Computational Investigation of the Effects of a Shroud to the Aerodynamic Characteristics of Rotors

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Abstract

Mutilcopters or multirotors have become standouts because they can hover and vertically take off and land. When they are in action, multirotors may need shrouds to protect their blades from impact and protect human from being wounded. However, the effects of shrouds to the aerodynamic characteristics of rotors must be considered. This paper will use computational fluid dynamics (CFD) to investigate the effects of a shroud to the thrust and power of a 9.5-inch rotor and 15-inch rotor. The results show that at the same rpm, a shrouded rotor can produce 20% more thrust than a free rotor. The power also increases but only by 6%. These results of 9.5-inch rotors agree with Baeder's results (2011), therefore, we apply to the case of 15-inch APC 15x4 blades in real life.

Keywords: shrouded rotor, ducted propeller, shrouded propeller

1. Introduction

UAVs are rising rapidly. There are many kinds of UAVs, such as fixed wings, rotary wings, flapping wings, hybrids, etc. Mutilcopters or multirotors have become standouts because they can hover and vertically take off and land. Some applications of multirotors are mapping, rescuing, broadcasting, shipping, military, agriculture, etc. When they are in action, multirotors may need shrouds. Trees and other obstacles could collide with blades.

Confined flying space with walls could also cause damages to the blades. When malfunctions occur, the vehicle falls and hits the ground. The shroud may help reduce damages.

Nevertheless, there is another usefulness of using shrouds. That is to protect human from being wounded by the high-speed rotating blades. Amazingly, using shrouds will significantly increase the aerodynamic performance of rotors [1]. Additional thrust comes from the shroud inlet as the low-pressure region of the blade propagates to the shroud inlet. Wake vortex contraction is reduced by using shrouds [2]. Therefore, using shrouds seems to have many benefits. But there are costs of using a shroud as its weights and sizes may reduce its advantages.

This paper will use computational fluid dynamics to investigate the effects of a shroud to the performance of rotors. Two main parameters are thrust and power. At first, the research will be carried out on a 9.5-inch rotor to validate the model. The results using SST *k-ω* turbulent model will be compared to Baeder's results (using Spalart-Allmaras turbulent model) [3] and experiments [4]. The results will also be compared with theoretical results from Pereira's [5]. Then, the simulation will be carried out on a 15-inch rotor which is used in our quarter rotor and in the experimental perspective project.

2. Nomenclature

A	shroud throat cross-sectional area
A_e	diffuser exit area
Ω	rotor rotational speed
σ_d	expansion ration = A_e/A
SR	shrouded rotor
OR	open rotor
P_i	ideal power
v_i	ideal induced velocity at rotor plane
w	induced velocity in far wake of rotor
D_t	shroud throat diameter
δ_{tip}	blade tip clearance
θ_d	diffuser included angle
L_d	shroud diffuser length
r_{lip}	shroud inlet lip radius
T	thrust
C_T	thrust coefficient = $T/\rho A(\Omega R)^2$
P	rotor shaft power
C_P	power coefficient = $P/\rho A(\Omega R)^3$
PL	power loading = T/P
FM	figure of merit = P_i/P
κ	induced power correction factor
N_b	number of blades
c	rotor blade chord
R	rotor radius
σ	rotor solidity = $N_b c/\pi R$

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3. Theory

Using momentum theory, we easily compare the ideal power of a shrouded rotor with that of a free rotor:

$$\frac{P_{iSR}}{P_{iOR}} = \frac{1}{\sqrt{2\sigma_d}}\left(\frac{T_{SR}}{T_{OR}}\right)^{3/2}\left(\frac{A_{OR}}{A_{SR}}\right)^{1/2} \quad (1)$$

If two cases produce the same thrust with the same disk area, then

$$\frac{P_{iSR}}{P_{iOR}} = \frac{1}{\sqrt{2\sigma_d}} \quad (2)$$

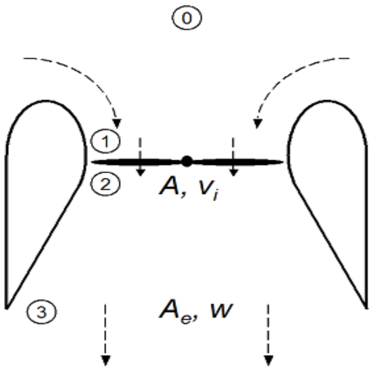

Fig. 1. Shrouded rotor schematic

That means if we can increase σ_d, we can reduce the ideal power. With shroud design in Fig. 1, we see that using $\theta d \geq 0$ would help increase σ_d. But we can not use large θd because of flow separation. If the two cases use the same amount of ideal power then

$$\frac{T_{SR}}{T_{OR}} = (2\sigma_d)^{1/3} \quad (3)$$

That means thrust of the shrouded rotor is greater than the open one ($\sigma_d \geq 1$). Blade tip clearance is believed to improve performance because it reduces the vortex tip losses.

C_P from theoretical analysis is:

$$\left(\kappa\frac{C_T^{3/2}}{\sqrt{2}} + \sigma\frac{C_D}{8}\right)/\eta \quad (4)$$

κ is chosen to be 1.75; $C_D = 0.1$; $\eta = 0.5$ [4]

To evaluate the performance, an efficiency parameter must be chosen. We could use either Power Loading or Figure of Merit:

- Power Loading (PL), the direct ratio of thrust to power, indicates the amount of thrust that can be generated with a given amount of power.
- Figure of Merit: $(FM) = \mathrm{Pi/P} = C_T^{3/2}/\sqrt{2}C_P$ (5), non-dimensional quantity.

This paper will be using PL because it gives us a direct and intuitively comparable quantity.

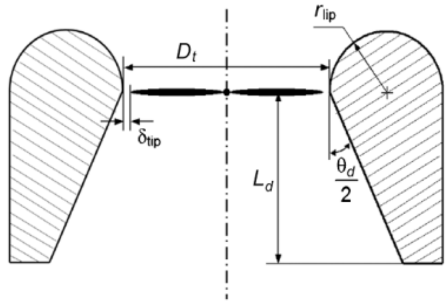

Fig. 2. Shroud design and its parameters

4. Methodology

The software used is Fluent. This research uses Single Rotating Reference Frame method. Turbulent model is chosen to be SST *k-ω* other than Spalart-Allmaras in Baeder's research [3]. The SST k-ω model was often merited for its good behavior in adverse pressure gradients and separating flow. The reason of this choice is to compare the differences between two turbulent models.

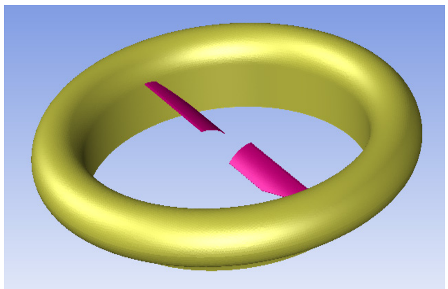

Fig. 3. Rotor and shroud model

Table 1. 9.5-inch rotor & shroud configuration

Rotor configuration	Shroud configuration
Rotor radius 121 mm	Throat diameter 247 mm
Taper ratio 2:1, leading edge remains straight	Tip clearance: 2.5 mm (1% D_t)
Taper starting point: 60% span location	Inlet lip radius: 9%
Blade chord: 25 mm	Diffuser length: 15%
Airfoil: Circular arc profile, 10% camber, 2% thickness, leading edge sharpened from the 8% chord location	Diffuser angle: 0º

The 15-inch rotor model is achieved from an APC propeller 15x4 by 3D scanning. Its shroud is scaled from that of the 9.5-inch rotor.

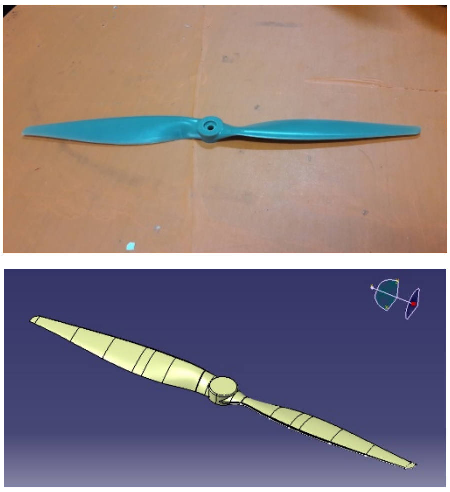

Fig. 4. APC propeller 15x4 & 15-inch rotor model

The rotating domain includes both the rotor and the shroud. The choice of blade tip clearance is important. If blade tip clearance is too small, the interfaces between two domains would affect the flow region between the blade and the shroud. That region is believed to have complex flow properties and we should avoid putting interfaces in that region.

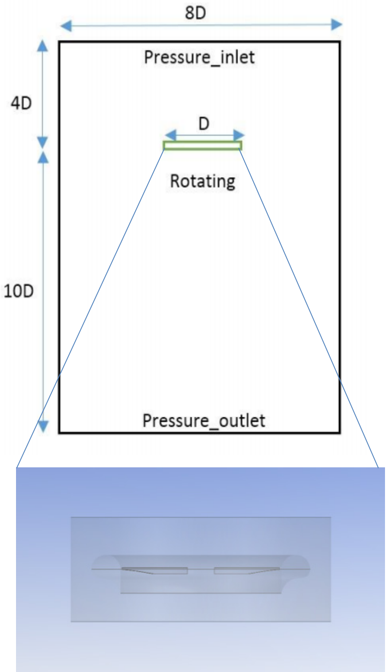

Fig. 5. Two flow domains & Rotating domain

The shroud is fixed to the ground reference frame by using appropriate boundary layers. Hence, the interaction between them is simulated with complete fidelity. Mesh is generated using Meshing module and then converted to Polyhedral mesh using Fluent.

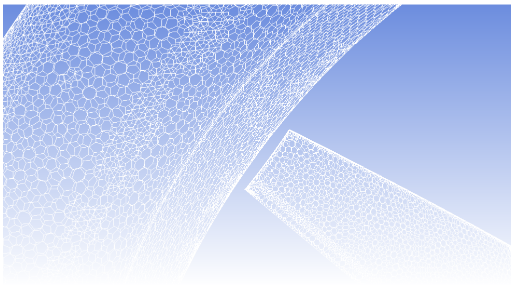

Fig. 6. Polyhedral mesh on blade and shroud surfaces

Because SST k-ω model requires y+ to be around 1 (smaller $y+$ is better if we can afford). We need to estimate the first layer cell heights (FLH) of blade and shroud. If the results do not give us desired y+, we need to come back to reduce this height. Using flat-plate boundary layer theory, we could introduce FLH:

$$Re = \frac{\rho U_\infty L}{\mu} = 3.035.201 \qquad (6)$$

$$C_f = \frac{0.026}{Re^{1/7}} = 0.0031 \qquad (7)$$

$$\tau_{wall} = \frac{C_f \rho U_\infty{}^2}{2} = 3.7 \qquad (8)$$

$$U_{friction} = \sqrt{\frac{\tau_{wall}}{\rho}} = 1.74 \qquad (9)$$

$$First\ Layer\ Height = \frac{y^+ \mu}{U_{friction} \rho} = 0.008\ (\text{mm})$$

FLH is rounded and taken by 0.01 mm.

Table 2. Inflation setup

Inflation Option	First Layer Thickness
First Layer Height	0.01 mm
Maximum Layers	10

This paper covers four series of simulations:

1) 9-inch free rotor from 1500 rpm to 3500 rpm

2) 9-inch shrouded rotor from 1500 rpm to 3500 rpm

3) 15-inch free rotor from 1000 rpm to 4000 rpm

4) 15-inch shrouded rotor from 1000 rpm to 4000 rpm

The results of the first two series will be compared with Baeder's CFD results [3] and their experiments [4] to validate the model. Then the last series will be used to predict the effects of a shroud to the performance of APC propeller 15x4.

4. Results

In order to see results, we first need to check the $y+$ values on blade and shroud surfaces

Y+ values at the leading-edge region and near the blade tip are greatest. This is predictable due to high local Reynolds numbers in this region. The region on the shroud near the blade tip also has higher *y+* values than that on the rest of the shroud, the reason is because the air is pulled by the blades. We see that maximum *y+* value is about 1.138, so our result is reliable.

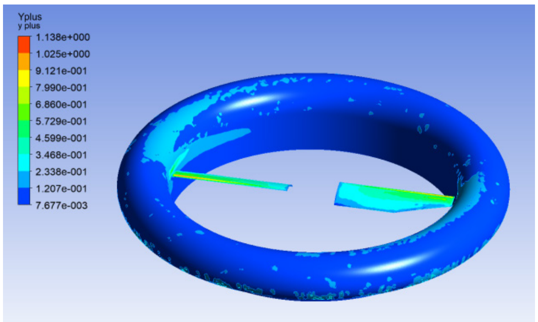

Fig. 7. Y+ values

Look at figure 8, we find that the low-pressure region on the blade is propagated to the inlet of the shroud. In addition, the maximum pressure is approximately equal to the atmospheric pressure located below the shroud. This is the source of extra thrust on the shroud. The small blade tip clearance also makes the low-pressure air on the blade not to go downward.

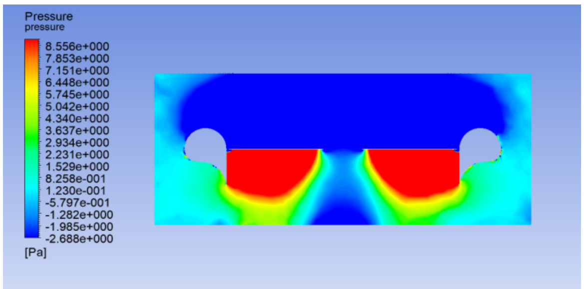

Fig. 8. Pressure contours

Results of 9-inch rotor

Figure 9 shows that power loading increases when shroud is used in the current research. Power loading increases about 12% to 16%. We also find that with higher RPM, power loading of both free and shrouded rotors decreases.

Look at figure 10, we see that the presence of the shroud reduces the slipstream contraction of open propeller. Especially, with the presence of the diffuser, the flow tends to stick to the wall of it. This increase σ_d, reduces ideal power and improves performance of the rotor.

The thrust and power are now compared with Baeder's results: the adherence among all results confirms the coherence of the present methodology. Figure 11 shows that the thrust and the power increase in the function of RPM. The thrusts in both cases (free and shrouded rotors) are very close to those of Baeder's simulation. The biggest difference is respectively 2.5% in the case of free rotors, and 4.5% in the case of shrouded rotors, at 1500 rpm. The power of the shrouded rotor seems to have large discrepancy, up to 9% at 3250 rpm, while that of the free rotor is 5.6% at 1750 rpm. The difference may be due to different turbulent models chosen.

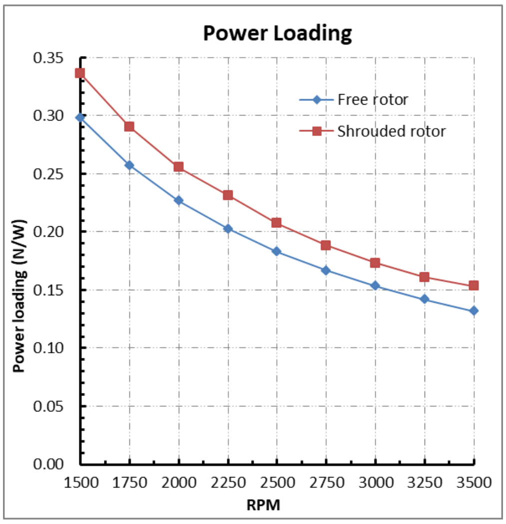

Fig. 9. Power loading of 9-inch rotor

However, when compared to experimental data, the present study results in a smaller error than the Baeder's study [3]. Figure 11 also shows the coherence between the present work and experimental data. The result is confirmed, with the difference of power being about 3% maximum in case of shrouded rotors. The difference of thrusts is 8% maximum in case of free rotors.

The *Cp* values above is of free rotors. *Cp* values from the current work and those from analysis [5] are relatively the same with different range of RPM. The coherence of the present methodology is confirmed.

Table 3. C_P comparison

RPM	C_p (analysis) [5]	Cp (numerical)	Error (%)
1500	0.00350592	0.00340746	2.8
1750	0.00350946	0.00341554	2.7
2000	0.00351202	0.00342019	2.6
2250	0.00351431	0.00342682	2.5
2500	0.00351626	0.00343389	2.3
2750	0.00351790	0.00343985	2.2
3000	0.00351939	0.00344565	2.1
3250	0.00352071	0.00345367	1.9
3500	0.00352184	0.00345976	1.8

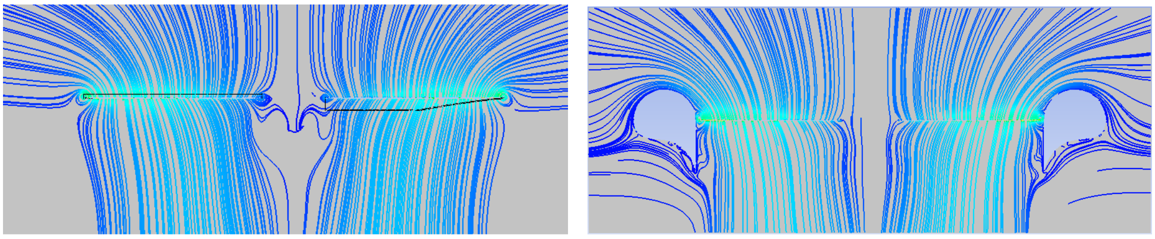

Fig. 10. Streamlines of free rotor (left) & shrouded rotor (right)

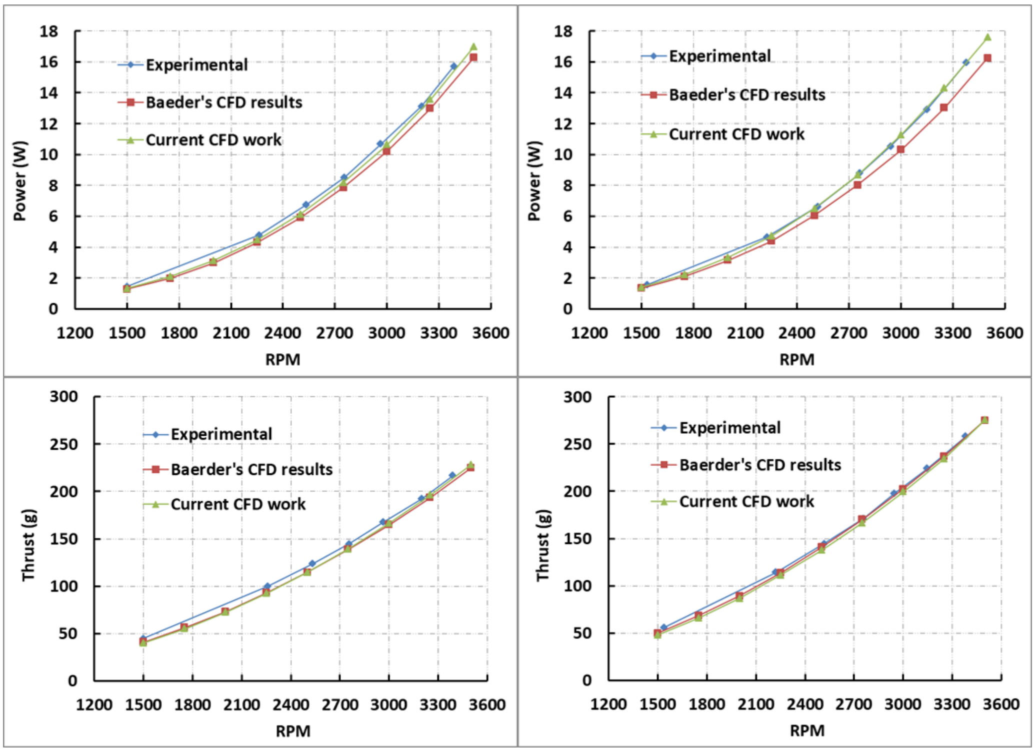

Fig. 11. CFD result comparisons: free rotor (left) & shrouded rotor (right)

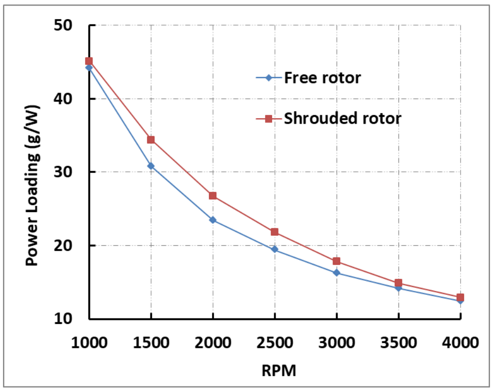

Fig. 12. 15-inch rotor: free rotor & shrouded rotor

Results of 15-inch rotor

The real propeller APC 15x4 was scanned and the output model is imported to the simulation. Like the 9-inch rotor case, the thrust and the power increase in the function of RPM while the power loading of both free and shrouded rotors decreases. Power loading of the 15-inch shrouded rotor is greater than the free rotor (Figure 12). From here, we can conclude that the shrouded rotor is more efficient than the free rotor despite of the rotor's diameter.

4. Conclusion

The shrouded rotor configuration gives better performance than the open propeller in the case of 9-inch rotor. Both experiments and computational fluid dynamics show the same trends. With current shroud configuration, the thrust is greater than the open propeller due to extra thrust on the shroud, while the power remains relatively the same. Power loading is hence greater for shrouded rotors. The values of C_P in CFD results are coherent with analysis results. From that, simulations of the 15-inch rotor are investigated to predict the thrust, the power and the Power loading. It will be the reference to develop an experimental band of the real propeller in the perspective project.

The results hold only for the hover mode with static wind. In addition, these simulations do not account for the weight of the shroud. If the weight of the shroud is greater than the extra thrust, using shrouds will be less effective.

STT *k-ω* turbulent model provides more accurate results than Spalart-Allamas in this research. The current work shows better results when compared to experiments [4].

There are a lot of other shroud configurations which can provide better performance, such as the shroud with elliptical inlet. With present configuration, we must do more research of changing other parameters such as inlet radius, blade tip clearance, diffuser angle, diffuser length, etc.

Acknowledgment

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References

[1] Vikram Hrishikeshavan, James Black, Inderjit Chopra; Design and Testing of a Quad Shrouded Rotor Micro Air Vehicle in Hover; Journal of aircraft Vol. 51, No. 3, p779-791 (2014).

[2] Jason L. Pereira, Inderjit Chopra; Hover Tests of Micro Aerial Vehicle–Scale Shrouded Rotors, Part I: Performance Characteristics; Journal Of The American Helicopter Society 54, 012001 (2009).

[3] Vinod K. Lakshminarayan, James D. Baeder; Computational Investigation of Microscale Shrouded Rotor (2011)

[4] Vikram Hrishikeshavan, Jayant Sirohi, Marat Tishchenko, Inderjit Chopra; Design, Development, and Testing of a Shrouded Single-Rotor Micro Air Vehicle with Antitorque; Journal Of The American Helicopter Society 56, 012008 (2011).

[5] Hover And Wind-Tunnel Testing Of Shrouded Rotors For Improved Micro Air Vehicle Design, Jason L. Pereira, Doctor of Philosophy (2008).