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Impacts of Design Parameters on Aerodynamic and Aeroacoustics Properties of a Propeller

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Abstract - *Propeller is a key component of a UAV, which helps with the vertical lift off by generating thrust. The analysis of lift, thrust and drag force is a highly complicated process as there are various parameters and boundary conditions that need to be considered to get accurate results. Various methods of simulating the fluid flow, velocity stream line, pressure counters, etc have been used in the past and various new methods for more accurate results are being built currently. This advanced software also help optimize the geometry parameters along with the selection of material and the practical usage of a propeller. These optimizations lead to better understanding and performance of Aerodynamic and aeroacoustics properties. This paper puts forth the relationship between Aerodynamic and aeroacoustics properties with respect to the size, shape and configuration of the drone.*

Key Words: propeller, angle of attack, coefficient of lift, coefficient of drag

1.INTRODUCTION

An UAV or Unmanned Aerial Vehicle, normally known as a Drone, is an automated airplane. It requires no human pilot. Flight can either be performed autonomously or with the help of a remote control from a ground station. Different needs and purposes are served by different types of UAVs. These UAVs vary in shape, size and configuration. Nowadays, the use of well-known equations during the design and fabrication process is not enough. A new design should consist of wide range of improvements and problem-solving capabilities. The aim of this paper is put forth an overview on the Aerodynamic and aeroacoustics properties of a drone and to show how they vary along with thrust, lift and drag.

Aerodynamics can be defined as the branch of physics in which the motions of the gaseous fluids interacting with the bodies is studied along with the forces acting on it. The Wright brothers' first manned flights. This marked the beginning of Aerodynamics. Ever since then, it has become crucial to the building of automobiles and aircraft along with ships, trains, rockets and missiles and so on which often have to withstand strong breeze. An aerodynamic automobile is one whose design assists it to attain the highest velocity and most productive utilization of fuel. We may casually call any sleek vehicle design aerodynamic. In actuality aerodynamics is rehearsed not by artistic designers but instead by highly experienced scientists, and lives depend on the quality of work. Aeroacoustics is a section of acoustics that deals with the study of noise production through either aerodynamic force interacting with its surfaces or turbulent movement of fluid. Acoustics is a division of physics that involves the study of topics such as sound, vibration, infrasound and ultrasound along with mechanical waves in all 3 states. The modern study of aeroacoustics can be said to have taken birth with the 1st publication of Lighthill in the decade 1950. UAV thrust is the quantity of vertical force a drone can produce when it is at full throttle. Lift of an UAV can be defined as the total load carrying capacity. Drag is the resistive force that is acting on the air foil of the propeller. Lower the drag, better the performance. Similarly, higher the lift, greater the performance. The most optimized condition would be to achieve highest possible lift to drag ratio. This paper will shed light on the variation of the aerodynamic and aeroacoustics properties of a drone with respect to propeller size, shape and configurations. It also speaks about a few of the bio inspired ideas for reduction on noise caused by the rotor propeller.

1.1. Principle of design of aerofoil

For the analysis of performance of a propeller, many theories can be considered. Some of them include Classical Momentum theory, Panel Method, Blade Element Theory, Lifting Line theory, Disk-Actuator theory, Blade Element Momentum Theory and Vortex Lattice theory.

Classical Momentum theory

It is well known that for driving powered aircrafts, propellers are commonly used. The operation of such a propeller can be defined by this theory. In this theory we need to assume that the production of thrust is because of the pressure difference i.e., static pressure difference across the propeller. There are some more assumptions that need to be considered,

- There needs to be constant pressure and velocity maintained over the surface of the disc.
- When air flows straight through the disc, there has to be no rotation.
- The flow has to be a stream line flow.
- The flow needs to be incompressible.

Blade element momentum Theory

Gustafson and Gessow were the first to introduce the Blade Element Momentum Theory in the year 1946. It is a theory which is considered for hovering rotors. It can be said to be a combination of Blade Element Theory and Momentum Theory. It can also be said that this theory is an upgraded version of the Blade element momentum theory. It was used to find out the distribution of flow (inflow) of air around the blade. For this theory the following assumptions needs to be considered.

- The blade needs to be considered as a disc that acts like an actuator.
- Conservation of mass, conservation of energy and conservation of energy needs to be applied.

In this theory the induced velocities are considered for calculations. The total velocity is decomposed induced velocities.

The thrust to power ratio is generally calculated by considering the coefficient of drag and coefficient of thrust force. These are usually generated on the propeller blade's surface. This theory also has its demerits as it has some complexities that limits its usage

2. LITERATURE REVIEW

2.1. Variation in Winglet Wingtip Design

Erdem Yilmaz and Junling Hu [1] design a propeller by adding a winglet (Fig. 1) feature to a original DJI Spark propeller design with the aim of improving thrust value and reducing noise level. They stated that the noise produced was a matter of concern to the user and residents. More research was being conducted on the designing of propellers with lesser noise. Based on previous studies they developed a new design with a winglet where the blade is bent by 25 degrees. The CAD model of the original design and the winglet design was generated in SOLIDWORKS and CFD stimulation was carried out in SIMSCALE. The rotational speed was kept constant. The CFD analysis showed that the pressure distribution on the lower surface was higher than that on the top surface. The velocity field showed that the vortex was created below the blade. They observed that the thrust generated was higher and the vortex was observing to be more intense. They concluded that the thrust generated by the winglet design was 21% more than the original propeller design. Thus, when this winglet design is used at lower rotational speed, noise can be reduced.

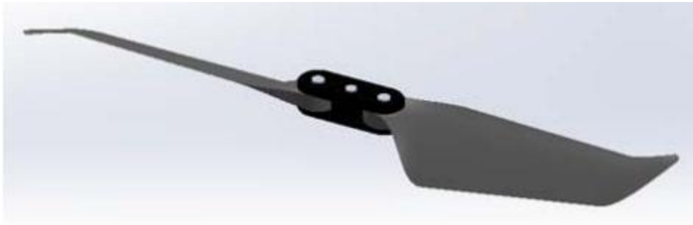

Fig -1: Modified propeller [1]

Eren and Nafiz [2] studied the effect of aerodynamic performances based on the design of wingtip (Fig. 2). They aimed at producing results with higher lift-drag ratio with lower power consumption. With regards to the objective, they studied 4 wingtip configurations. They concluded that the blended type wingtip had better aerodynamic efficiency.

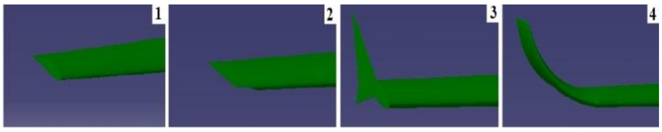

Fig-2: The Three Wingtip Modifications [2]

Zaimi and Zulkifi [3] analyzed the aerodynamic efficiency with the change in the wingtip modification, angle of attack and airspeed. It involved 4 wing designs, a blended winglet design and 3 modified winglet designs at 15deg 30deg and 45deg. They were tested under 4 different air speeds and 4 different angles of attack. It was seen that the lift-drag ratio increases with the increase in the angle of attack. It was concluded that the introduction of wingtip helped in the reduction of the vortex which is usually found at the tip of the wing. The result from the analysis provided that the wingtip with 45deg modification was found to have the highest lift-drag ratio.

2.2. Deformable Propeller

Nguyen and Loianno [4] aimed at designing a propeller (Fig. 3) that could absorb impact forces upon collision. Safety of humans is jeopardized by the sharpness of high rotating propellers. With this in mind they designed a propeller based on a dragonfly wing. The propeller had a deformable segment and a bending segment. Upon experimentation, it was found that the thrust generated by the deformable propeller was lower than the rigid propeller. Upon collision testing it was found out that the deformable propeller was stable and did not break easily upon collision.

Fig- 3: Deformable Propeller [4]

2.3. Normal, Bullhorn and Hybrid Bullhorn Propeller

Bardai, Ahmad Maulan, Azri Nazarain Afandi, and Mohammad Iqmal Mohd Ali [5] aimed at analyzing the effect of different shape of propellers. They generated 3 different shapes namely normal, bullhorn and hybrid bullhorn propeller. By keeping the rotational speed constant and varying the airspeed, they compared the values of the lift drag coefficients of the three propellers. CATIA was used to generate the 3 models and ANSYS was utilized for CFD analysis. They concluded that the difference in the pressure on the top and bottom side of the propeller created the lift necessary. It was seen that thrust and drag vary with different shapes of propeller at different airspeeds. Thus, it is critical to select the shape that is best suitable for the required working conditions.

2.4. Bio-mimetic Propeller

Noda R., Nakata T, Ikeda T, Chen D, Yoshinaga Y, Ishibashi [6] worked on a bio inspired propeller for noise reduction (figure 4). It was observed that addition of edge fringes along the edge of the propeller was found to be effective in suppressing the noise.

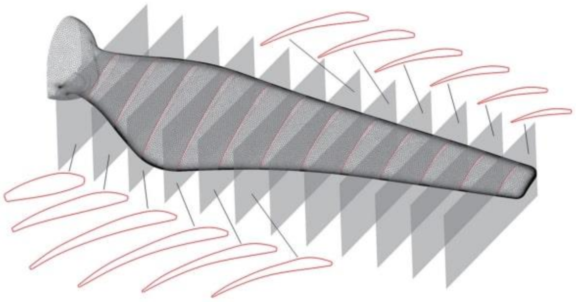

Fig-4: Bio-inspired Propeller [6]

2.5. Propeller with Bumped Leading Edge

ElGhazali and Dol [7] suggested that the performance of a UAV can be improved by modifying the profile of the propeller. They state that the performance of the UAV can be enhanced by studying the improvised propeller design (Fig. 5). They performed a numerical investigation of the modified propeller with reference to the same propeller using ANSYS Fluent and compared the lift- drag coefficients under the same boundary conditions and different angle of attack. The objective was to observe how the improved lift would extend the time of flight and increase payload with lesser power consumption. The propeller was geometrically modified by implementing ducts, increasing aspect ratio and introducing leading edge bumps. The ducting was considered to increase the lift and reduce drag enhancing the flight time. The design of the ducted propeller creates lower pressure at the inlet relative to the outlet. The difference in pressure increases the thrust value. This is only useful in hovering conditions and not in forward flights. However, the barriers created the ducts limits the air intake and rather than increasing the thrust generated, it reduces it. Aspect ratio is another parameter that can improve the design of the profile. With the increase in aspect ratio, it was seen that the overall pressure losses can be reduced. It was presented that the leading edge had two advantages; first it is stall mechanism is delayed, preventing the drone from dropping from a height and crashing. Second it was seen that the propellers produced more thrust with lesser power consumption and the time of flight was increased. It was concluded that the performance of the modified geometry i.e., sinusoidal leading edge was better compared to the straight leading edge with an increase in the lift force and lift coefficient and increased payload and flight time.

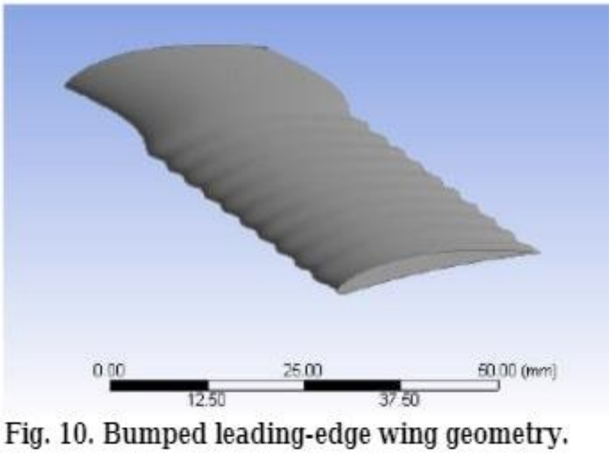

Fig-5: Wing Geometry with Bumped Leading Edge [7]

2.6. Saw Tooth Serration Type Propeller

Ning, Zhe, Richard W. Wlezien, and Hui Hu [8] conducted a study where they applied saw tooth serrations on the edge of the profile of the propeller to attain noise attenuation (Fig. 6). The experiment was conducted on 3 different serration sizes at low Reynolds number and hover conditions. The aerodynamic and aeroacoustics properties were measured in this paper. The results were compared with a baseline propeller. They state that the noise generation is said to be a major problem for both human life and wild life and there is a need to reduce it. They defined the serration with parameters like height, amplitude, inclined angle and width. It was stated that the ratio of half of the height to the boundary thickness should be more than 0.25, the inclined angle less than 45 deg and width to height ratio should be less than 4 for the serrations to work efficiently. Three different serrations of width to height ratio 0.6, 0.9, 1.2 were selected. All three propellers were subjected to almost same rotational speed and in the same direction. The experiment was conducted in a low turbulent wind tunnel for two conditions namely hover flight and forward flight (with different pitch angles). The experiment to measure aerodynamic forces was conducted and it was seen that there was no difference in the aerodynamic performance of the baseline propeller and the 3 different propellers with different serration sizes. It was also observed that the power input required to generate a thrust 3N was the same in all the 4 cases. Flow field measurements showed that the flow field of three propellers when compared with baseline propeller, they were found to be alike and a slight variation was found in the velocity distribution at a selected distance. It was stated that the same mean flow was generated at both forward and hover flight conditions. The sound measurements yielded that noise attenuation was attained by the serrations at higher frequency and its affect was found to be increasing with increase in the size of the serrations.

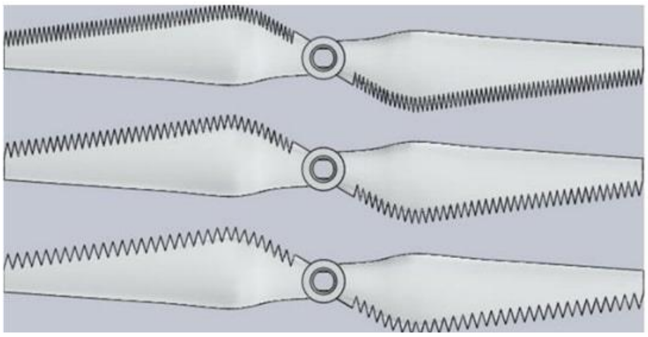

Fig-6: Different Serrations added [8]

2.7. Cicada Shaped Propeller

Zhe Ning and Hui Hu [9] designed a bio inspired propeller that took the shape of a cicada (Fig. 7) which was tested for aerodynamic and aeroacoustics properties and compared with respect to a base line propeller. They state that the planform of the cicada wing was found to differ in geometries when compared to a traditional propeller. The designed planform area was considered to be the same, weight and cross-sectional shape. The analysis with respect to the baseline propeller was conducted in hover conditions. Particle Image Velocimetry system was utilized to study the field of flow in an anechoic chamber. The design was generated to accomplish a thrust of 3N. The experiment was conducted at varying speeds having a range of 0 to 6000 rpm for both propellers. It was seen that the thrust of 3N was generated by both the propellers at the same power consumption. The rotational speed of the modified wing was lower than that of the baseline propeller indicating that the thrust coefficient was larger in case of the bio inspired propeller. The aeroacoustics testing was conducted in hover condition. It was observed that the modified propeller generated lower sound pressure level when compared to a baseline propeller indicating that it has better noise attenuation properties.

Fig-7: Propeller shaped like cicada [9]

2.8. Wavy Rotor Design

Yang, Y., Liu, Y., Hu, H., Liu, X., Wang, Y and Arcondoulis [10] designed a wavy rotor which is a modification of a baseline rotor (Fig 8). The aerodynamic and aeroacoustics properties were tested. They state that the wavy planform could increase the aerodynamic efficiency and also enhance noise reduction. The rotor used was of eHANG Ghost Drone. The material of both the rotors was chosen to be Aluminum 6068. The wavy pattern was generated by moving alternative cross sections towards the leading edge. The experiment was conducted in a low-speed anechoic wind tunnel. The speed of the wind tunnel was set at 15m/s and rpm values of the range 3000 to 7200 were tested. It was seen that thrust generated by the wavy rotor was almost similar to that of the baseline rotor at the given range of rotational speeds. It was also observed that the wavy rotor generated higher thrust at lower rotational speeds when compared to the baseline propeller and the aerodynamic performance is not affected by the wavy planform. The noise reduction was observed in a higher frequency at all RPM ranges. It was said to be suitable for forward flight condition.

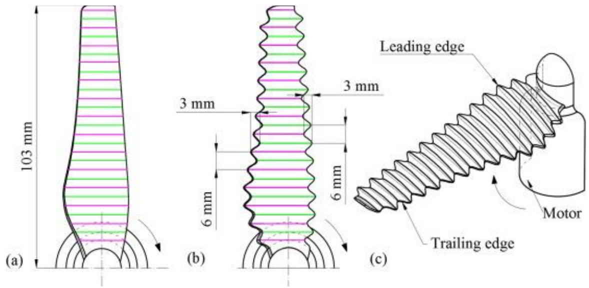

Fig-8: Wavy rotor [10]

2.9. Propeller efficiency

John B. Brandt et al [11], based on the propeller chord at 75% propeller blade station it was noted that UAVs uses propeller that operates under Reynolds number ranging from 5000 to 100000. More demonstration was done at University of Illinos to assess the efficiency of propeller used under these conditions. The diameter range of the propellers which was used were 9 inches to 11 inches. 79 set of propellers were used for the test. Varying velocities were considered for the windmill during the test period, which helped overcome the wide range of ratios till the windmill state was reached i.e., zero thrust condition. To study the consequence of propeller due to varied Reynolds number, a range of 1500rpm to 7500rpm were used. The outcome was observed to vary from 0.28 to 0.68, that is worst and best condition respectively. It was thus observed that the performance of UAV and aircraft operation is affected by the propeller design.

2.10. Static Structural Analysis, Modal analysis and Harmonic Analysis of quadcopter

Javir A V, Pawar K, Dhudum S, Patale N & Patil S [12] worked on a paper concentrating on the aerodynamic impacts of quad copter. It gives out all the features of quad copter varying from electronic components used to Mechanical Designs. It gives accurate solutions with respect to weight of parts and their respective costs. Through different formulas and research paper it provides clear knowledge for selecting appropriate components. Along with this, FEA was conducted in order for the frame to resist the load acting on the copter. Three analyses were done on the assembly: Static Structural Analysis, Modal analysis and Harmonic Analysis. The results of Static Structural Analysis showed that the minimum deformation was 0 m and the maximum deformation was 1.317e-006 m. The deformation was acceptable. Modal analysis is required to find out the natural frequencies of different modes. Minimum frequency was 0 Hz and Maximum frequency obtained was 637.12 Hz. Ten modes were considered for getting the results. Harmonic analysis is used to foretell the steady/constant state dynamic response of a structure put through sinusoidal fluctuating loads. For different stress and different frequencies Stress amplitude and Deformation amplitude was noted down. The deformation and stress outcomes for various types of analysis were in limit range. Hence, it was deduced that the design of quad copter is fully safe.

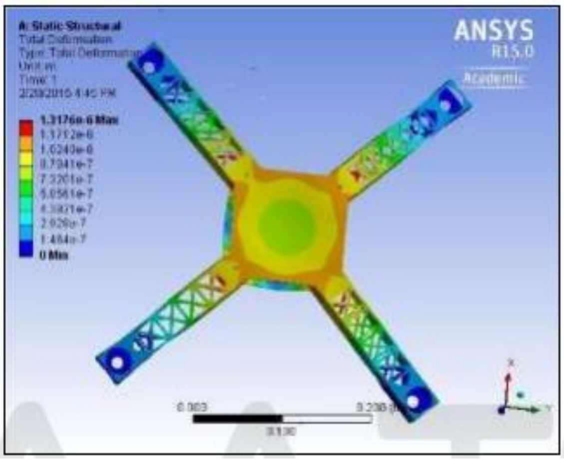

Fig-9: Total Deformation Analysis [12]

2.11. Discover the weight and stress of quadcopter frame

Kuantama E, Craciun D & Tarca R [13] in this paper designed a quadcopter using Finite Element Analysis (FEA) and SolidWorks to discover the weight and stress of quadcopter frame. Computer-Aided Design (CAD) was used to help in the optimization, modification, creation and analysis of the design. The design of quadcopter which was done by solid works has a good rigidity. And the size was also well-matched with the type of propeller used. The rigidity of plastic-based frame with a weight of 560gm has a greatest displacement of 3.3mm for 52N thrust on the wing frame part. For reducing the disturbances created by propeller we can select smaller size propeller or cutback the voltage on rotor to reduce the produced thrust. The maximum angular velocity of 7680rpm with supply of 12v voltage generated 21N thrust. And wind velocity of the propeller was 1m/s. For the early analysis, the produced thrust can be calculated using fluid dynamic theory and momentum. However, to obtain an improved outcome, an experimental method is favored.

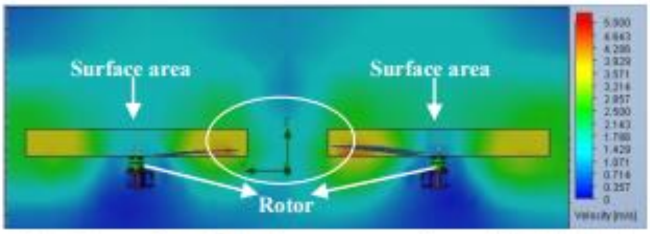

Fig- 10: Iso-surface airflow between propellers with 7680 (rpm) [13]

2.12. Relationship between airspeed and propeller thrust coefficient

T. Oktay et al [14] in this paper CFD inspection of Quadcopter propeller has been carried out to find out the relationship between airspeed and propeller thrust coefficient. The analysis was done by means of Navier-Stokes solver (Ansys Fluent v17.2) by using K-Omega SST turbulence model. The geometry chosen was of 11 inches diameter and 4.7 inches pitch diameter. It is also known as 11*4.7 propeller. The domain was divided into 2 parts; Static and rotating domains. The tip speed of the propeller calculated was 0.213 Mach number at 5000 rpm angular velocity which was used in this study. Numerical predictions of thrust coefficient were found to be in good agreement with experimental results. And it showed difference approximately ranging between 14%-18%. In addition to the above, thrust coefficient was found to decrease with increase in airspeeds. Numerical predictions were getting closer to experimental results at lower airspeeds.

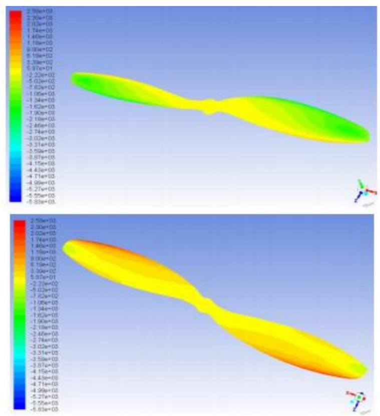

Fig-11: Static pressure (Pa) distribution on propeller surface at 2.4 m/s airspeed:

(top) Suction side (bottom) pressure side [14]

2.13. Drag and thrust co-efficient considered inter-rotor interferences

Nguyen et al. [15] presented a paper in which he considered inter-rotor interferences acting at low Reynolds number and calculated drag and thrust co-efficient after initial presentation of analytical model. This model was based on momentum and blade element theories. Open-type wind tunnel analysis was considered for this study. Considering an angle of attack of 0 degree with speed of 6 m/s, the analysis was conducted on single rotor. Tandem rotor experiment was later on conducted with an objective to attain inter-rotor interference effect. The results of this study showed good overlap in values of theoretical and experimental models with 0 degree to 18-degree, angle of attack and airspeed between the range of 0 m/s to 10m/s. Moreover, one factor that indicated inter-rotor interference was the thrust co-efficient of rare rotor which was noted to be 11% lower than the front one approximately. The decline in rear rotor thrust because of the interference of front rotors degrades hovering performance.

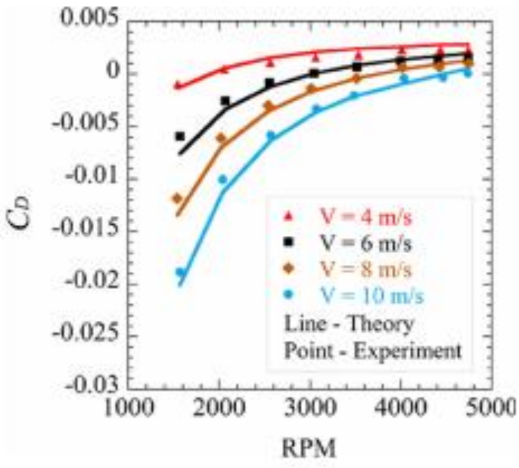

Fig-12: Thrust coefficient during forward flight at angle 18 degree [15]

3. CONCLUSION

In this review paper, we have studied and summarized researches done in recent years on properties of drone. The main focus being aerodynamic and aero acoustic properties. Another key observation was that, the CFD methods have proven to be effective for numerical simulation of many types of propeller geometry. It can clearly be noticed that the design parameters of a propeller have major impact of the Aerodynamic and Aeroacoustics the performances. To finally conclude, research is still being conducted with one main objective being to increase the efficiency by varying design parameters.

REFERENCES

[1] Yilmaz, E., & Hu, J. (2018, April). CFD Study of Quadcopter Aerodynamics at Static Thrust Conditions. In Proceedings of the ASEE Northeast 2018 Annual Conference, West Hartford, CT, USA (pp. 27-28).M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.

[2] Turanoğuz, E., & Alemdaroğlu, N. (2015, June). Design of a medium range tactical UAV and improvement of its performance by using winglets. In 2015 International Conference on Unmanned Aircraft Systems (ICUAS) (pp. 1074-1083). IEEE.K. Elissa, "Title of paper if known," unpublished.

[3] Zaimi, M. Z. M., & Zulkifli, M. A. Analysis on the Aerodynamic Efficiency of Modified Blended Wingtip.

[4] Nguyen, D. Q., & Loianno, G. (2020, May). Towards Design of a Deformable Propeller for Drone Safety. In 2020 3rd IEEE International Conference on Soft Robotics (RoboSoft) (pp. 464-469). IEEE.

[5] Bardai, A. M., Afandi, A. N., & Ali, M. I. M. (2019). Analysis on Propeller Design for Medium-Sized Drone (DJI Phantom 3).

[6] Noda, R., Nakata, T., Ikeda, T., Chen, D., Yoshinaga, Y., Ishibashi, K., ... & Liu, H. (2018). Development of bio-inspired low-noise propeller for a drone. Journal of Robotics and Mechatronics, 30(3), 337-343.

[7] 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.

[8] Ning, Z., Wlezien, R. W., & Hu, H. (2017). An experimental study on small UAV propellers with serrated trailing edges. In 47th AIAA Fluid Dynamics Conference (p. 3813).

[9] Ning, Z., & Hu, H. (2017). An experimental study on the aerodynamic and aeroacoustic performances of a bio-inspired UAV propeller. In 35th AIAA Applied Aerodynamics Conference (p. 3747).

[10] Yang, Y., Liu, Y., Hu, H., Liu, X., Wang, Y., Arcondoulis, E. J., & Li, Z. (2020). Experimental study on noise reduction of a wavy multi-copter rotor. Applied Acoustics, 165, 107311.

[11] B. Brandt John, "Modeling of Flow Around a Marine Propeller Using a Potential Based Method," 2011.

[12] A. Javir, K. Pawar, S. Dhudum, N. Patale, S. J. J. o. A. R. i. M. Patil, and C. Engineering, "Design, analysis and fabrication of quadcopter," vol. 2, no. 3, pp. 16-27, 2015.

[13] Kuantama, E., Craciun, D., & Tarca, R. (2016). Quadcopter body frame model and analysis. Ann. Univ. Oradea, 71-74.

[14] Oktay, T., & Eraslan, Y. (2020). Computational Fluid Dynamics (Cfd) Investigation Of A Quadrotor Uav

Propeller. In International Conference on Energy, Environment and Storage of Energy (ICEESEN 2020) (pp. 1-5).

[15] Nguyen, D. H., Liu, Y., & Mori, K. (2018). Experimental study for aerodynamic performance of quadrotor helicopter. Transactions of the Japan Society for Aeronautical and Space Sciences, 61(1), 29-39.