

Propeller shrouding influence on lift force of mini unmanned quadcopter

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ABSTRACT

This article discusses the lift force generated by a mini unmanned aerial vehicle. Shrouded propellers were considered and analyses of shroud influence on lift force and energy saving were done. By help of laboratory experiments and computational fluid dynamics simulations (propeller velocity varied from 1000 rpm to 6000 rpm, shroud height from 20 mm to 60 mm, gap from 3 mm to 28 mm), it was shown that the shroud diameter influenced the rotor energy consumption up to 30% at velocities of more than 4000 rpm. With the increase shroud diameter (increase of distance between shroud and propeller borders), the lifting force increased. A gap of more than 30 mm practically did not influence the lifting force. Shroud height (from 20 mm to 60 mm, gap is 28 mm) also influenced the propeller efficiency (up to 10%) on small shroud heights (up to 30 mm). With the increase of the shroud height, the lift force decreased about 3% and then it increased up to 12%. From a value of about 50 millimetres, this influence will be unchanged but the total lifting force will be about 5% less in comparison with the force produced by propeller without shroud.

Keywords: UAV; CFD simulation; lift force; shrouded propeller; energy saving.

INTRODUCTION

There is a wide range of applications performed by Unmanned Aerial Vehicles (UAV) in the civil sphere such as police [1], rescue [2] and fire fighter needs [3]; for example, for traffic monitoring [4], navigation [5, 6], and aerial mapping. UAVs are also used for agriculture [7-10] needs, press, television, cinematography [11, 12], marine application, pollution detection, and other fields. They have generated a great interest in industrial and academic areas [13-17] due to their small size, unique flight capacities [18-21], outstanding maneuverability and low cost. A lot of researches related to stability and controllability have been conducted [22-24]. Screw theory [25, 26] and mathematical calculation methods are also usually applied when considering mini UAVs. Application areas lead to more advanced research for increasing the level of autonomy and reducing the size of UAVs. UAVs can be classified into two main categories: fixed-wing UAVs and rotary-wing UAVs. Fixed wing UAVs [27] constitute the richest group among these categories in terms of both research and utilisation. They are able to fly for a long duration at high speeds and their design is simple in comparison with the other types of UAVs. However, these UAVs suffer from the requirement of runways or additional launch and recovery equipment for takeoff and landing. Rotary wing UAVs [28], on the other hand, are advantageous since they do not require any infrastructure for takeoff and landing and

do not need any forward airspeed for flight and maneuvering, which make them useful particularly in urban areas and indoors. This leads to a large variety and size of rotary wing UAVs. Research and development of different UAVs are conducted in many universities around the world and also at well-known companies. A wide variety of completely manufactured UAVs or custom mini UAVs built from off the shelf parts available are using standard power sources [29] whereas energy saving is a vital issue. Lots of researchers [30] have considered this problem. One of the most important factors influencing UAV power consumption is the design of aerial vehicle. Conceptual and detailed designs need deep analyses of different parameters [31, 32]. Optimisation of size and mass parameters increase the efficiency of the flying system [33, 34] and optimisation of design increases system stability and controllability [35, 36].

The main purpose of this research is the optimisation of shrouded multicopters with respect to efficiency. Firstly, the influence of gap between propeller and shroud on lifting force produced by rotor will be considered. Then, the influence of shroud height will be analysed.

METHODS AND MATERIALS

Shrouded Propellers

The quadrotor helicopters are enclosed within a protective frame permitting flights indoors and in obstacle-dense environments with a reduced risk of damage to the vehicles, their operators or surroundings. The propellers with a protective shroud around them are usually called shrouded propellers or ducted fans. These added safety benefits greatly accelerate the design and test flight process by allowing testing to take place indoors or out, by inexperienced pilots, and with a short turnaround time for recovery from incidents [37]. The shrouds around propellers can also be used to change the path of air flow around and near the propellers. Pressure difference between upper and lower surfaces can be changed and should be verified to know the influence of shroud parameters on the lifting force [38].

Theory of Shrouded Propellers

According to the Rankine-Froude momentum theory (propeller is modelled as an infinitely thin disc, inducing a constant velocity along the axis of rotation), the thrust of a propeller (T) at hovering flight is given by Eq. (1) [39]:

$$T = \frac{1}{2} \rho S_l V_e^2 \quad (1)$$

where ρ is air density; S_l is the disk propeller area (Figure 1(a)); V_e is velocity of the air stream coming out.

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

$$T = \rho S_e V_e^2 = \sigma \rho S_l V_e^2 \quad (2)$$

where S_e is terminal section of the air flow (Figure 1(b)); $\sigma = S_e / S_l$ is diffusion factor.

As shown in Eq. (1), the diffusion factor is equal to 0.5 for a free propeller and for a shrouded σ is approximately equal to one. For special shrouds with spherical diffusors, σ can be greater than three or five [39].

According to CFD (Computational Fluid Dynamics) optimisation results, lifting force can be increased using a shroud that has a conical geometry ($S_e > S_l$).

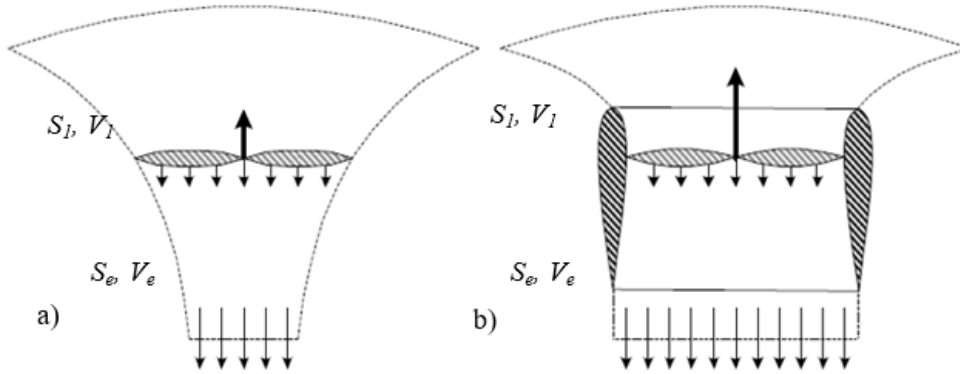


Figure 1. Airflow near the propeller without a duct (a) and with a duct (b) [39].

This research has incorporated a shroud with a shape of cylindrical tube around the propeller for safety purposes (for example, Safeflight Copters, USA). A minimal gap between the propeller and the shroud was set to 3 mm. The use of a smaller gap (less than one millimetre) between the propeller and the shroud will work similarly to the impeller model [40] where the closeness of the internal propeller and the inner surface of the impeller housing minimises turbulences created near the rotating propeller ends. Therefore, the lifting force will improve. In usual multi-rotor helicopters, sufficiently flexible light materials (usually carbon fibre, plastic or styrofoam) are used. Creating a stiff shroud around the propeller with a gap of less than one millimetre is not reliable (mass and/or price of helicopter will increase).

Simulations

Simulations and experiments were made to understand how the shroud affected the lifting force. It is possible to modify shroud dimensions to understand how its size affects the lifting force. The diameter varied from 260 to 310 mm (Fig. 2) while the propeller used for calculations had a standard and not varied diameter equal to 254 mm (10 in). The height of the shroud changed between 20 mm and 60 mm.

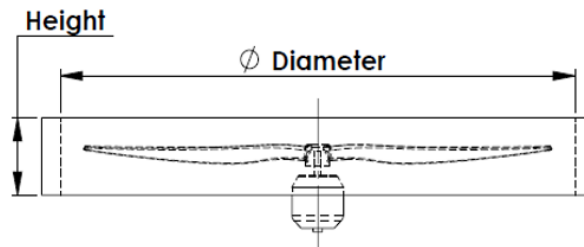


Figure 2. Changes of dimensions of the shroud around the propeller.

First, simulations were accomplished with CFD software to determine the lifting force. The lifting force produced by the propeller was determined at the propeller rotation

speed of 5000 rpm with a different diameter and height of the shroud. Next, the diameter of the shroud around the propeller was changed. Lifting force and motor power consumption were measured at different rotor angular velocities. Simulations and experiments for a case without a shroud around the propeller were also done. The lifting force created by propellers was calculated with the use of SolidWorks Flow Simulation. CFD results were confirmed by experiments. The propeller with diameter of 254 mm and standard pitch of 127 mm (10 x 5 inches) was used and the shroud diameter and its height were changed. All the simulations were made with rotor angular velocity of 5000 min^{-1} .

Figure 3 shows the dependency of the lifting force produced by one propeller with a certain diameter of the shroud around it. The shroud height was fixed to 40 mm. Minimum diameter was 260 mm (when the gap between the rotor and the shroud was only 3 mm at each side) and maximum was 310 mm. The graph shows that with an increase in the shroud diameter, the lifting force also increased. This happened because of airflow going into the upper part of the system and did not cover the shroud (Figs. 4 and 5). The dashed line shows the lifting force of the propeller without any shroud around it. It can be seen that even the gap equal to 30 mm decreased the lifting force but the decreasing was insignificant (about 6%). With further increasing of gap values, the influence of shroud disappeared.

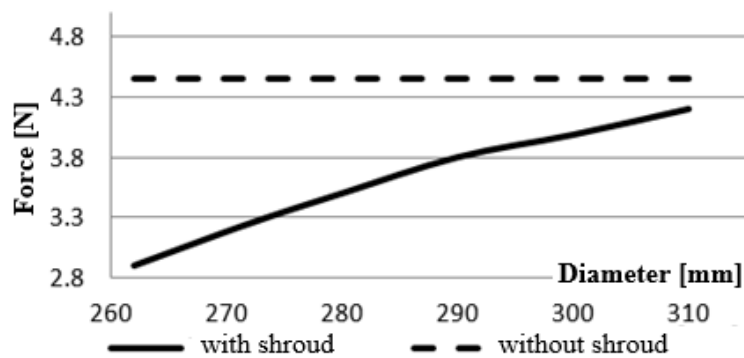


Figure 3. Experimental dependency of the lifting force on the diameter of the shroud around the propeller.

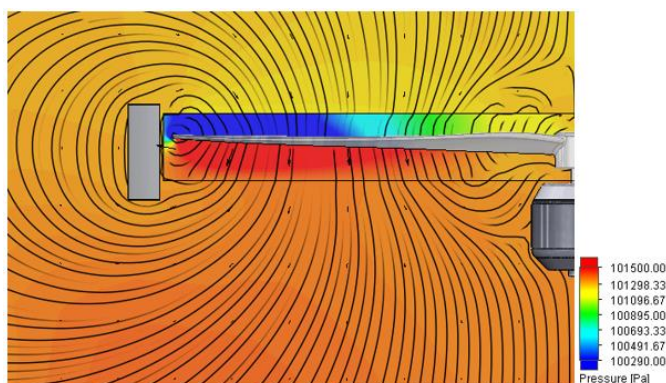


Figure 4. Pressure (colours) and velocity (vectors) distribution around the rotating propeller with the shroud with a diameter of 260 mm, gap was 3 mm.

Near the ends of the rotating propeller, vortices were created. Those areas led to the “overflow” of air from the higher-pressure region near the bottom surface of the

propeller to the lower pressure area near the top propeller surface. In Figure 4, the shroud diameter was 260 mm. When the shroud was maximally close (gap was only 3 mm) to the propeller, turbulence on the propeller ends changed and the vortex went around the shroud. In Figure 4, the colours show pressure while vectors show velocity direction and flow magnitude. When the propeller was surrounded by the shroud with diameter 290 mm and more (gap was more than 20 mm), vortex flow near the propeller ends went around the shroud partly only (Figure 5). With an increase of the shroud diameter, the propeller worked more like a separately standing (with no shroud) propeller. By changing the height of the shroud (Figure 6), the lifting force was decreasing from the height of 20 mm to 30 mm. This happened because of the small shroud height and small gap. If the shroud height was very small (less than 20 mm), airflow moved around it and produced a lifting force. With the increasing of shroud height (up to 30 mm), airflow was divided into two parts and the inner part will produce forces in the opposite side of the lifting force. With the increasing of shroud height to 40 mm and more, all useful airflow will be inside of the shroud and will produce a lifting force. At a larger height (up to 60 mm), the vortex moved to the inside of the formed tube (Figure 7) and this promoted a decrease of pressure difference reduction between the upper and lower surfaces of the propeller.

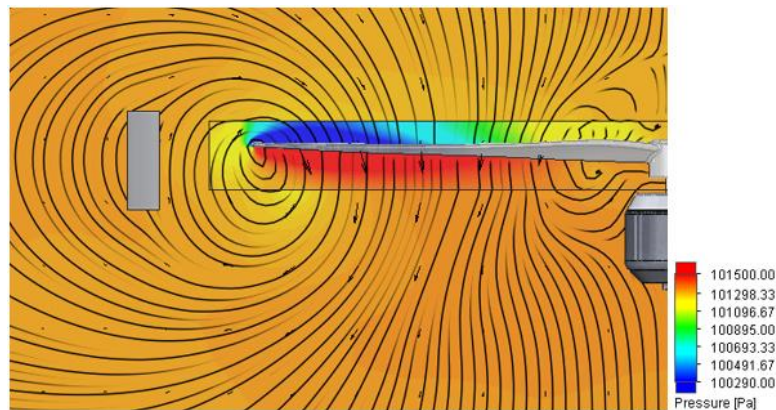


Figure 5. Pressure (colours) and velocity (vectors) distribution around the rotating propeller with a shroud diameter of 310 mm, gap was 28 mm.

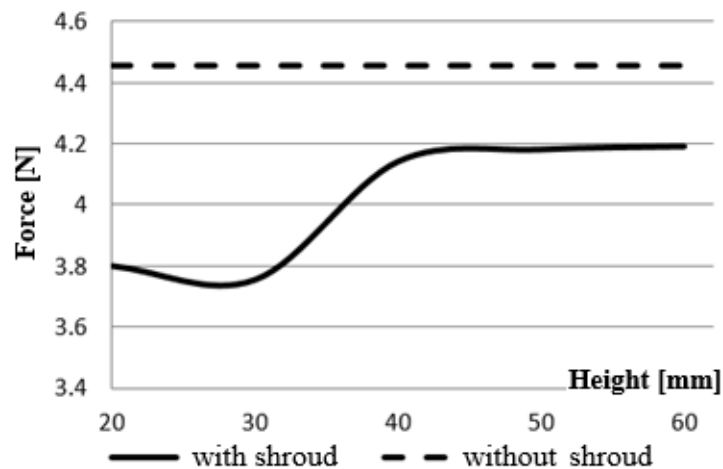


Figure 6. Dependency of the lifting force on the height of the shroud around the propeller, gap was 3 mm.

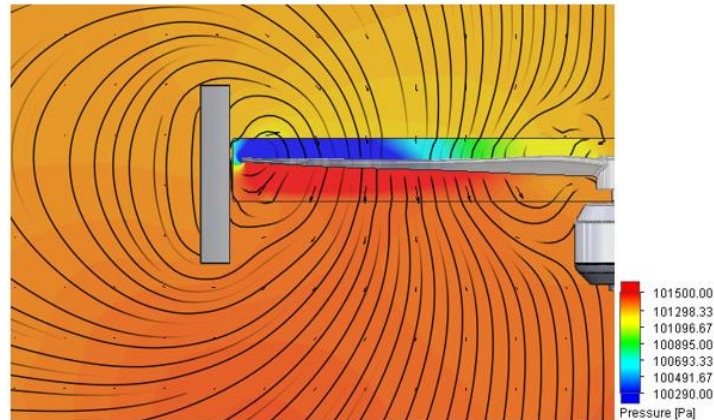


Figure 7. Pressure (colours) and velocity (vectors) distribution around the rotating propeller with a shroud height of 60 mm, gap was 3 mm.

Experiments

A shroud with a height of 60 mm and changeable diameter was made of steel sheet metal and fixed by three support stands (Figure 8). Altogether, measurements for five different diameters (from 270 mm to 310 mm with step of 10 mm) of the shroud were made. Experiments without a shroud around the propeller were also done.



Figure 8. Experiment set up.

The graph in Figure 9 shows the dependency of the lifting force on propeller angular velocity for different diameters of the shroud around the propeller. With the increase of the shroud diameter, the lifting force produced by the propeller also increased. This happened because of airflow that moved more smoothly around the propeller edge. Magnitudes of lifting force with the increase of gap values approached the lifting force produced by the propeller without any shrouds. Graphs in Figure 9 and 10 have a great correlation where the experiments were made at the propeller angular velocity of 5000 min^{-1} . During the experiments, power consumption measurements were also made using a bypass resistor. Figure 11 shows the dependency of the lifting force on the motor's power consumption. With the increase of the shroud diameter, the rotating propeller produced a higher lifting force and the system efficiency increased (power consumption decreased).

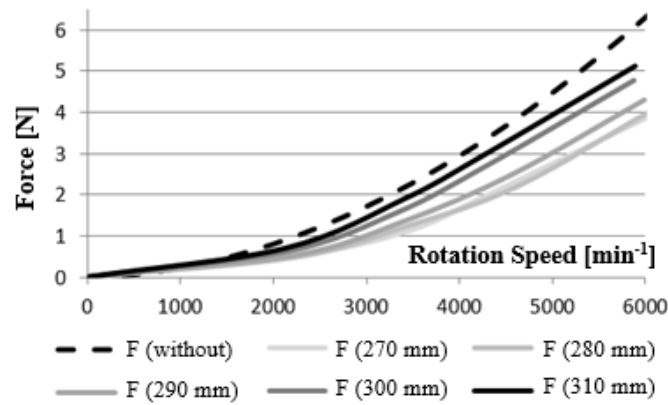


Figure 9. Dependency experiments of the lifting force on the propeller rotation speed for different diameters of the shroud around the propeller.

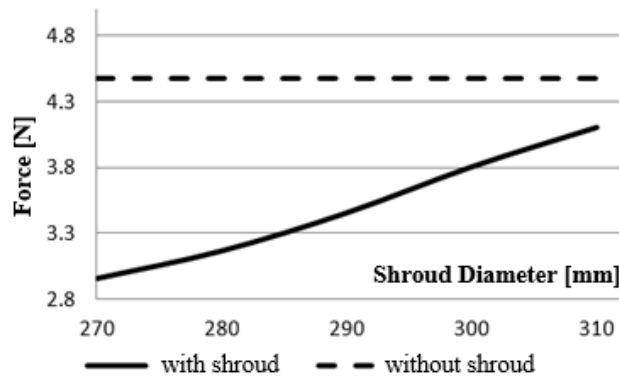


Figure 10. Dependency experiments of the lifting force on the diameters of the shroud around the propeller.

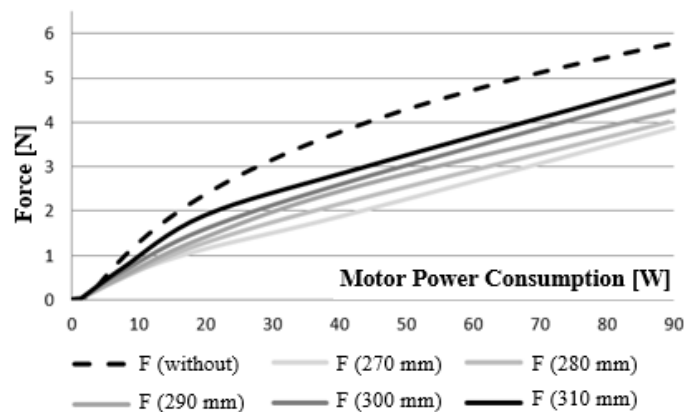


Figure 11. Dependency experiments of the lifting force on the motor power consumption.

The propeller created the highest lifting force when the shroud around the propeller was not used. Changing of the shroud diameter led to changing the lifting force. The smaller shroud diameter leads to the smaller the lifting force that can be produced at certain angular velocity and certain motor power. With an increase in the shroud height,

the lifting force increased up to 40 mm in height and then stabilised (similar to the rotor working in a long tube). The lifting force of a propeller with different diameters and height dimensions of straight safety shroud around it was less than the force produced by the propeller without the shroud.

CONCLUSIONS

The lifting force depends on the height of the shroud around the propeller and distance between the propeller and shroud. By changing the height of the shroud (with gap equal to 3 mm), the lifting force decreased about 3% from the height of 20 mm to 30 mm and then increased about 12% with the increase of shroud height to 50 mm. From a shroud height of 60 mm, the magnitude of lifting force stabilised and it was about 5% less than the force produced by the propeller without shroud. Shroud diameter (gap) also influenced the lifting force. At small gaps (3 mm), the lifting force decreased about 30% in comparison to the propeller without shroud. With the increase of the gap, lifting force increased but even at large gaps (more than 30 mm), it will be about 6% less than the force produced by the propeller without shroud.

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