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Effect of Ring Surface Design on the Thrust of a Rotor using in Multirotor UAV

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Abstract

This work employs ANSYS fluent CFD tool to calculate thrust generated a rotor covered by a ring surface using in UAV. The aim of this paper is to characterize the effects of geometry parameters of the ring surface such as diameter and height on the thrust of the rotor. Firstly, the simulations of a full-open rotor at different RPMs is carried out. The results are compared to experiment results to validate the numerical model. Then, the simulations of the rotor covered by a ring surface with different geometry parameters are carried out. The results show that changing diameter of the ring surface leads to thrust generated by rotor also changing. With an increase in the ring surface height thrust increase up to a certain value and stabilizes.

Keywords: Multirotor, ring surface propeller, ring surface, thrust.

1. Introduction

Nowadays, unmanned aerial vehicles (UAV) have a huge potential in both military [1] and civilianlife. UAVs can carry out work conditions where the surrounding environment is dangerous or not available to human. Among many UAVs types, multirotor UAVs have exclusive capabilities like hovering, vertical takeoff and landing, limited launching spaces and good maneuvering. There is a wide range of applications performed by multirotor UAVs, such as police, rescue and firefighter need, research, cinematography and other spheres. Also, multirotor UAVs have generated great interest in industrial and academic circles. Nowadays, multirotor UAVs are very popular but are still developing very quickly. Many research works focus on controllability, stability and aerodynamics performance of multirotor UAVs [2].

For multirotor UAVs, the rotation speed of propeller can be tens thousands of RPMs. Thus, it is very dangerous and limited when operating at small space areas. Some multirotor UAVs (example in Fig. 1) are equipped with a safety frame (ring surface frame) to protect propellers. However, the aerodynamics performance of ring surface is needed to be investigated.

Many attempts have been made to create a ring surface UAVs. Most of them relates to ducted-fan UAVs with only one rotor (also called ring surface). The reason is that according the Rankine–Froude theory it can be more efficient than a usual helicopter with one fully opened rotor. A model of a ring surface propeller was calculated [3]. The theoretical calculation shown that the efficiency was 167.5% as compared to opened propeller. However, the effects of the geometry of the ring surface and its weight were not investigated.

Fig. 1. Quadrotor with a safety frame [6]

In this paper, we employ CFD tools to characterize the effects of geometry parameters of the ring surface such as diameter, height on thrust generated by the rotor. Firstly, the simulations of a full-open rotor at different RPMs is carried out. The results are compared to experiment data to validate numerical model. Then, the simulations of ring surface rotor are carried out with different geometry parameters: the diameter of ring surface varies from 1.05D to 1.30D, where D is the diameter of rotor and the height of ring surface varies from 20mm to 75mm.

2. Theory of ring surface

According to Rankine–Froude momentum theory (rotor is modeled as an infinitely thin disc, inducing a constant velocity along the axis of

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rotation), thrust of a propeller (T) at hovering flight is given by Eq. (1) [4].

$$T = \frac{1}{2}\rho S_1 V_e^2 \qquad (1)$$

where

ρ – air density,

S_1 – the disk rotor area (Fig. 2-a),

V_e – velocity of the air stream coming out.

With a ring surface fan, direct application of the momentum theory ensures the following:

$$T = \rho S_e V_e^2 = \sigma \rho S_1 V_e^2 \qquad (2)$$

where

Se – terminal section of the air flow (Fig. 2-b),

$\sigma = Se / S1$ – diffusion factor.

As it is shown in Eq. (1), σ is equal to 0.5 for a free propeller, and for a ducted-fan 20, σ is approximately equal to 1. For special ducts with spherical diffusors, σ can be greater than 3 or 5.

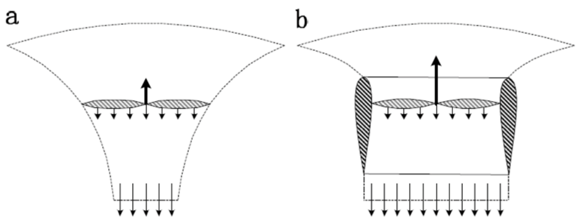

Fig. 2. Air flow near the rotor without a duct (a) and with it (b) [2]

According to CFD optimization results, thrust can be enlarged by using a duct that has conical geometry (Se > S1).

This research has supplied a ring surface with a shape of cylindrical tube around the rotor for safety purposes (for example, Safeflight Copters, USA). Minimal clearance between the rotor and the ring surface is set to 9.5 mm. The use of a smaller clearance (less than 1 mm) rotor with a rim will work similarly to the impeller model. In the impeller model the closeness of the internal rotor and the inner surface of the impeller housing minimizes turbulences created near the rotating rotor ends. Therefore, thrust will improve. In usual multirotor helicopters sufficient flexible light materials (usually carbon fiber, plastic or styrofoam) are used. Creating stiff ring surface around the rotor with a clearance less than 1 mm is not reliable (mass and/or price of helicopter will increase).

3. Simulation study

3.1 Simulation cases

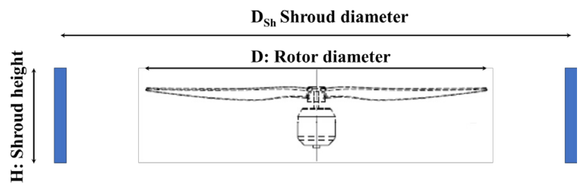

Fig. 3. Geometries parameters of ring surface

Different series of simulations are carried out:

- Case #1: Simulation of a full-open single rotor configuration. Thrust generated by single rotor are calculated at different rotational speed. The results are then compared with data given by manufacturer to validate the simulation model.

- Case #2: Simulation of rotors covered by a ring surface with different diameters. Thrust generated by ring surface rotor are calculated at different rotational speed and different ring surface diameter varies from 105% to 130% of rotor diameter.

- Case #3: Simulation of rotors covered by a ring surface with different heights. Thrust generated by ring surface rotor are calculated at different rotational speed and different ring surface height varies from 105% to 130% of rotor diameter.

All simulations are carried with the same T-motor 15x5 propeller (diameter 15 in and pitch 5 inches) (Fig. 4).

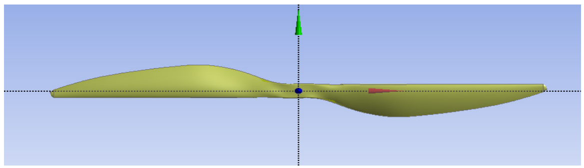

Fig. 4. 3D model of T-Motor 15x5 Propeller

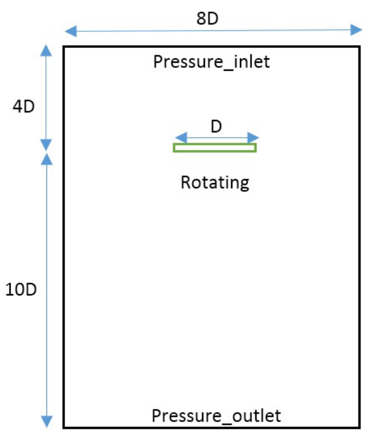

Fig. 5. Description of geometry.

3.2 Simulation model

Geometry

Fig. 5 shows the geometry of the simulation domain. The dimension of the simulation domain is 8Dx14D, where D is the diameter of the rotor.

Mesh

Using CFD tool in ANSYS software, the 3D model of the rotor blade was meshed by about $3.6*10^6$ elements (Fig. 6, Table 1).

The boundary conditions include: the pressure at inlet and outlet set to the pressure of the air, the stationary domain is set to wall condition. For this case the $k-\omega$ SST viscous model combined with the inflation in the surface of the blade were used to calculate accurately the forces through the rotor.

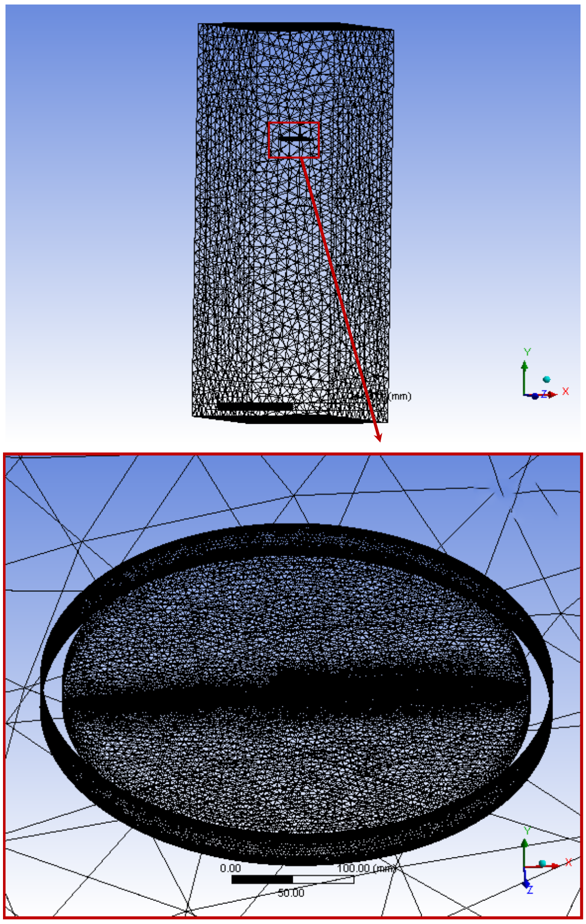

Fig. 6. Mesh model

Table 1. Mesh Properties

Nodes	1709251
Elements	6196018
Skewness Quality	0.2298
Orthogonal Quality	0.85912
Y^+	2.0

Simulation were conducted to understand how the closing rim affects thrust. It is possible to modify ring surface dimensions to understand how its size affects thrust. Diameter was varying from 400mm to 495 mm (Fig. 7) while the rotor diameter used for simulations was 381 mm (15 in). The height of the ring surface changed between 20mm and 70 mm.

Firstly, simulations were made by CFD software to determine thrust. Thrust produced by the rotor was determined at the rotor rotation speed of 6000rpm with a different diameter and height of the ring surface. Next, the diameter of the ring surface around the rotor was changed. Thrust and motor power consumption were measured at different rotor angular velocities. Simulations and experiments for a case without a ring surface around the rotor were done earlier to prove that the model works properly (Fig. 8).

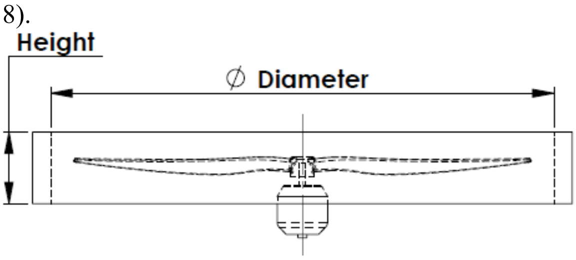

Fig. 7. Changes of dimensions of the ring surface around the rotor

4. Results and discussions

4.1. Full-open single rotor

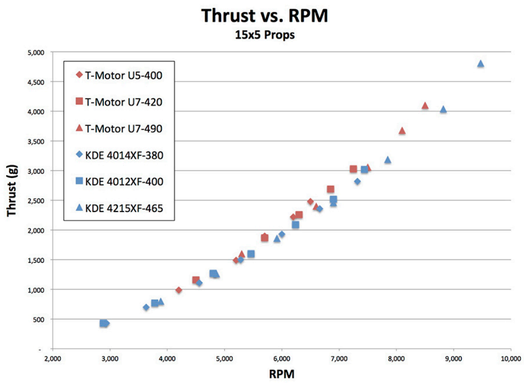

Fig. 8. Experiment results: evolution of thrust generated by T-motor 15x5 propeller in function of rotation speed when using with different T-motor U7 and KDE motors [5].

Fig. 8 shows the evolution of thrust generated by T-motor 15x5 propeller in function of rotation speed when using with different T-motor U7 and KDE motors [5]. In Fig. 9, we compared our simulation result of thrust generated by a full-open rotor in function of rotation speed with experiment results of the case of T-motor U7-490. Fig. 9 shows that the simulation points are well corelated with experiment points. The maximal different between experiment and simulation point is 8.8%.

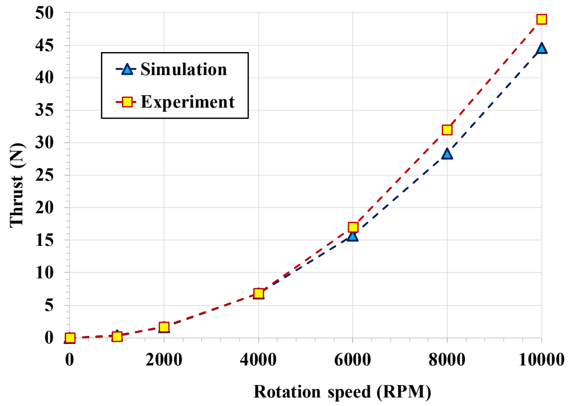

Fig. 9. Comparison between simulation and experiment results: evolution of thrust in function of rotation speed of T-motor 15x5 propeller using in T-motor U7-490 motor.

4.2. Effect of ring surface diameter

Fig. 10 shows the dependency of the thrust produced by one rotor on a certain diameter of the ring surface around it. Ring's height is fixed to 60 mm. Minimum diameter is 400 mm (when the clearance between the rotor and the ring surface is only 9.5 mm at each side) and maximum is 495 mm. The graph shows that thrust increases when the ring surface diameter increases. Dashed orange line shows the thrust of the rotor without ring surface around it.

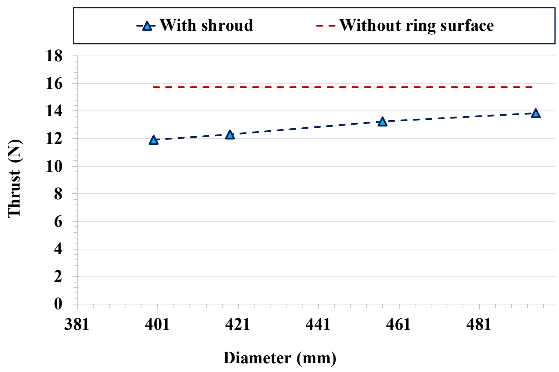

Fig. 10. Evolution of thrust generated in function of ring surface diameter.

From Fig. 11 we can see how ring surface affect to the air flow through the rotor. For the 1st case (without ring surface) the rotor generates more thrust than the 2nd case (with ring surface).

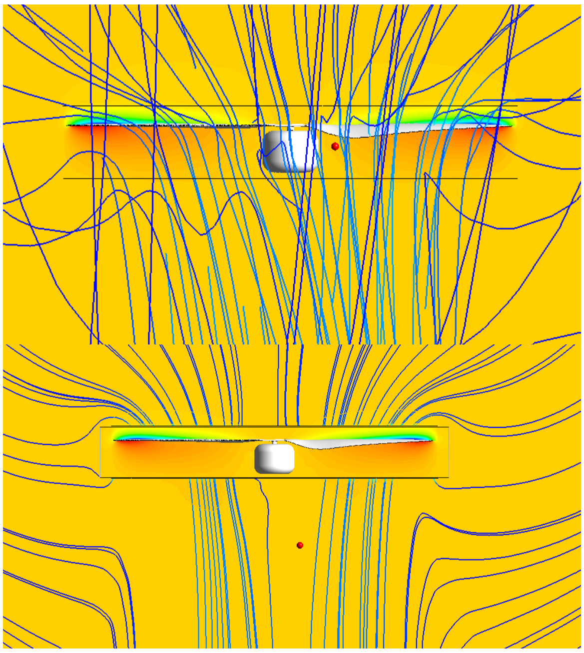

Fig. 11. Pressure and velocity distribution around the rotating rotor without ring surface and with ring surface.

4.3. Effect of ring surface height

When changing the height of the ring surface (Fig. 7), the thrust decreases from the height of 20 mm to 50 mm and then increases to 60 mm. At the start of this point the thrust stays stable even when the height continues increasing (see Fig. 12).

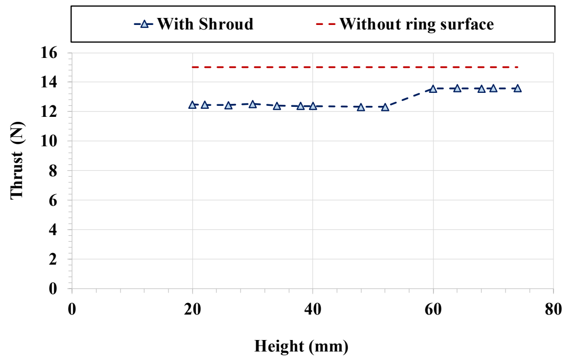

Fig. 12. Evolution of thrust at rotation speed of 6000rpm in function of ring surface height.

Fig. 13 shows the relation between the thrust on rotation speed of rotor with different diameters of the ring surface around the rotor. The thrust produced by the rotor increases while increasing the diameter of the ring surface. And, thrust generated by a full-open rotor (without ring surface) is higher than this generated by the rotor covered by a ring surface.

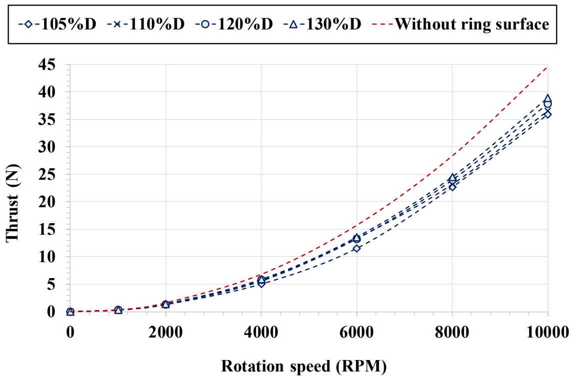

Fig. 13. Evolution of the thrust in function of the rotation speed for different ring surface diameter.

5. Conclusions

In some multirotor UAV, a ring surface is added to protect the rotors while operating at small space areas. In this paper, we investigated the effects of the ring height and diameter to the thrust generated by rotor by employing CFD method. The numerical simulations were validated in comparison with experimental data for the case without ring surface. A parametric study was performed to find the effect of geometric on the performance of the rotor. In general, the thrust generated by ring surface rotor is lower than full-open rotor while varying ring surface height and diameter. The results show that:

Changing diameter of the leads to the thrust also changing. The bigger the ring surface diameter, the bigger thrust can be produced at certain angular velocity and certain motor power.

With an increase in the ring surface height the thrust increases up to 60 mm height and then stabilizes. The thrust of a rotor with different diameter and height dimensions of straight safety ring around it is smaller than the force by the rotor without the ring.

In this work straight and non-profile ring surface was investigated, and the results show that the thrust generated by ring surface rotor is lower than full-open rotor. It is interesting to characterize the thrust generated by a surface with profile section and a cone angle.

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