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Fluid-structure coupled simulation-based investigation and thrust/efficiency calculation for a UAV twin-blade propeller

Metin UZUN[1], Hasan ÇINAR[2], Abdullah KOCAMER[3], Sezer ÇOBAN*[4]

[1,2,3,4*] Iskenderun Technical University, Department of Airframe and Powerplant Maintenance, 31200, İskenderun, Hatay, Türkiye.

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Keywords

Propeller aerodynamics,
Thrust,
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Propeller design

Abstract: This study presents a coupled numerical investigation consisting of fluid and structural analysis for a UAV propeller. Flow and structural analysis are carried out in ANSYS Fluent and Static Structural modules, respectively. The mechanical properties of the propeller are investigated for Plastic ABS and Carbon Fiber (395 GPA) materials at 2000, 6000, and 10000 rpm rotational speeds. Consequently, it is observed that the total deformation and equivalent elastic strain of Carbon Fiber (395 GPA) material are less at all rotational speeds. In addition, the thrust and power of the propeller are calculated for these rotational speeds and their change in UAV forward speeds (1, 5, 8, 10, and 12 m/s) is examined at 6000 and 10000 rpm. Accordingly, it is observed that the power and thrust of the propeller decreased with the increase in the forward speed of the UAV at constant propeller rotation speed. It has been observed that the propeller produces 5 N thrust at 6000 rpm. In addition, in 6000 rpm and 0.3 advance ratio, the propeller provided approximately 65% efficiency.

Çift palli bir insansız hava aracı pervanesinin, akışkan ve yapısal tabanlı simülasyonu ile itki/verim hesaplaması

Anahtar Kelimeler

Pervane Aerodinamiği,
İtki,
İHA,
Pervane Tasarımı

Öz: Bu çalışma, bir İHA pervanesi için akışkan ve yapısal analizden oluşan birleşik bir sayısal araştırma sunmaktadır. Akış ve yapısal analiz sırasıyla ANSYS Fluent ve Static Structural modüllerinde gerçekleştirilmiştir. Pervanenin mekanik özellikleri Plastik ABS ve Karbon Fiber (395 GPA) malzemeler için 2000, 6000 ve 10000 rpm dönüş hızlarında incelenmiştir. Sonuç olarak, Karbon Fiber (395 GPA) malzemenin toplam deformasyonunun ve eşdeğer elastik gerinimlerinin tüm dönüş hızlarında daha az olduğu gözlenmiştir. Ayrıca bu dönüş hızları için pervanenin itkisi ve harcadığı güç hesaplanarak İHA ileri hızlarındaki (1, 5, 8, 10 ve 12 m/s) 6000 ve 10000 rpm'deki değişimleri incelenmiştir. Buna göre sabit pervane dönüş hızında İHA'nın ileri hızının artmasıyla pervanenin harcadığı güç ve itkisinin azaldığı görülmektedir. Pervanenin 6000 devirde 5 N itki ürettiği gözlemlenmiştir. Ayrıca 6000 rpm ve 0.3 ilerleme oranında pervane yaklaşık %65 verim sağlamıştır.

*Corresponding Author, email: sezer.coban@iste.edu.tr

1.Introduction

The propeller is an important component in the propulsion system of an unmanned aerial vehicle, which affects the performance and power consumption of the UAV [1,2]. The aerodynamic performance of propellers directly affects many parameters such as flight time, range, and power consumption of UAVs [3,4]. For these reasons, examining the efficiency and thrust production of the propeller in terms of aerodynamics is among the important research topics in unmanned aerial vehicles.

The aerodynamic performance of propellers can be studied with experiments in a wind tunnel or numerical studies by using computational fluid dynamics (CFD) [5]. The equations used for the aerodynamic performance analysis of the propellers are given in Equations 1-4 [6,7]. The advance ratio (J), thrust coefficient (C_T), power coefficient (C_P), and efficiency (η) of the propeller are expressed by Equations 1,2,3, and 4, respectively. Propeller measurements and calculations are non-dimensionalized to acquire the performance data. The power and thrust coefficient can be calculated by using CFD data for a propeller (Equation 1-2). In these equations, V (m/s), T (N), ρ (kg/m3), D (m), and n (rpm) are the free stream velocity, the thrust produced by a propeller, the density of the air, the diameter of a propeller, and the rotational speed of the propeller, respectively. For hovering flight phases, J becomes zero (because V is zero).

$$\mathbf{J} = \frac{\mathbf{V}}{\mathbf{nD}} \tag{1}$$

$$\mathbf{C_T} = \frac{\mathbf{T}}{\boldsymbol{\rho}\mathbf{n^2D^4}} \tag{2}$$

$$\mathbf{C_P} = \frac{\mathbf{P}}{\boldsymbol{\rho}\mathbf{n^3D^5}} \tag{3}$$

$$\boldsymbol{\eta} = \mathbf{J}\frac{\mathbf{C_T}}{\mathbf{C_P}} \text{ or } \boldsymbol{\eta} = \frac{\mathbf{TV}}{\mathbf{P}} \tag{4}$$

Many researchers have presented various numerical aerodynamics studies for UAV propellers using CFD to increase the efficiency of the propeller. For instance, authors in Reference [8] examined the effect of propeller position on the performance of a fixed-wing 25 kg small-class UAV by using CFD. In Reference [5], the aerodynamic performance of the Small APC Slow Flyer Propeller has been examined by CFD and verified with experimental data. Similarly, authors in References [9-11], a literature search was conducted for the calculation of quadrotor unmanned aerial vehicles' propeller thrust and power coefficient and the effects of rotational speed and airspeed on the thrust coefficient for a propeller were investigated using CFD. In Reference [12], the performance of different propeller types at different angles of attack for a solar cell HALE-type (high altitude long endurance) UAV was investigated. In Reference [13] , the authors conducted CFD analysis in terms of thrust by adding a winglet to the DJI Spark drone propeller. As a result, they achieved a 21% increase in propeller thrust. In reference [14], the authors conducted aerodynamic shape optimization studies on a UAV propeller in OpenFOAM, resulting in an improvement in the hover performance of this propeller. In reference [15], the structural behavior of the UAV propeller is studied for different material types by using ANSYS software.

According to the literature review presented, it is seen that the focus of propeller numerical analysis studies is propeller performance improvement with the help of CFD. In this context, in this study, to predict aerodynamic performance, numerical analysis studies of a propeller were carried out that can be used in small-type unmanned aerial. The power consumption and thrust production of this propeller at variable speeds were calculated with the help of CFD. In addition, the efficiency, power coefficient, and thrust coefficient of the propeller were calculated using CFD. For this propeller, thrust is calculated for the propeller's constant rotation and the UAV's speed in the longitudinal flight of the unmanned aerial vehicle. The contribution of this study to the literature is to examine the aerodynamic and structural performance of the propeller with a coupled simulation technique consisting of CFD and FE. Thus, using the results obtained from CFD, the mechanical performance of the propeller was investigated for two different material types (Plastic ABS and Carbon Fiber (395 GPA)) in the structural module of ANSYS software. Another contribution is to investigate the thrust production and power consumption of the propeller according to the forward speed of the UAV.

The study is organized as follows. Firstly, the methodology of the study is presented in section 2. Afterward, in section 3, by conducting CFD and FE (finite element) combined simulation studies of the propeller, thrust and efficiency are calculated by investigating pitch angle and rotational speed change. Finally, the results of this study are summarized in the conclusion section.

2.Methodology

The general purpose of this study is to examine the performance of a propeller used in small type unmanned aerial vehicles by considering the computational fluid dynamics and structural analysis together. In this context, Fluent and Static Structural modules were used within the ANSYS package program. The topology of the coupled analysis using these two modules is presented in Figure 1. Fluid simulations were carried out in the Fluent module and the mechanical properties of the propeller were examined by transferring the results to the Static Structural module.

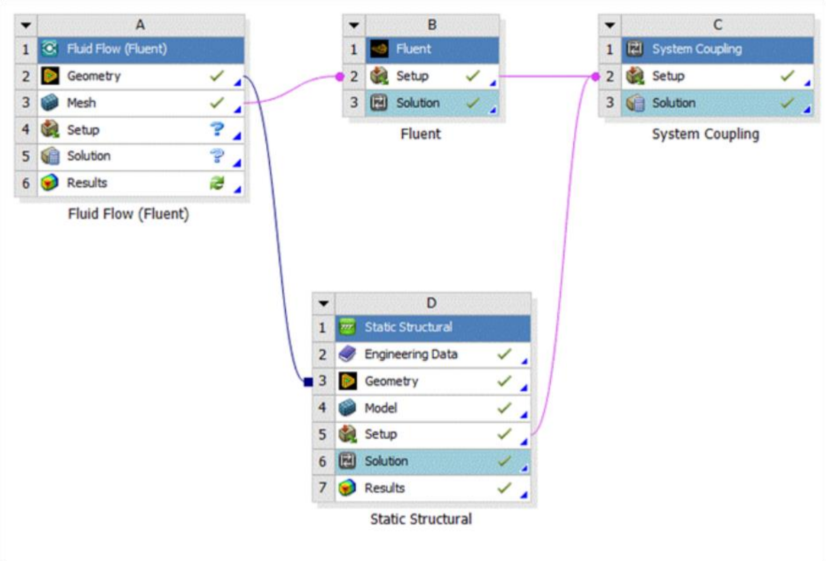


Figure 1. Systematics of coupled analysis consisting of CFD and structural

Propeller designs are generally based on momentum theory, blade element theory, and hybrid blade element momentum theory [21]. The propeller investigated in this study was designed according to the hybrid blade element momentum theory, as explained in detail in the Reference [21]. The thrust that this propeller can produce and its consumption power have been determined through CFD analysis. In the CFD study, the rotating flow field of the impeller is shown in Figure 2. Accordingly, the diameter and thickness of the rotating flow area were determined as 1.1 and 0.4 times the propeller diameter (28 cm), respectively. The flow domain and its dimensions used in CFD simulations are given in Figure 3. Here again, the dimensions of the flow domain are adjusted to be multiples of the propeller diameter. In addition, the picture of the mesh created for the propeller is given in Figure 4.

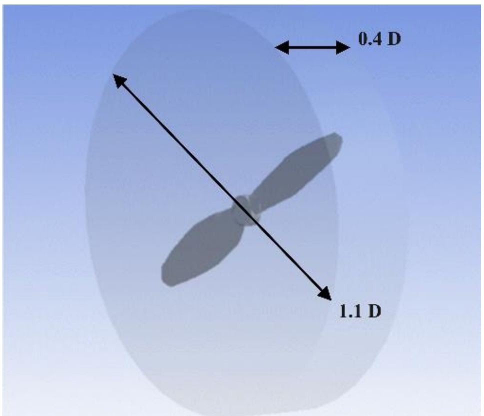


Figure 2. The rotating flow field in which the impeller is located.

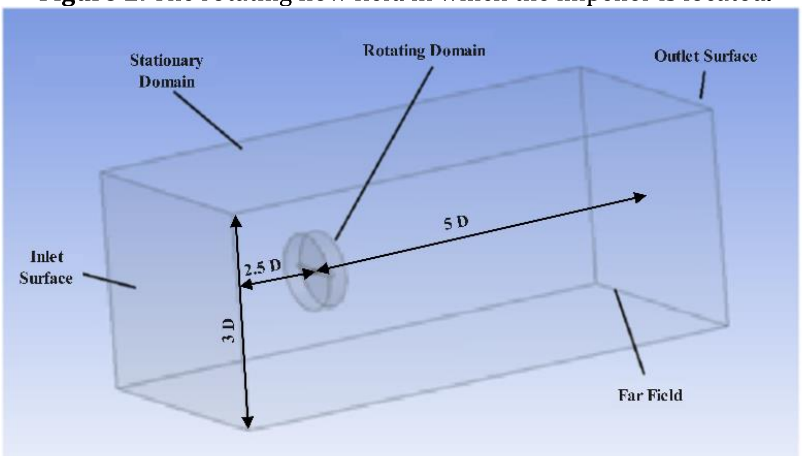


Figure 3. Flow domain of CFD simulation.

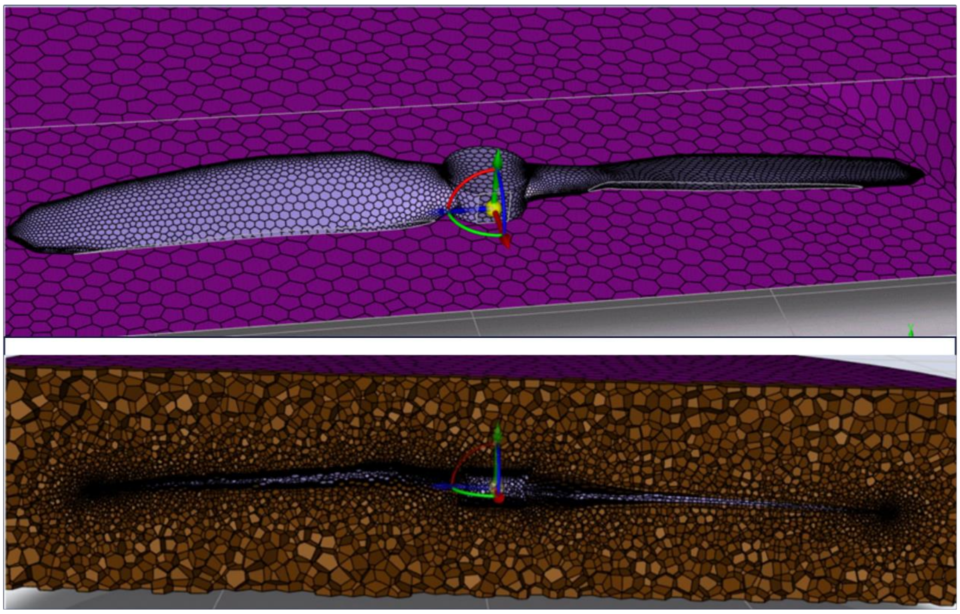


Figure 4. Mesh structure created for the propeller flow field.

Ensuring an irreproachable transition between surface and volume from different mesh element types has always been one of the important problems for simulation programs. ANSYS has started to use polyhedral elements to solve such problems. Polyhedral mesh elements can acquire any shape needed to create a conformal mesh. This property ensures that the transition zone is filled with fewer and higher-quality elements, resulting in a more acceptable result. Polyhedral elements figure out simulations with fewer computational burdens, and with more accuracy. In CFD simulations, the poly-hexcore mesh can improve the resolution time by 20 to 50 percent over a hexahedral core or polyhedral core mesh with the same accuracy [22]. Therefore, poly-hexcore mesh elements were preferred in this study, especially since the use of poly-hexcore mesh elements in the latest versions of ANSYS allows the solutions to be more accurate and to get solutions in a shorter time. The properties of the mesh structure created in the study are summarized in Table 1. In addition, the results of the mesh independence tests are given in Figure 5.

Table 1. Specification of the mesh structure.

Minimum Element Size	0,00005 m	**Skewness (max)**	0,72599
Number of Elements	2120212	**Growth Rate**	1,12
Maximum Size	0,1 m	**Curvature Normal Angle**	18°
Orthogonal Quality	0,2702	**Mesh Method**	Poly-hexcore

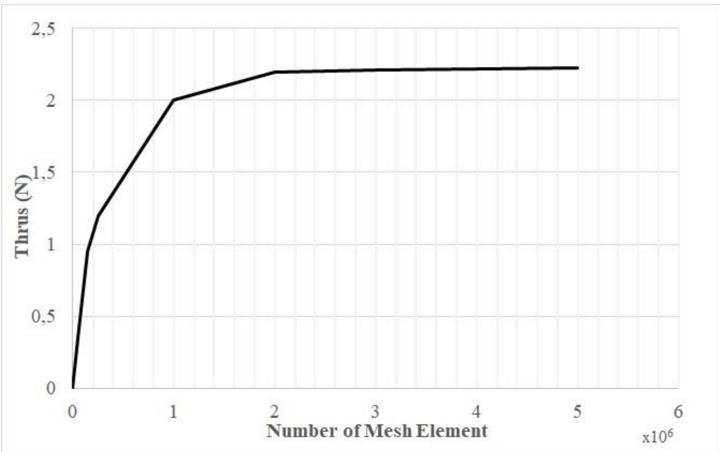


Figure 5. The mesh independence test results

3.Results and Discussion

The design rotation speed of the propeller investigated in this study is 6000 rpm. In other words, it is aimed to reach maximum efficiency at this speed. For this reason, the results presented in this study are presented at design (6000 rpm), lower limit (2000 rpm), and upper limit (10000 rpm) rotational speeds. In addition, these lower and upper limit rotational speeds are determined according to the working range of this propeller. The efficiency, thrust, and consumption power of the propeller were calculated by using Equations 1-4 given in the introduction and the data obtained from the CFD simulations.
The numerical results of the propeller consisting of plastic ABS and Carbon Fiber (395 GPA) materials are given at 3 different rotation speeds (2000, 6000, and 10000 rpm) in Table 2. Accordingly, it was observed that the total deformation of the propeller was big approximately 270%, 224%, and 280%, respectively, at speeds of 2000, 6000, and 10000 rpm for Plastic ABS material than for Carbon Fiber /395 GPA) material. In other words, the total deformation rate of the two materials was approximately 3.5 at these 3 rotational speeds. Similarly, in terms of equivalent elastic strain values, it has been observed that Plastic ABS material provides higher values at all rotation speeds. In addition, the equivalent elastic strain value increased with the increase in rotation speed for each material. When Table 2 is examined, it is seen that the total deformation and Equivalent Elastic Strain values are more dominant in abs material, but shear stress is higher in carbon fiber material at each rev/min. When the regions where the maximum shear stress occurs in the simulation images are examined, it is observed that for carbon material it is in a small area at the blade connection points, and for abs material it is almost the entire blade surface.

Table 2. The mechanical properties of the propeller according to the material and rotational speed.

Material	Number of revolutions (rpm)	Total deformation (m)	Equivalent Elastic Strain	Maximum shear stress (Pa)
Plastic ABS	2000	0,00054195	0,00017201	1,44E-05
Carbon Fiber (395 GPA)	2000	0,0001465	0,00007996	0,000019197
Plastic ABS	6000	0,0044837	0,0015672	1,41E-06
Carbon Fiber (395 GPA)	6000	0,001384	3,3625E-06	1,8235E-06
Plastic ABS	10000	0,01455	0,0045508	0,0065082
Carbon Fiber (395 GPA)	10000	0,0038284	0,0020897	5,0062E-06

In this study, thrust production and power consumption according to the rotational speeds of the propeller examined numerically are given in Figure 6. Accordingly, it has been observed that the thrust production and consumption power produced at the design speed of the propeller are 5 N and 60 W, respectively. These results were found to be compatible with some commercially produced propeller models of the same diameters at the same rotational speed. For example, it was seen that the thrust value produced by the propeller (28x5,5 cm) in this study is compatible with the results of the thrust calculation tool of Mejzlik company for the propeller of the same dimensions [17]. Similarly, it has been observed that the thrust, efficiency, and consumption power for 6000 rpm and 0.3 advance ratio are compatible with the propeller performance data of APC and T-MOTOR companies of the same dimensions [18,19].

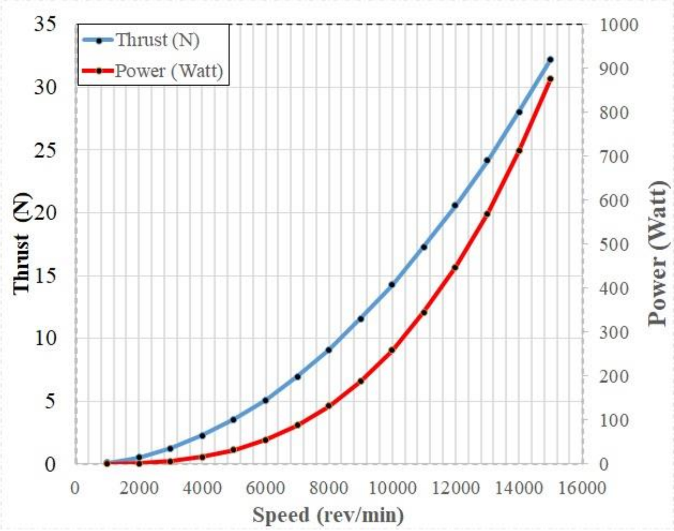


Figure 6. Consumption power and produced thrust according to rotational speed.

The Thrust of the propeller was examined according to the UAV's forward speed at 6000 and 1000 rpm and the results were given in Figure 7. Accordingly, it was observed that the thrust produced by the propeller decreased as the forward speed of the UAV increased at both rotation speeds. This decrease in thrust was found to be consistent with the literature [16]. Similarly, as increased forward speed of the UAV, it was observed that there was a decrease in the power produced by the propeller (please see Figure 8).

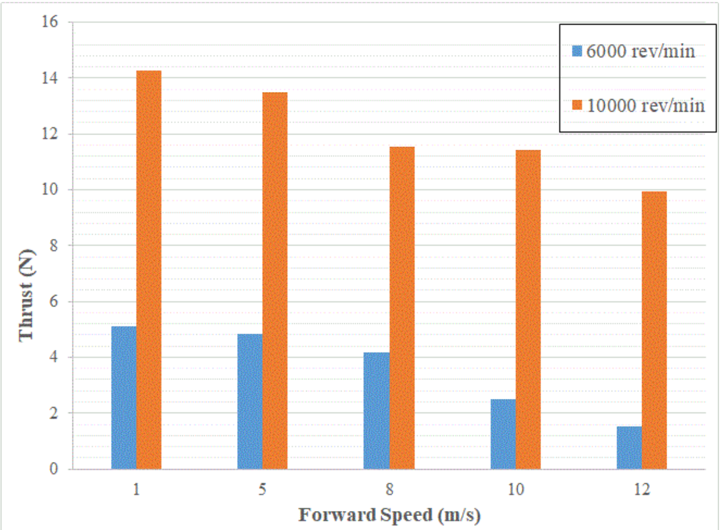


Figure 7. Effect of forward speed on thrust at 6000 and 10000 rpm.

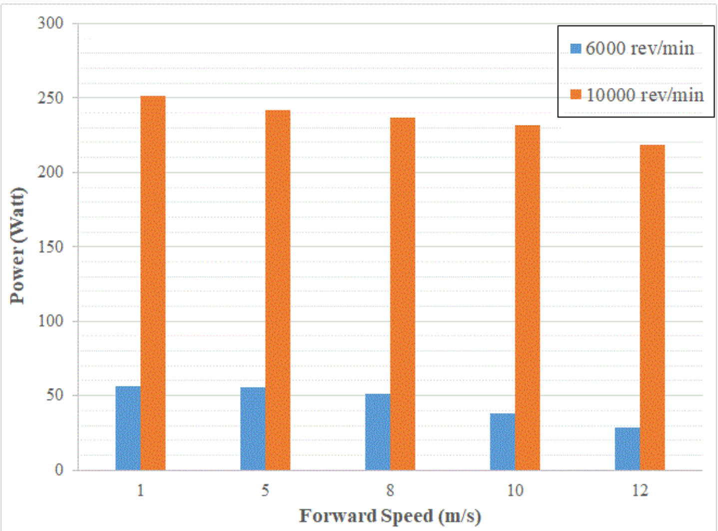


Figure 8. Effect of forward speed on power consumption at 6000 and 10000 rpm.

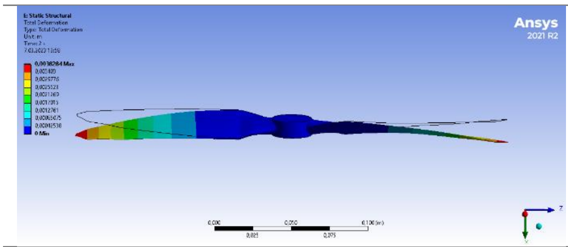
Mechanical features such as total deformation, equivalent elastic strain, and maximum shear elastic strain obtained from the Fluent-Static Structural coupled analysis of the propeller for Carbon Fiber and ABS materials are for 10000 rpm given in Table 3. The static analysis values of the 2 different material types tested at rev/min and comparatively were expressed as numerical values in Table 2. In Table 3, the static analysis images obtained in the highest rev/min data applied in the study are given. It has been observed that the total deformation occurs higher in the Plastic ABS material at each rev/min compared to the Carbon Fiber (395 GPA) material, especially in the propeller tip chord regions. It is clearly seen in the simulation values that Equivalent Elastic Strain occurs at higher values in ABS material, similarly. The maximum value of shear stress, which is another parameter value in this study, was higher in carbon fiber material. When looking at the shear stress image for each material, it was observed that it was affected in a higher area in the Plastic ABS material, but it was realized in carbon fiber material as the maximum value.

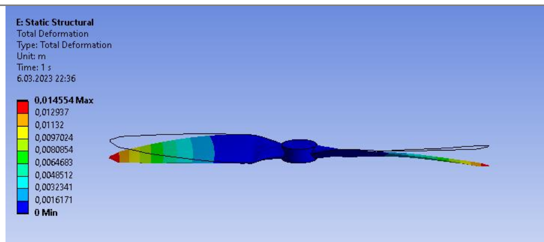
Performance parameters such as thrust, thrust coefficient, power coefficient, and efficiency of the propeller examined in this study were calculated by substituting the data obtained from the CFD analysis in Equations 1-4. Accordingly, the change of power and thrust coefficient with rotational speed was given in Figure 9. In addition, the change in the efficiency of the propeller according to the advance ratio is given for 6000 and 10000 rpm in the same Figure. Accordingly, it has been observed that maximum efficiency is approximately 65% for 6000 revolutions with 0,3 advance ratio.

Table 3. The mechanical properties of the propeller according to the material and rotational speed.

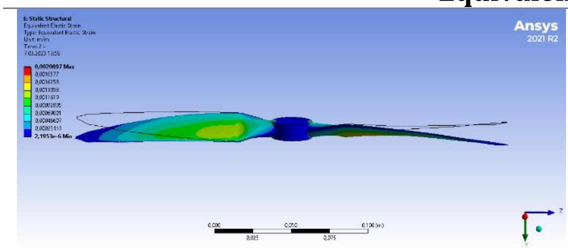
Carbon fiber	**ABS**

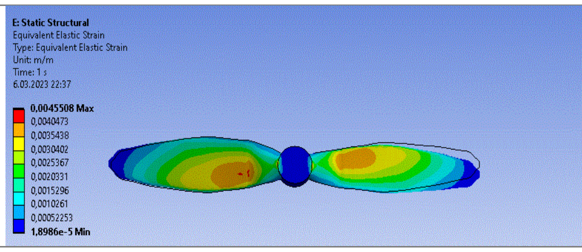
Total deformation



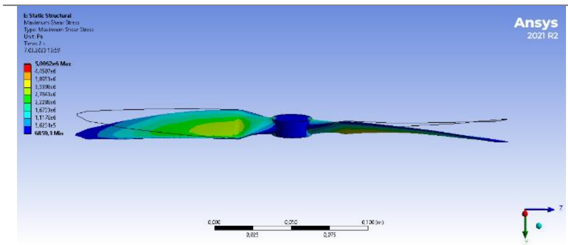


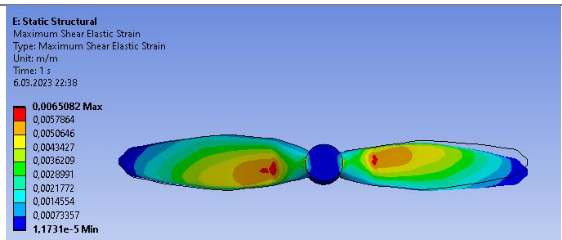
Equivalent elastic strain





Maximum shear elastic strain





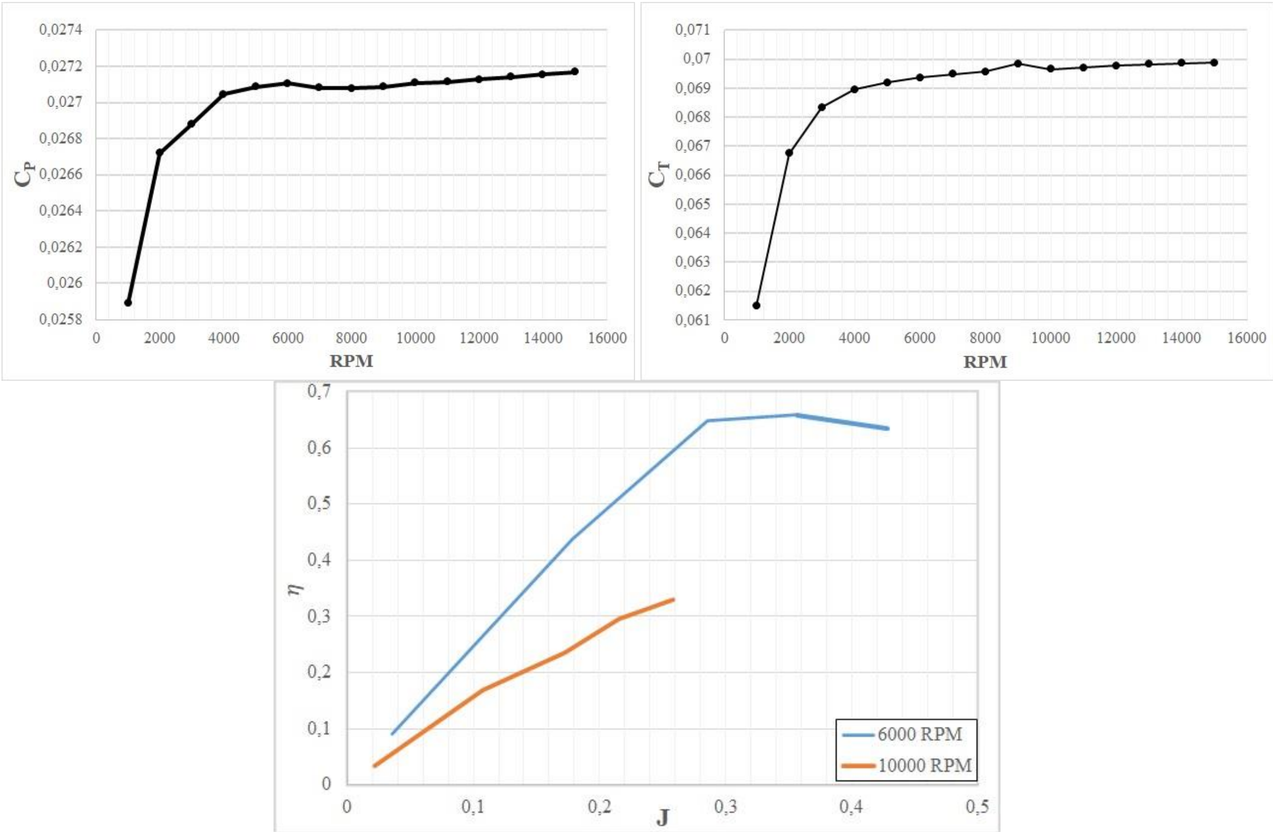


Figure 9. Propeller performance data

Using the Equations 1-4, the performance data of our propeller with a diameter of 28 cm, for which numerical tests were performed at different rpm, are given. The power coefficient and thrust coefficients were calculated according to different rpm values, as well as the propeller efficiency at 1.5, 8, 10, and 12 m/sec forward speeds.

4.Conclusion

In this article, the aerodynamic performance characteristics and numerical analysis results of a propeller are given. CFD analyses on a Navier-Stokes solver were conducted as a numerical method for thrust coefficient estimations. In addition to these, the structural analysis data of our propeller, whose CFD analyses were performed at different rpm, were examined schematically and in tables with 2 different material options. When our propeller is examined in terms of efficiency, both thrust and power consumption increase with increasing rpm data. However, after about 10000 rpm, the power consumption increases more than the generated thrust. When examined in terms of material selection, the deformation that occurs with increasing RPM in ABS material occurs much more than in carbon fiber material.

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