propeller design may be possible through direct imitation, but any work outside the engineering discipline at the fluid mechanics level will be fruitless. Therefore, references to flow theories are necessary to adapt the biomimetic design to existing technologies. Otherwise, any success would be purely accidental and unrepeatable. Using the explanation of buoyancy here, understanding the evolution of living things and analyzing why they evolved into the wing shapes they have is the best way to lead to a successful design.

There are many studies on increasing the efficiency of wind turbines using genetic algorithms and topological optimization logic based on artificial intelligence (37). In one of these studies, Pourrajabian (38) studied the determination of blade chord length distribution, airfoil, and propeller torsion variables with genetic algorithms to increase efficiency. In this study, the design of the wind turbine blade was determined by operating the process applied by nature on living things through an algorithm. Of course, it is only possible for this algorithm to model some of the laws of nature and operate iteratively. In this study, the parameters above are copied from the simulated creature, and the copied propeller blade is numerically analyzed. These numerical results are compared with the experimental results of similar propellers in the literature.

2.2. Wing Profile Determination

Pourrajabian (38) pre-selected the profile he used in his study and kept it as a constant variable without an iterative approach to this variable. Airfoils are geometric shapes determined after many experimental studies and partly inspired by nature. Since it would be difficult to address innovative issues in the case of a numerical study on this subject, it is expected that existing airfoils in the literature will be used directly in numerical studies. In the profiles of existing composite propellers, a sponge core is placed inside the propeller to create a familiar profile that forms a three-dimensional shape. However, this is a challenging process. It increases the cost as well as the weight of the propeller.

Garinis (39) studied the shape of conventional composite propellers using different shapes of foam cores to improve existing helicopter blades. However, when we examine a dragonfly's wing, we observe a very different structure from conventional airfoils. This structure is a flat plate-shaped profile that covers the webbed veins with a transparent membrane. Koehler (2012) investigated this airfoil's 3D deformation and kinematics using high-speed cameras.

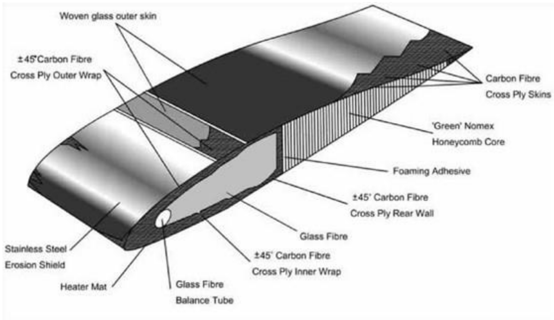


Figure 2. Structure of a helicopter propeller (Garinis, 2012)

As seen in Koehler's (40) study, the profile is humped, and its thickness does not change. Using the visualization obtained in this study, the wing profile of the dragonfly was copied. Such an airfoil will facilitate the production of the carbon fiber composite propeller by removing it from the mold. It was determined that the best decision to produce a propeller was to lay a single row of layered carbon fiber fabric on the mold and curve it into a volumeless profile resembling the wing structure of the dragonfly.

The difference in the thickness of the trailing edge and the attacking edge of the profile is designed to depend on the compression ratios in the molding. It is entirely dependent on the technique used in production. The thicker profile side holds more resin and cures under less pressure. The narrower profile edge is the part that is more compressed by the mold and, therefore, contains more carbon fiber fabric and less resin. This variable resin ratio gives flexibility to the trailing edge and stiffness to the leading edge, which is precisely what you want in a propeller.

2.3. Determination of Chord length Distribution

The chord length of an airfoil is the distance between the leading edge and the trailing edge. Variations in this length along the wingspan determine the aerodynamic characteristics of the wing. Typically, the chord length narrows from the root to the tip of the wing. In designing the biomimetic propeller, the distribution of this length along the wing will be inspired by the wings of a dragonfly. Thus, the wing silhouette has been modeled in Autodesk Inventor. During the flapping of the dragonfly's wings, it has been observed that the wings connect to the body through a ball-and-socket joint, allowing a certain degree of freedom. This feature enables the dragonfly to flex its wings forward during gliding flights.

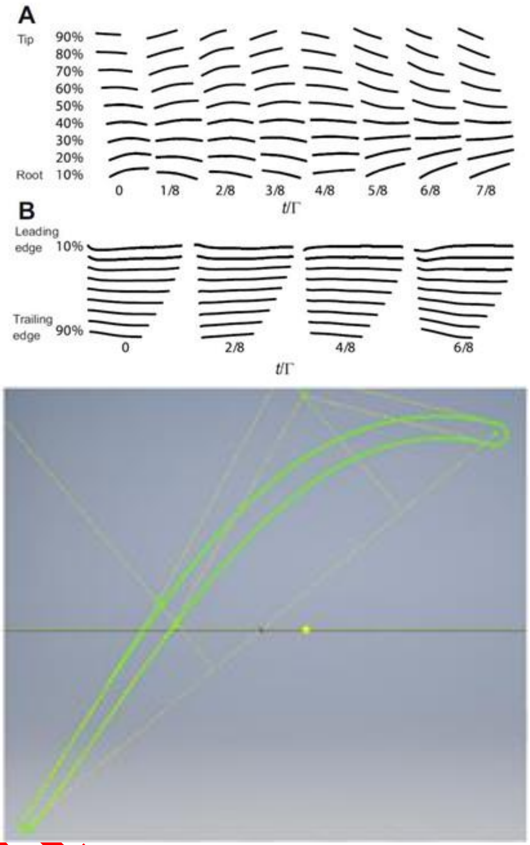
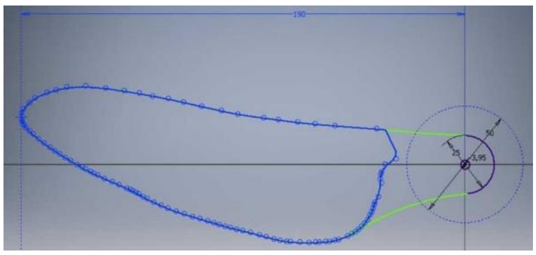


Figure 3. (a) The right-wing flapping from the lower position to the upper position; A: Sections taken in the direction of the vet line, B: Sections taken along the wingspan (40 Koehler, 2012), **(b)** Wing profile of a dragonfly simulated from Koehler (40)

a)



b)

Figure 4. (a) Chord length distribution of the wing of a dragonfly (Inventor Sketch **(b)** Transferring the seating angle of the wing breaking forward to the design (Inventor Sketch)

The design of the forward-swept dragonfly wing has been derived from high-speed camera footage. Although the organic nature of the drawing poses a challenge for replication, the wing's placement in the drawing has been set at an angle of 9.2 degrees based on the photograph of the dragonfly's wing. This configuration enables the chord distribution of a 380mm diameter propeller to be inspired by the dragonfly's hind wings.

The difference between the hind and forewings is in the more significant thrust requirement for the hind wings. The forewing root is narrower than the hindwing root due to the dragonfly's body structure. During the flapping of the forewings, the dragonfly's body prevents the forewing root from expanding over time. However, the dragonfly's tail begins at the point where the hind wings attach to the body, and since the tail is thinner than the body, it allows the hindwing roots to be broader. In this case, it is concluded that the evolution towards highly efficient wings has been towards broader wing roots. The propeller veter length distribution was therefore inspired by the hind wings of the dragonfly.

2.4. Determination of Propeller Torsional Distribution

The propeller torsional distribution is the most critical variable for a rotary blade. It is necessary to optimize this angle distribution to obtain a fluid interaction compatible with the linear velocity changing from the blade root to the blade tip. In this direction, a torsional distribution was created by considering the wing deformations that were tried to be visualized as much as possible in Koehler (40).

When the videos of the wing taken by high-speed cameras were examined, it was seen that the dragonfly's wings during suspension had wing deformations similar to the study. In this context, a torsion angle distribution was determined from the wing root to the wing tip. In his research, the author stated that downward wing flapping occurs faster than upward flapping. At the same time, it was mentioned that the dragonfly also forms an active wing hump with the capillary blood circulation in the wing roots where the wing deformation is the highest (40) For this reason, the wing lift force in the wing roots, where the deformations seen in the wing are faster than the wing flapping speed, caused the wing lift force to increase parabolically. All this made it difficult to directly replicate the wing deformation of the dragonfly at any given moment in time in the propeller design. The assumption is that there is more lift, whereas there is more wing curvature. However, while the wing deforms, this deformation is faster at the root of the wing than in other parts of the wing, indicating that more thrust is generated at the root of the wing. In this context, in the CFD analysis, the angle of the wing root was exaggerated and increased until the point where the wing did not stall. Thus, by shifting the lift force's junction point to the root of the wing, wing tip vortices are also reduced. Koehler (40) stated that the angular change is from the attacking edge to the trailing edge by 30% of the chord length and changes in the direction of this axis. In line with this information, the 30% axis was transferred to the 3D model file (Figure 5).

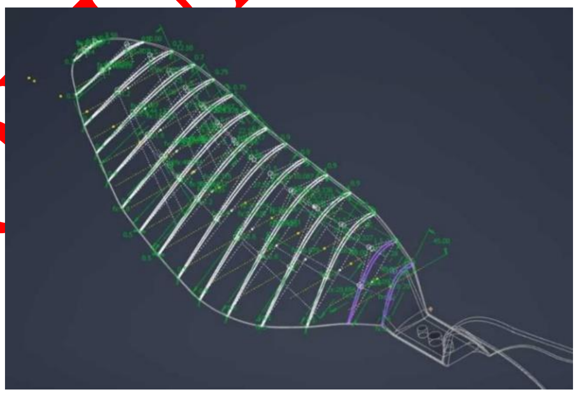


Figure 5. Blade torsional angle distribution of the developed biomimetic propeller

Table 1. Variation of torsion and vet length from propeller root to tip

Propeller length (mm.)	19	25	37,5	50	62,5	75	87,5	100	112,5	125	137,5	150	162,5	175	187,5
Torsion angle (deg.)	42	37	38	36	32	29	25	22	19	16	14	10	8	4,5	2
Chord length Length (mm.)	20	32	38,6	46,7	50,4	51,6	50,6	49,4	48,4	47,3	44,1	40,1	35,4	26,5	10,4

In this study, assuming that the deformation is directly proportional to the magnitude of the thrust created, the speed that provides the flow condition in which the blade tip vortices formed in the range of 1200-4000 rpm are trapped by curling on the blade was selected by CFD flow visualization.

The designed propeller is optimized only for a specific speed. This will require the propeller to be used with continuous speed control. For the propeller to be used in electric rotary wing aircraft, the critical propeller stall speed, which will vary depending on the speed of the flight, must be continuously measured, and the propeller must be forced to operate at the (designed) speed at which it will be in a continuous high-efficiency regime. Such a measurement requires an integrated flight control technique. In this thesis, a static, i.e., stalling, rotary-wheel system is assumed to have an engine speed range of 2000-6000 rpm per engine.

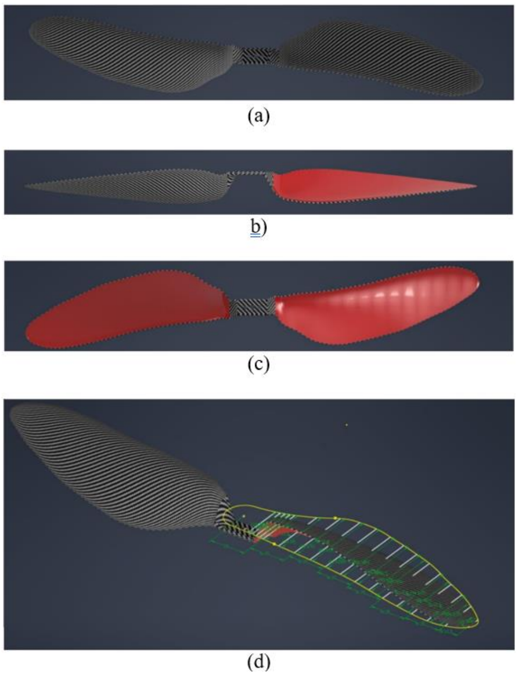


Figure 6. Top (a), Side (b), and Bottom (c) and 3D view of the developed biomimetic propeller

Accurate results in propeller analyses are achieved using the rotating region method. In their study, Kutty and Rajendran (2017) reported that a cylindrical rotating fluid domain with a height equal to 0.4 times the propeller diameter and a radius 1.1 times the propeller diameter provides more reliable outcomes. They defined the boundary conditions as follows: the inlet surface of the stationary region was set as a velocity inlet with a turbulence intensity of 0.1%, and the outlet surface was defined as a pressure outlet representing free flow. To simulate forward motion, inlet velocities ranging from 2.44 m/s to 10.15 m/s were applied, and for each case, thrust coefficients, power coefficients, and efficiency were calculated.

In accordance with this approach, the biomimetic propeller operating at 1000 RPM was analyzed using the rotating region method under the condition of zero forward velocity, corresponding to a hovering UAV. These simulations were performed using the Autodesk CFD software.

Static flight conditions are assumed to be an average engine speed of 3500 rpm for a four-engine rotary-wing UAV system with a cruising speed of 16m/s. In line with this assumption, the propeller modeled as fluid under normal conditions and made of carbon fiber was analyzed using the CFD method.

3. DESIGN VERIFICATION AND ANALYSIS

The flow environment mentioned in Kutty and Rajendran (41) was used to improve the accuracy of CFD analysis. Accordingly, the diameter of the rotational fluid cylindrical region was created as 1.2D and the height as 0.28D, with the propeller diameter as D. The diameter of the stationary fluid cylindrical region was created as 5D diameter and 8D height as mentioned in Wei (27). The 10D diameter and 37D height in Kutty and Rajendran (41) were unnecessary as they would create too many mesh nodes. In a smaller area, it was tried to increase the analysis speed without affecting the sensitivity of the CFD analysis. Since Kutty and Rajendran (41) placed the rotational fluid field 10D behind the cylinder (27D above the base) in the constant fluid field, the same ratio was kept constant and proportioned to the cylinder with a total height of 8D. Approximately 2D - 6D was determined in this study. Since it was seen that it did not affect the result in the analyses, the diameter of the constant fluid cylinder was reduced to 8D with a height of 8D, and the speed of the analysis was increased for different propeller speeds. In this direction, a rotational fluid region was placed 2D from the ceiling and 6D from the base with a total height of 8D. The airflow is assumed from the ceiling to the floor, and gravity is defined accordingly for suspended flight.

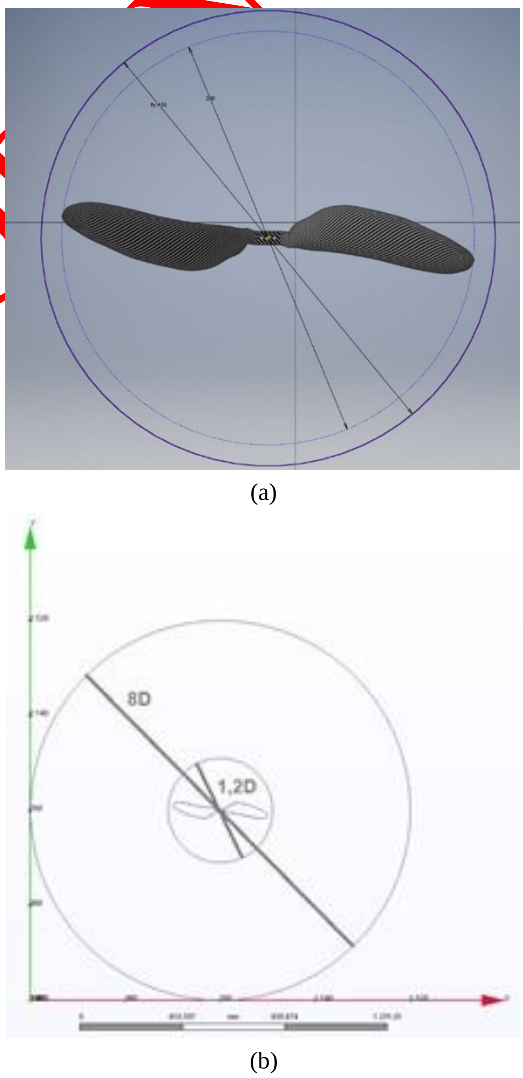
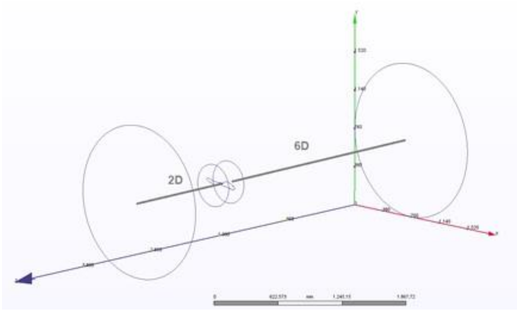


Figure 7. (a) Rotational fluid region "D" The ratio of 1.28D for a propeller diameter of 380mm, (b) the ratio of the constant fluid cylindrical area to the rotational fluid area, which is 8D,



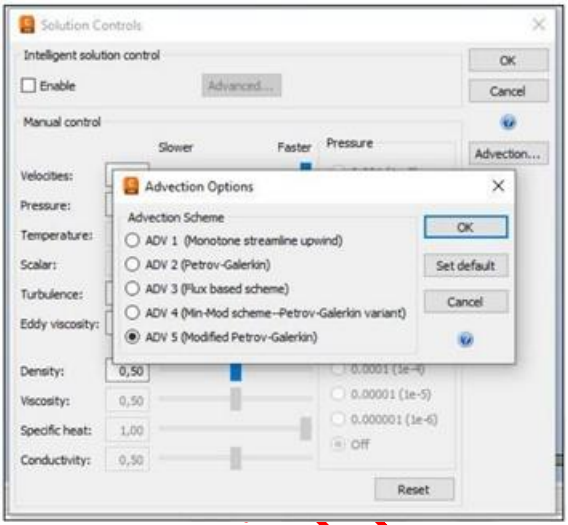
(c)

Figure 7. (Cont.) (c) Distance of the impeller from the air intake and air exhaust boundary zones

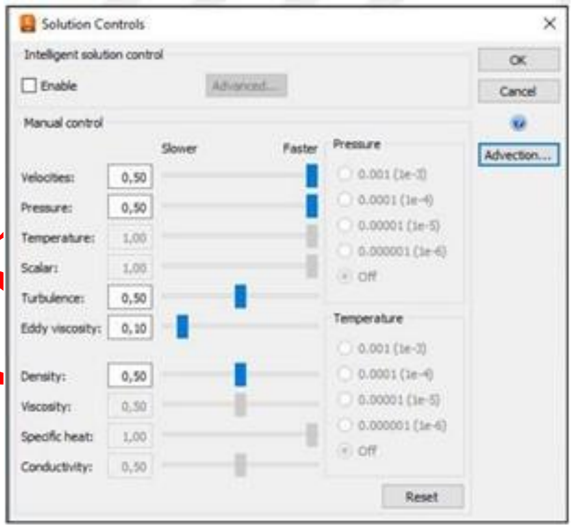
The 8D length was sufficient for the flow to enter the regime, and the simulation was optimized for process-intensive analyses using extensively ordered variables. The necessary simulation setup was made through the CFD application. In this study, the AutoDesk Nastran program integrated with Inventor was used to perform CFD analyses. The impeller rotating at 3746 rpm was analyzed under 100kpa inlet and outlet pressure conditions. As seen in the study tree, comparisons were made by analyzing differently designed propellers.

(a)

Figure 8. (a) Number of process points generated in the analysis



(b)



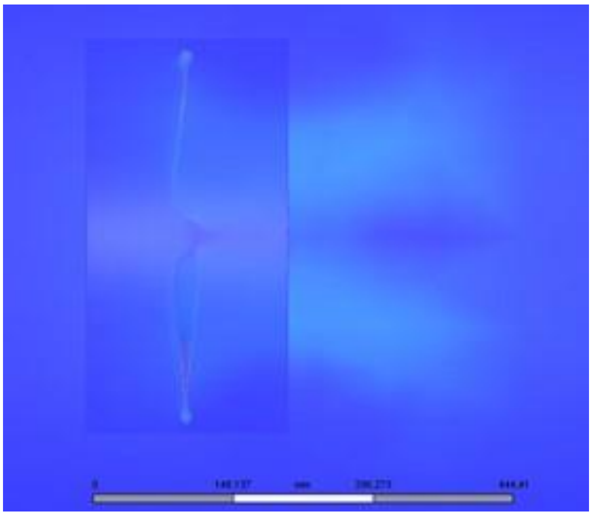
(c)

Figure 8. (Cont.) (b) solution method and (c) boundaries

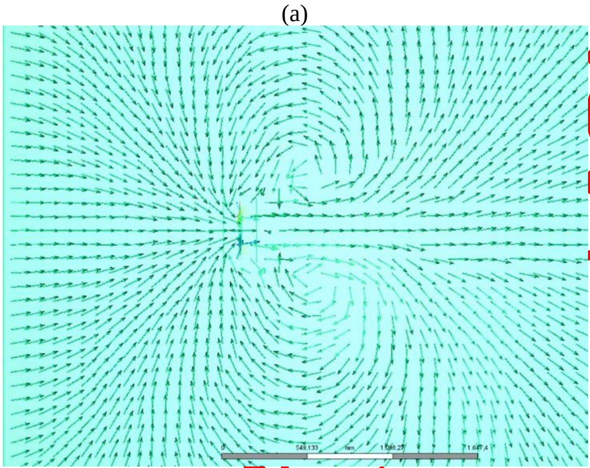
The analysis obtained results by selecting the solution with the Petrov-Galerkin method with an analysis network created with 1.7 million process points. The density of the analysis network was automatically generated by the application to be dense in the rotational fluid region and sparse in the constant fluid region. Thus, considering the sensitivity of the analysis, the network forming the process points of the rotational fluid region is dense and detailed in the sensitive areas.

3.1.Analysis Results

The results obtained are shared visually in the section. Depending on the increasing velocity profile from the propeller center to the blade's tip, the velocity of the interacting fluid was kept constant from the propeller root to the tip. As a result, a fluid velocity distribution was obtained for 3746 rpm. The uniform velocity distribution along the blade was achieved as much as possible by examining the velocity vectors. As seen in the pressure distribution, the pressure distribution is balanced along the wing due to the proportionality of the torsion and vet length distribution. This way, while the lift force is concentrated towards the wing root, vortex formation at the wing tips is minimized. In the pressure distribution on the wing, it is seen that the pressure at the wing root can be reduced more, but since the torsion at these root parts has limitations due to composite production, the torsion angle is limited.



(a)



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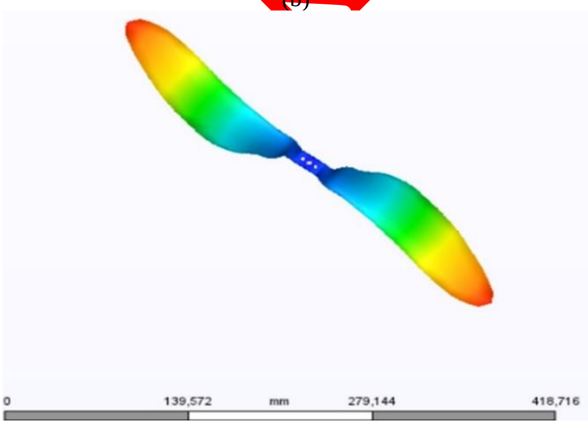
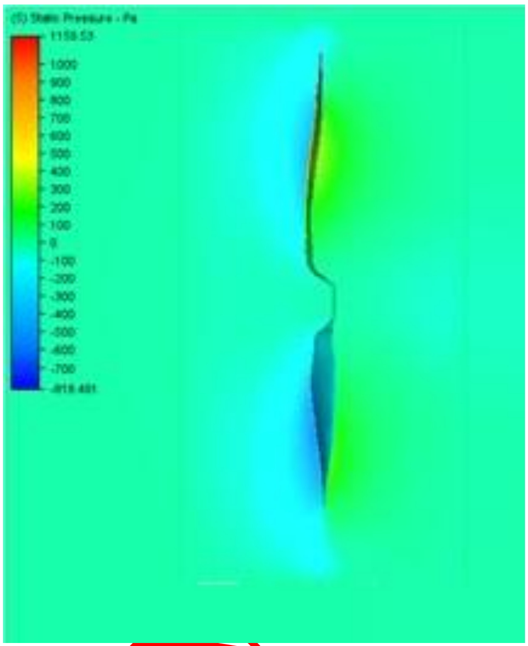
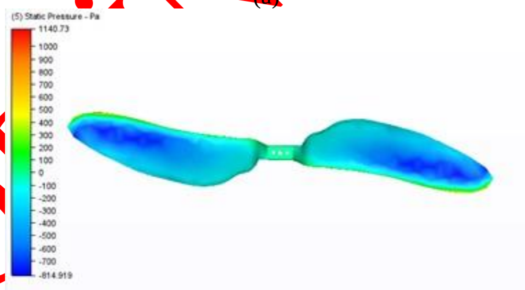


(c)

Figure 9. (a) Velocity distribution of the flow, (b) Distribution of velocity vectors, and (c) Velocity profile of the propeller



(a)



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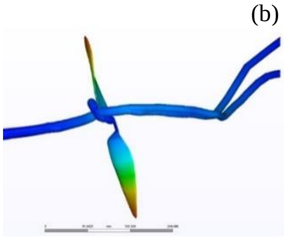

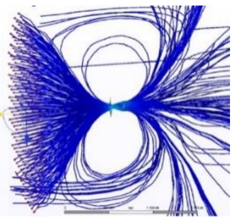

(c)

Figure 10. (a) Pressure distribution of the fluid, (b) Pressure distribution on the flow blade, and (c) Illustration of flow percolation (right) and its interaction with the boundary layer (left)

3.2. Comparison of Results with Commercial Product

In the numerical analysis of the commercial products at the same engine speeds, the torque and thrust values of the propeller rotational solid design were calculated for each speed under the 'wall results' tab of the boundary layer analysis. Then, using these torque and thrust values, the power values consumed by the propeller were calculated and shared in the table.

The benchmark propeller was tested on the same manufacturer's MN4006 KV380 motor. The 15-inch diameter and 5-inch pitch propeller were driven by a 24V motor controller (store.tmotor.com). A comparison was made by showing the data obtained from these test results and the results obtained from the numerical study in a table.

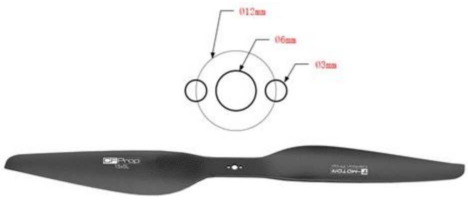

Figure 11. Image of the benchmarked commercial product (42)

The torque and speed relationship obtained from the numerical analysis was obtained using the conversion Power (kW) = Torque (N.m) x speed (RPM) / 9.5488. The power value in the test results of the commercial propeller is the electrical power consumed, so the work done to the fluid should be found by considering the torque and speed of the propeller in the thrust test.

Table 2. Processing of commercial propeller test results

	Commercial Propeller						
Revolutions (rpm)	3746	4089	4358	4634	5215	5627	6177
Torque (Nm)	0,15	0,18	0,20	0,23	0,29	0,33	0,40
Thrust (g)	805	959	1093	1236	1561	1823	2228
Power (kW)	0.06	0.08	0.09	0.11	0.16	0.19	0.26
Power Thrust	13,42	11,99	12,14	11,24	9,76	9,59	8,60

Table 3. Numerical results of a biomimetic propeller

	Biomimetic Design Propeller						
Revolutions (rpm)	3746	4089	4358	4634	5215	5627	6177
Torque (Nm)	0,21	0,23	0,26	0,31	0,35	0,41	0,66
Thrust (g)	1080	1221	1310	1477	1825	2220	2623
Power (kW)	0,08	0,10	0,12	0,15	0,19	0,24	0,43
Power Thrust efficiency (g/W)	13,48	12,21	10,92	9,85	9,61	9,25	6,1

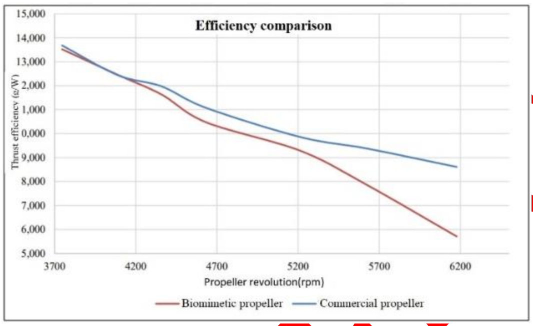

Figure 12. Comparison of propeller efficiencies

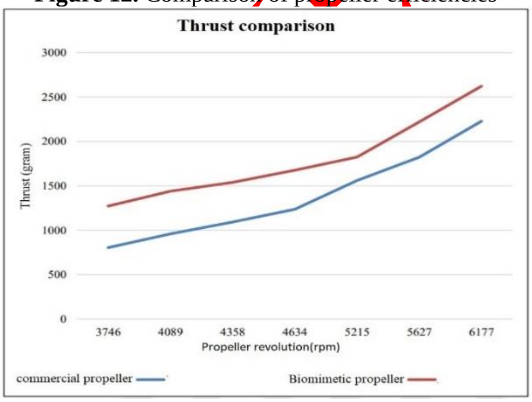

Figure 13. Comparison of propeller thrusts

4. CONCLUSIONS AND RECOMMENDATIONS

In light of the results obtained with the designed biomimetic propeller, it was improved by successive iterative analysis and efficiency-improving design updates. The design was tried to be improved by considering the interaction of the flow bundles with the boundary layer, comparison of the thrust obtained at the speed at which the analysis was performed with commercial propellers, pressure distribution, and reduction in blade tip vortices. The results obtained in this direction were compared with the values of a commercial product in a similar class, and it was observed that the biomimetic design was able to achieve the same thrust at lower speeds. Although there are margins of error in this numerical study, results close to the power consumption of the commercial product were obtained.

Although both propellers were compared at equal speeds, it was observed that the biomimetic propeller produced 1080 grams of thrust, and the commercial propeller produced 959 grams of thrust for the consumption of 80W, corresponding to equal propeller work. In this study, where numerical results are compared with experimental results, future studies are possible where experimental comparisons can be made by 3D printing the biomimetic propeller.

Since it will not be possible to drive the 3D printed propellers at speeds such as 3000 rpm since their strength is not very high, the commercial propeller should be purchased and tested for low speeds in a propulsion test system, and data should be obtained for comparison. Since the customers do not need data on low speeds in the test results of commercial products, this data is kept private.

The results were similar to those of other biomimetically designed propellers in the literature. The high speed obtained at lower speeds is a common point with previous studies. Although some increase in thrust efficiency was observed, unlike previous studies, this is likely to be an error due to simplifications in the numerical analysis. For verification, the propeller should be manufactured, and the results obtained by numerical analysis should be compared with an experimental study of a propeller manufactured from the same design. In light of this study, it is predicted that biomimetic propellers can reduce the noise caused by electric propulsion systems.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in their study do not require ethics committee approval and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS

Hüdayim BAŞAK: Yapılan tüm çalışmalar için danışmanlık yapmıı ve control sağlamıştır**.**

Ahmet TAVŞAN: Literatür, Modelleme ve sayısal analizleri yapmıştır.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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