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Numerical Investigation of Effects of Airspeed and Rotational Speed on Quadrotor UAV Propeller Thrust Coefficient

Tuğrul OKTAY[1], *Yüksel ERASLAN*[2]*

[1] Erciyes University, Department of Aeronautical Engineering, Kayseri, Turkey
[2] İskenderun Technical University, Unmanned Aerial Vehicle Technology and Operator Program, Hatay, Turkey

Abstract

In this article, a numerical investigation was performed on a quadrotor unmanned aeroial vehicles (UAV) propeller to examine the effects of airspeed and rotational speed on thrust coefficient, which is one of the most important parameters on propeller aerodynamic performance. For that purpose, Computational Fluid Dynamics (CFD) analyses of an 11-*inch* propeller were carried out at different airspeeds and rotational speeds in vertical climbing flight conditions. In order to have the optimum number of mesh elements in the computational domain, mesh independence analyses were also conducted. In conclusion, the results of the analyses with the *k-ω* SST turbulence model were shown that increase in rotational speed was led to higher turbulent kinetic energy. Furthermore, higher rotational speeds also resulted in higher differences between numerical estimations and experimental data but were found to become more independent from airspeed.

Keywords: Computational Fluid Dynamics, Unmanned Aerial Vehicle, Propeller, Aerodynamics, Thrust Coefficient

1. Introduction

Nowadays, multi-rotor unmanned aerial vehicles (UAVs) are commonly preferred in commercial, military, and industrial applications due to their not only low weight, but also superior abilities in maneuvering and hovering flight [1]. As rotary-wing aerial vehicles, Quadrotor UAVs are one of the most popular configurations, which are named by the number of rotors they have [2]. In order to improve flight performances of these types of vehicles, propellers are one of the most important components that need to be investigated [3]. Small scale unmanned aerial vehicle propellers are continued to rise in importance parallel with the increase in popularity of these unmanned technologies, especially since the 1990s.

Quadrotor UAVs have low rotor inertia, which provides them to be able to easily control by adjusting rotational speeds of their propellers separately [4]. Moreover, in dimension, small-scaled propellers resulted in performance losses in

Corresponding Author: Yüksel ERASLAN yuksel.eraslan@iste.edu.tr
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ORCID:[1] https://orcid.org/0000-0003-4860-2230 [2] https://orcid.org/0000-0002-5158-5171
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terms of payload, range, and endurance due to dominant viscous effects at low-Reynolds number (Re) flows [5]. Thus, the performance of propellers is an important issue for not only aerodynamic manner but also control considerations of these vehicles.

Propeller aerodynamic performance, η is defined in terms of unitless thrust coefficient, C_T and power coefficient, C_P together with the advance ratio, J as given in Equation 1,

$$\eta = J\frac{C_T}{C_P} \tag{1}$$

and the advance ratio, J is defined in airspeed, V propeller rotational speed, n and diameter, D in Equation 2 [6].

$$J = \frac{V}{nD} \tag{2}$$

Thus, the change in thrust coefficient and power coefficient with respect to change in airspeed and rotational speed is an important consideration that needs to be investigated to determine a propeller's performance.

In order to obtain thrust and power coefficients, there are analytical, experimental or numerical methods applied in the literature. Today, as a numerical method, Computational Fluid Dynamics (CFD) applications come to the fore, which helps to obtain aerodynamic investigation results of complex geometries in a short time [7]. In the literature, there exist various studies including CFD investigation on multi-rotor UAV propeller aerodynamic performance parameters.

Yener et. al. [8] were carried out a CFD investigation on the interaction between the propeller and various frame arm geometries. Their study was also included wind tunnel experiments at static conditions on two different propellers, and results were found to be in good agreement with literature data in terms of thrust and power coefficients. On the other hand, CFD analyses were performed at both vertical climb and hovering flight conditions, after validating the simulation condition with experimental data. They obtained that while the square frame arm has the highest propulsive efficiency, the Eppler arm yielded the highest total thrust value. Moreover, the propeller thrust coefficient was found to be decreased with increasing distance between the propeller and frame arm.

Kutty et al. [9] were performed computational fluid dynamics analyses on a small-scale propeller using Ansys FLUENT program. Their study was also included mesh independence analyses and turbulence model comparison, in terms of thrust coefficient, power coefficient and propeller efficiency. Numerical estimations on thrust coefficient were found to show slight under-prediction at low advance ratios. Moreover, power coefficient results were found to show under-prediction at low advance ratios and over-prediction at high advance ratios. Overall, it was concluded that small-scale low-Re number propeller performances could be reliably predicted by numerical methods.

Yeong et al. [10] were carried out a CFD investigation on the propeller of a micro quadrotor UAV design with the aim of aerodynamic performance optimization. To improve the performance of the base model, various airfoils were compared in terms of their aerodynamic performances. The superior airfoil was applied on the new design and numerically investigated both on the single rotor and multi rotor configurations. In addition, grid independence analyses were conducted for computational analyses and experimental validation was conducted for the airfoil. As a result, the optimized propeller design was found to generate a higher thrust force and have a higher lift to drag ratio. On the other hand, quad rotor configuration outperformed due to higher induced drag.

Cespedes and Lopez [11] simulated single and quad rotors with overset mesh and analyzed at different rotational speeds on ANSYS Fluent CFD analysis program. The overset and far-field meshes generated with Pointwise v18 for a single rotor and then scaled to quad rotors. In addition, an experimental analysis for a single rotor was performed to obtain thrust and torque values. Single rotor CFD analysis was found to predict thrust value 7% and torque value 22% less than experimental results.

A number of the quadcopter ducted-fan models investigated by Kuantama and Tarca [12] in terms of their air velocity behaviors. Thrust force, frame material and power consumptions compared by means of CFD analyses they performed at various propeller rotational speeds.

The aim of this study is to investigate the effects of airspeed and rotational speed on the thrust coefficient of a quadrotor UAV propeller by means of CFD analyses. For that purpose, an 11-*inch* diameter propeller from the literature was investigated in terms of thrust coefficient by means of a Navier-Stokes solver (Ansys Fluent v17.2) at four different vertical climbing airspeeds and three different rotational speeds.

2. Numerical Method

In this study, the CFD analysis procedure was included three steps named pre-processing, solver and post-processing in Ansys Fluent program. In pre-processing, propeller Computer Aided Design (CAD) geometry was imported to the Ansys SpaceClaim environment. The propeller geometry of 11-*inch* in diameter and 4.7 *inch* in pitch diameter (11x4.7) was given in Figure 1 [13].

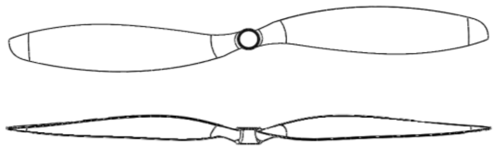

Figure 1. Top and side views of propeller CAD geometry

In order to have a proper structure for overset mesh application, the computational domain was composed of rotating and static zones as given in Figure 2 [2].

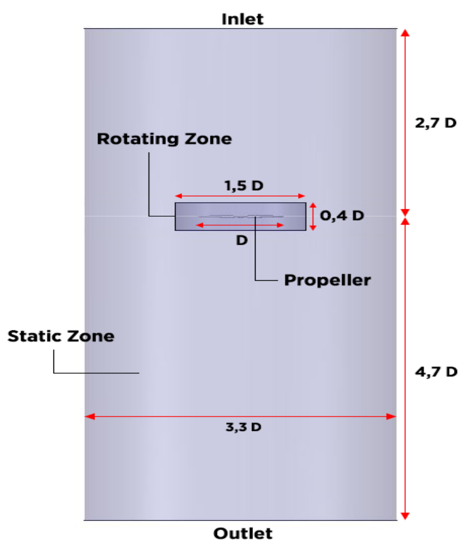

Figure 2. Dimensions of the computational domain composed of rotating and static zones

Computational domain mesh structure was prepared in Ansys Mesher with tetrahedral and hex elements as given in isometric and section views in Figure 3. Mesh quality metrics were obtained as a maximum skewness value of 0.704 and a maximum aspect ratio of 5.994.

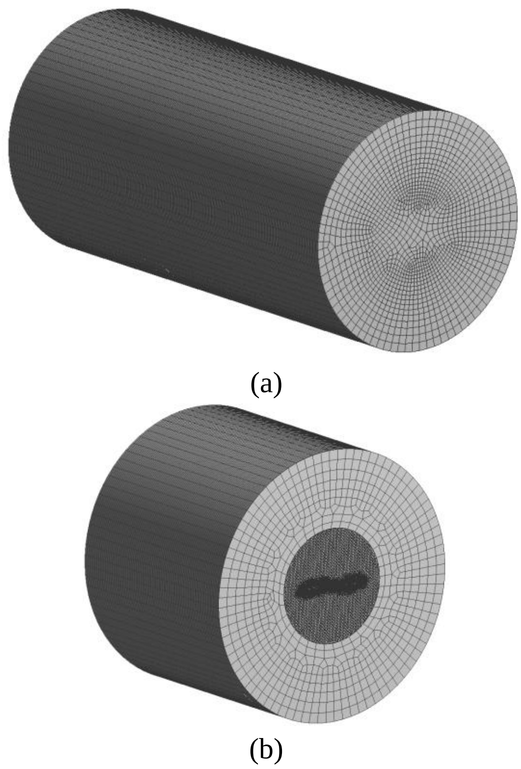

Figure 3. Mesh structure of computational domain (a) isometric view, (b) section view

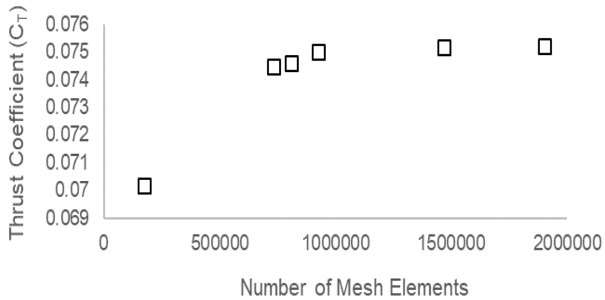

Figure 4. Thrust coefficient changing with the number of mesh elements

The rotating zone was composed of tetrahedral elements and the static zone was mostly included hex elements. The number of mesh elements was determined as 925x10^3 with respect to the results of the mesh independence study plotted in Figure 4 [14]. Grid independence analyses were performed at 3000-RPM rotational speed and 2.41 *m/s* vertical climbing airspeed using *k-ω* SST turbulence model with curvature correction.

In the solver step, ANSYS Fluent solves mass and momentum conservation equations for all flows. The flows with heat transfer and compressible effects have additional energy conservation equations. In this study, the highest rotational speed applied was 6000-RPM, which leads to a tip speed of 0.255 Mach and can be defined as incompressible flow.

The turbulence model was selected as *k-ω* SST with curvature correction, which involves modifications for low-Re effects, compressibility, and shear flow spreading. The model is based on model transport equations for the turbulence kinetic energy, *k* and specific dissipation rate, *ω*. SST *k-ω* model is another version of *k-ω*, which accurate formulation near-wall region and independent from freestream in the far-field [15]. The model is able to predict the laminar-to-turbulent transition, which makes it to estimate a wide range of flows such as adverse pressure gradient flows or transonic shock waves. Inlet was defined as velocity inlet, the outlet was defined as pressure outlet and frame motion was also defined for the rotating zone. Air density and viscosity are defined as sea-level conditions.

3. Results and Discussion

GWS 11x4.7 propeller was investigated by means of CFD analyses at 3000-RPM, 5000-RPM and 6000-RPM rotational speeds at various vertical climbing airspeeds. Results of thrust coefficients changing with respect to airspeed were plotted in Figure 5. Moreover, numerical results of the analyses were listed in Table 1, Table 2 and Table 3. Both of the results shown that numerical estimations become more accurate in lower airspeeds.

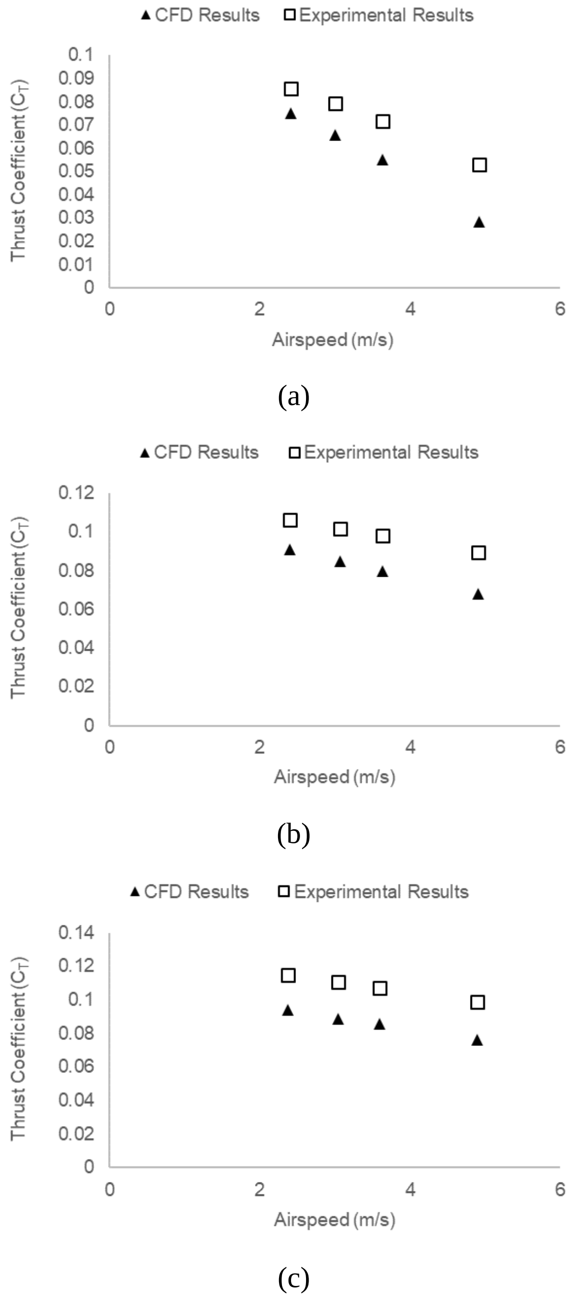

Figure 5. The change in thrust coefficient with airspeed at rotational speeds of a) 3000-RPM, b) 5000-RPM, c) 6000-RPM

Numerical estimation discrepancies with experimental data were found to range between 12.69% and 46.42% at 3000-RPM rotational speed. In addition, discrepancies were found to range between 14.61% and 24.30%, 18.46% and 22.78% at 5000-RPM and 6000-RPM, respectively. These results have shown that, in higher rotational speeds, numerical estimation discrepancies became more independent from airspeed. As the *k-ω* SST is a low-Re turbulence model, higher discrepancies found to be acceptable in results for higher Re conditions, where the boundary layer is thicker [16].

Table 1. Computational estimations of thrust coefficient changing with airspeed at 3000-RPM rotational speed

Airspeed (*m/s*)	Numerical Result	% Difference from Experimental Result
4.93	0.02840	46.42
3.64	0.05520	23.18
3.00	0.06611	16.98
2.41	0.07510	12.69

Table 2. Computational estimations of thrust coefficient changing with airspeed at 5000-RPM rotational speed

Airspeed (*m/s*)	Numerical Result	% Difference from Experimental Result
4.91	0.06790	24.30
3.63	0.08005	18.48
3.07	0.08487	16.47
2.40	0.09085	14.61

Table 3. Computational estimations of thrust coefficient changing with airspeed at 6000-RPM rotational speed

Airspeed (*m/s*)	Numerical Result	% Difference from Experimental Result
4.9	0.076220	22.78
3.6	0.085664	20.16
3.04	0.088750	19.97
2.37	0.093768	18.46

Figure 6 and Figure 7 represent turbulence kinetic energy contours on propeller and wake region at different airspeeds and rotational speeds. It is clear from the figures that turbulence tendency is higher at lower airspeeds and higher rotational speeds.

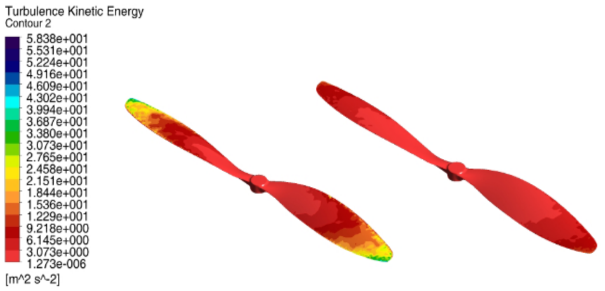

Figure 6. Turbulent kinetic energy contours of 6000-RPM (left) and 3000-RPM (right) at 2.4 *m/s* airspeed

Moreover, Q-criterion plots of 3000-RPM and 6000-RPM rotational speeds at 2.4 *m/s* vertical climbing airspeed was given in Figure 8. Q-criterion of larger than zero means existence of turbulence, where vorticity magnitude is greater than the rate of strain. Thus, at same airspeed, higher rotational speeds led to higher turbulence, where the strong turbulence intensity found to be resulted in turning laminar flow to turbulent flow and correspondingly lower thrust coefficient.

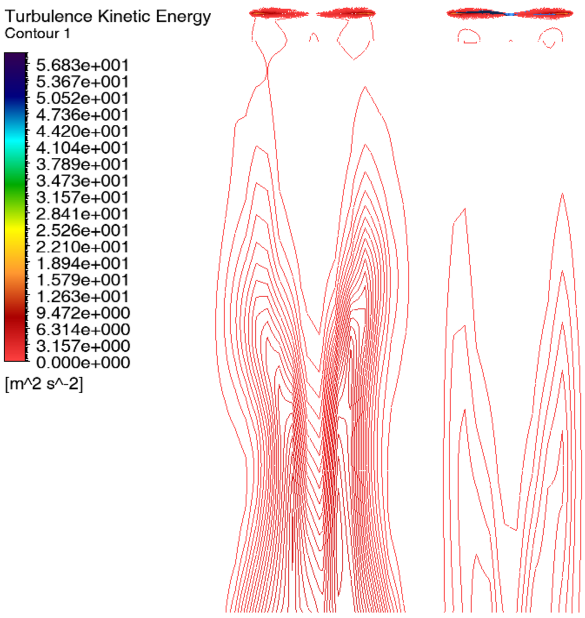

Figure 7. Turbulent kinetic energy contours of 2.37 *m/s* (left) and 4.9 *m/s* (right) airspeed at 6000-RPM rotational speed

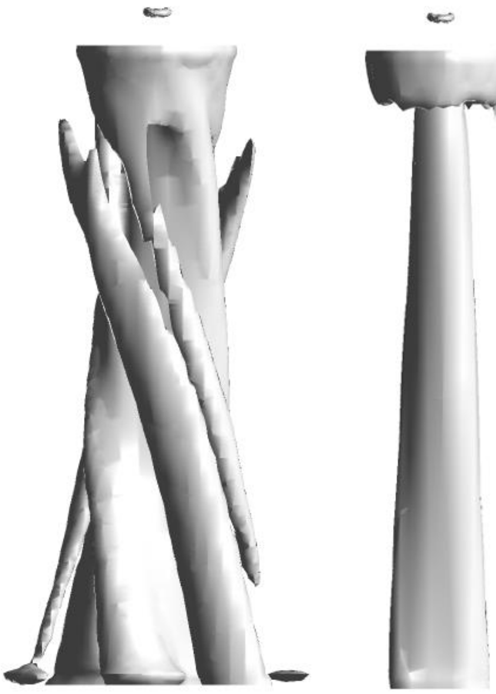

Figure 8. Q-criterion distribution at 6000-RPM (left) and 3000-RPM (right) in three-dimensions with level of $3x10^{-5}$

4. Conclusion

In this article, the effects of airspeed and rotational speed of a quadrotor UAV propeller on thrust coefficient were investigated. CFD analyses on a Navier-Stokes solver were conducted as a numerical method for thrust coefficient estimations. Consequently, it was obtained that, increase in rotational speed was led to higher turbulent kinetic energy especially at blade tip regions. Furthermore, higher rotational speeds also resulted in higher differences between numerical estimations and experimental data but shifted as more independent from airspeed.

Ethical Approval
Not applicable

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