Estimation of the thrust coefficient of a Quadcopter Propeller using Computational Fluid Dynamics

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**Abstract.** A Quadcopter is a mechatronics device with complex dynamics, because six degree of motion is control by four thrust forces. These thrust force are generated by propellers rotation, driven by DC motors. The main objective of present study is to perform the flow analysis on a Quadcopter propeller, to find out the propeller thrust coefficient \((K_t)\). The flow analysis of Quadcopter propeller is essential as it opposes the gravitational and aerodynamic forces due to the drag and weight mounted on it. So, a 3D CAD model of Quadcopter propeller was designed in Catia and imported to Ansys fluid flow (fluent) module for fluid flow simulation. The flow over propeller was simulated under different angular speed with k-epsilon turbulence model. The obtained results conclude that the designed propeller can generate the required amount of thrust force to lift additional payloads. Furthermore the generated thrust force at different angular speed was used to find out the thrust coefficient. This thrust coefficient will used in developing the mathematical dynamic model of Quadcopter UAV.

**Keywords:** Quadcopter propeller, CFD, Thrust force, payload, thrust coefficient.

1. **Introduction**

A Quadcopter is a multi-rotor vehicle, consisting of mechanical and electronic equipment. It has a vertical take-off and landing capability due to which it can be used in congested and dangerous area. Furthermore it also used in military spy vision and aerial photography [1-6]. It replaces the human in transporting the goods in toxic environment. Quadcopter has better steering control since four propellers control its motion in three dimensional space. Its increasing application in daily life motivates the researcher to improve its maneuverability and stability.

Penkov et al. [1] performed the CFD analysis on a Quadcopter propeller and determine the shroud influence on propeller lift force. M.P. Kishore et al. [7] studied the velocity and pressure distribution around a marine quadcopter propeller. E. Kuantama et al. [8] analyzed the Quadcopter propeller at different speed to determine the thrust force with respect to the angular speed of propeller. S. Wang et al. [9] analyzed an agricultural unmanned aerial vehicle on the basis of static structural and fluent flow analyses. F. Ahmad [10] performed the vibration analysis on a Quadcopter propeller to find out the best suited material, which can sustain the failure frequency. Kuantama et al [11] analyzed the Quadcopter body frame by static structural analysis. Furthermore, air flow between the propellers was analyzed using CFD analysis and a optimum propeller speed was find out which can fly the Quadcopter without creating vibration on the body frame.

From the existing literature it was found that, less work was performed on propeller flow analysis. The experimental flow analysis of propeller cause high initial cost but computer makes it
easy and provides changeability in boundary condition. The main objective of present study is to perform flow analysis on a Quadcopter propeller to find out the thrust force. Furthermore this thrust force was used to determine the value of thrust coefficient \((K_t)\). It helps in designing the mathematical model of Quadcopter. The present study is divided into following sections, 1) describe the introduction with literature, 2) describe the boundary condition with flow analysis, 3) describe the simulation result, and 4) describe the conclusion.

2. Flow analysis and boundary condition
Quadcopter propeller plays an important role in its flight performance. Bad design of propeller decreases the Quadcopter performance in terms of stability, maneuverability and load lifting capabilities. When we provide DC current to the motor, propeller starts rotate and generate a thrust force. This thrust force propels the Quadcopter in upward direction, when the value of thrust force become greater than the value of force generated by the self mass of the Quadcopter (Critical force \(F=m*g\) ). It is well known that thrust force is the function of angular speed \(\left( F = K_t \times \omega^2 \right)\), where \(K_t\) is the thrust coefficient which depends on propeller shape, air density and \(\omega\) is the angular speed of propeller [12]. So the main objective of this study is to find out the value of thrust force generated by the rotation of Quadcopter propeller and to find out the thrust force coefficient by performing the CFD analysis. Figure 1 and 2 shows the design of Quadcopter in which the design propeller has a total blade length of 318 mm. Figure 3 shows the geometry of the propeller. This propeller was selected because of high resonance frequency [10]. Figure 4 shows the developed enclosure with inlet and outlet boundary condition. Figure 5 and 6 shows the mesh model of rotary domain and enclosure respectively. To perform the flow analysis the geometry of designed propeller was transfer to the Ansys fluent flow module. Two enclosures were created around the propeller, named as rotary domain and static domain (enclosure) as shown in Figure 3. The parameters used for the CFD simulation are listed in Table 1.

![Figure 1 CAD model of quadcopter.](image1)

![Figure 2 Schematic diagram with dimension.](image2)

![Figure 3 Propeller geometry.](image3)

![Figure 4 Propeller with enclosure.](image4)
3. Simulation Result

The complete domain was meshed with maximum mesh size of 20 mm and 40 mm by mesh sizing tool. The complete analysis was repeated for 20 and 40 mesh size at 6000 and 1134 RPM to perform grid independence test, and the comparison are listed in table 2. Figure 7 and 8 shows the value of thrust force at 6000 RPM with mesh size 20 and 40 respectively. From the table 2 we can see that, there is not much difference in thrust force at 20 and 40 mm mesh size that’s why the analysis was repeated for different value of propeller speed with 40 mm mesh size to save the simulation time and different thrust forces were calculated.

![Figure 6 Meshing of enclosure.](image)

**Table 1** Data Used In the Simulation.

| Parameter               | Parameter value          |
|-------------------------|--------------------------|
| Gravity                 | 9.81 m/s²                |
| Time                    | Transient                |
| Time step size          | 0.15                     |
| Number of time step     | 26                       |
| Number of iteration per step | 100            |
| Viscous model           | K-Epsilon (realizable)   |
| Near wall treatment     | Scalable wall function   |
| Flying medium           | Air                      |
| Specified operating density | 1.225 kg/m³             |
| inlet velocity of air   | 0.1 m/s                  |

**Table 2** Data used in the simulation.

| S. no | Element size (mm) | No of element | Thrust force at 6000(RPM) | Thrust force at 11341(RPM) |
|-------|-------------------|---------------|---------------------------|----------------------------|
| 1     | 20                | 486358        | 5.94 N                    | 21.10 N                    |
| 2     | 40                | 133198        | 5.91 N                    | 21.37 N                    |

Figure 9 and 10 shows the pressure variation on the propeller surface and streamline result respectively. Frome Figure 9 we can see that the upper surface of the propeller has lower pressure value as compare to the bottom propeller surface.
Table 3 shows the value of simulation result at different angular speeds. Figure 11 and 12 shows the response of thrust force and payload capacity with respect to propeller angular speeds. If the considered Quadcopter is made up of CFRP material then it will have a total mass of 0.94768 Kg. The
thrust force required to fly the Quadcopter $F = m \times g = 0.94768 \times 9.81 = 9.297$ N. From the table 3 we can say that Quadcopter will not fly at 3586 RPM because the thrust generated (8.44 N) will not overcome the weight. However, the Quadcopter will fly at other RPM. Furthermore, the value of thrust coefficient was calculated by taking the average of thrust coefficient calculated at different angular speeds.

Table 3 Simulated results at different angular speeds of propellers.

| Angular speed (RPM) | Angular speed (rad/sec) | Thrust force $F_i$ by CFD(N) (Single propeller) | Total thrust force $= (F_i \times 4)$ | Payload Estimation $m_r = \frac{4F_i - m \times g}{g}$ (Kg) | $K_t = \frac{F_i}{\omega^2}$ (N-s^2/rad^2) | Average of $K_t$ |
|---------------------|-------------------------|-----------------------------------------------|-----------------------------------|-------------------------------------------------|-------------------------------------|-----------------|
| 3586                | 375.53                  | 2.11                                          | 8.44                              | 0.089653415                                      | 1.49621 x 10^-5                     |                 |
| 4811                | 503.81                  | 3.81                                          | 15.24                             | 0.60351682                                       | 1.50104 x 10^-5                     |                 |
| 5072                | 531.14                  | 4.24                                          | 16.96                             | 0.778848114                                      | 1.50296 x 10^-5                     |                 |
| 5783                | 605.59                  | 5.51                                          | 22.04                             | 1.296687054                                      | 1.50243 x 10^-5                     |                 |
| 6000                | 628.32                  | 5.91                                          | 23.64                             | 1.459785933                                      | 1.49701 x 10^-5                     |                 |
| 6500                | 680.67                  | 6.97                                          | 27.88                             | 1.891997961                                      | 1.50439 x 10^-5                     | 1.50200 x 10^-5 |
| 6991                | 732.09                  | 7.98                                          | 31.92                             | 2.30382263                                       | 1.48893 x 10^-5                     |                 |
| 7857                | 822.78                  | 10.17                                         | 40.68                             | 3.196788991                                      | 1.50229 x 10^-5                     |                 |
| 8239                | 862.80                  | 11.23                                         | 44.92                             | 3.629001019                                      | 1.50855 x 10^-5                     |                 |
| 8930                | 935.15                  | 13.23                                         | 52.92                             | 4.444495413                                      | 1.51285 x 10^-5                     |                 |
| 9037                | 946.35                  | 13.51                                         | 54.04                             | 4.558664628                                      | 1.50852 x 10^-5                     |                 |
| 10016               | 1048.87                 | 16.49                                         | 65.96                             | 5.773751274                                      | 1.49892 x 10^-5                     |                 |
| 11341               | 1187.63                 | 21.37                                         | 85.48                             | 7.763557594                                      | 1.5151 x 10^-5                      |                 |

Table 4 shows the thrust result comparison with the previously publish literature [13]. Considering the difference in radius of propellers the thrust values are reasonably close. The value of thrust force coefficient ($K_t$) can also be validated by Muhammad Zaki Mustapa published study [14] where experimentally estimated value of $K_t$ was 1.50x10^-5, which also validates our estimated value (1.50200 x 10^-5) using CFD.

Figure 11 Response of thrust force at different angular speed of propeller.
Figure 12 Load carrying capacity at different angular speed of propeller.

Table 4 Result validation with the publish literature in terms of thrust force.

| S. No | RPM | Simulated thrust in Newton (for our propeller of radius 0.159m) | Shenet al. [13] thrust in Newton (for propeller of radius 0.1143m) |
|-------|-----|---------------------------------------------------------------|---------------------------------------------------------------|
| 1     | 3586| 2.11                                                          | 1.261                                                         |
| 2     | 4811| 3.81                                                          | 1.593                                                         |
| 3     | 5072| 4.24                                                          | 2.865                                                         |
| 4     | 5783| 5.51                                                          | 3.909                                                         |
| 5     | 6991| 7.98                                                          | 6.12                                                          |
| 6     | 7857| 10.17                                                         | 8.073                                                         |
| 7     | 8930| 13.23                                                         | 10.93                                                         |
| 8     | 9037| 13.51                                                         | 11.35                                                         |
| 9     | 10016| 16.49                                                        | 14.34                                                         |
| 10    | 11341| 21.37                                                        | 19.24                                                         |

4. Conclusion
The present work deals with the CFD analysis of a Quadcopter propeller. A CAD model of propeller was designed in CATIA and analyzed by Ansys using k-ε turbulence model. The air flow over propeller was simulated at different angular speeds. Response of the thrust was analyzed and payload capacity was determined (see Figure. 11 and 12). The simulated values of thrust force at different angular speeds were used to determine the value of thrust coefficient ($K_t$). Furthermore, the simulated result of thrust force was validated by the publish results. For future work, it will be interesting to develop a mathematical model of Quadcopter considering the generated thrust coefficient and analyze the dynamics of Quadcopter UAV.

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