Variable Speed Tail Rotors for Helicopters with Variable Speed Main Rotors

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ABSTRACT

Variable tail rotor speed is investigated as a method for reducing tail rotor power, and improving helicopter performance. A helicopter model able to predict the main rotor and tail rotor powers is presented, and the flight test data of the UH-60A helicopter is used for validation. The predictions of the main and tail rotor powers are generally in good agreement with flight tests, which justifies the use of the present method in analyzing main and tail rotors. Reducing the main rotor speed can result in lower main rotor power at certain flight conditions. However, it increases the main rotor torque and the corresponding required tail rotor thrust to trim, which then decreases the yaw control margin of the tail rotor. In hover, the tail rotor may not be able to provide enough thrust to counter the main rotor torque, if it is slowed to follow the main rotor speed. The main rotor speed corresponding to the minimum main rotor power increases, if the change of tail rotor power in hover is considered. As a helicopter translated to cruise, the induced power decreases, and the profile power increases, with the profile power dominating the tail rotor. Reducing the tail rotor speed in cruise reduces the profile power to give a 37% reduction in total tail rotor power and a 1.4% reduction to total helicopter power. In high speed flight, varying the tail rotor speed is ineffective for power reduction. The power reduction obtained by the variable tail rotor speed is reduced for increased helicopter weight.

Keywords: Tail Rotor; Main Rotor; Variable Speed; Power

NOMENCLATURE

A_b	blade area
C_{d0}	airfoil drag coefficient
D	fuselage drag
K	empirical coefficient
P	power
P_b	baseline power
q	dynamic pressure (fuselage)
R	rotor radius
S_{FN}	fin area
S_{TR}	tail rotor area
S	rotor disk area
T	rotor thrust
T_{TR}^{net}	net tail rotor thrust
V	forward speed
v_i	induced velocity
α_{CANT}	canted angle

α_s	aircraft pitch angle
μ	advance ratio
ρ	air density
Ω	rotor speed

Subscript

MR	main rotor
TR	tail rotor

1.0 INTRODUCTION

Varying the helicopter main rotor speed is understood to be an effective means to reduce main rotor power required in hover and forward flight [1-8]. However, varying the tail rotor speed to improve helicopter flight performance has not yet been addressed. This may be attributed to two factors. Tail rotors usually consume a small amount of total helicopter power (typically, 10%-20%). Varying tail rotor speed saves a small amount of tail rotor power, which means that even substantial savings to tail rotor power have a small impact on overall helicopter power. Secondly, a variable speed tail rotor will incur increased weight and complexity that further reduce the overall system efficiency.

Decreasing rotor speed can effectively reduce the rotor power in cruise at low altitude, and light weight conditions, though the power reductions diminish with increasing altitude and/or gross weight, and at low speed flight [5]. However, it should be noted that an increase of the main rotor torque accompanies the decrease of main rotor speed [6], especially in hover and low speed forward flight. To counter the increase in torque, the tail rotor thrust has to be increased, which increases the tail rotor power, and decreases the yaw control margin. Reducing the tail rotor speed to reduce tail rotor power may become limited if the tail rotor cannot produce enough thrust to counter the main rotor torque and provide enough yaw control margin for maneuvers, gusts or crosswinds. However, the power savings by optimizing the tail rotor speed may be worthwhile in some flight conditions.

Typically, the tail rotor to main rotor speed ratio is fixed by a constant transmission [8], so that varying the main rotor speed implies a variation of tail rotor speed by the same ratio. An alternative is to vary the tail rotor speed independently with either a variable speed tail rotor transmission, or an independent motor [9, 10]. For variable speed main rotors, there are three strategies of changing tail rotor speed: 1) the tail rotor operates with constant speed; 2) the tail rotor changes speed following the variation of the main rotor speed, and the transmission ratio is fixed; 3) the tail rotor can change speed independently and operate at the speed corresponding to the minimum power.

A helicopter model is developed to evaluate and compare the additional power savings available by changing the tail rotor speed for a variable speed main rotor. The flight data of the UH-60A helicopter [11] is utilized for validation. The tail rotor thrust and power for each tail rotor speed strategy are analyzed to investigate the benefit of variable tail rotor speed for an variable speed main rotor.

2.0 MODELING AND VERIFICATION

A helicopter power prediction model is used in this work. The main rotor blade model is based on a rigid beam with a hinge offset and a hinge spring, which are used to match the fundamental flap-wise blade frequency. Look-up table aerofoil aerodynamics is used to calculate the lift and drag coefficients of blade elements according to the local resultant Mach number and angle of attack. The induced velocity over the rotor disk is predicted by the Pitt-Peters inflow model [12], which captures the first azimuthal harmonic variation of the induced velocity. The hub forces and moments of the main rotor are derived from the resultant root forces and moments of rotor blades by the blade element theory. The fuselage is treated as a rigid body with aerodynamic forces and moments. These forces and moments acting on the main rotor, tail rotor and fuselage contribute to the equilibrium equations of the helicopter [13], which are solved to obtain the converged or trimmed pitch controls and rotor attitude angles. The yaw degree is not considered in the trim.

The required tail rotor thrust to counter the main rotor torque is determined by the torque divided by the distance from the hub center of the tail rotor to the main rotor shaft. The tail rotor thrust and power are obtained by performing a numerical integration over the blade elements along the blade radius and azimuth with uniform induced velocity [13]. Accounting for the canted angle of tail rotor, the net thrust provided by the tail rotor to counter the main rotor torque can be written as

$$T_{TR}^{net} = F_{TR} T_{TR} \cos \alpha_{CANT} \tag{1}$$

The tail rotor blockage effects due to the vertical tail are accounted for following the approach of [14, 15]. The scaling factor F_{TR} is

$$F_{TR} = 1 - \frac{3}{4}\frac{S_{FN}}{S_{TR}} \tag{2}$$

The helicopter model is validated by the flight data of the UH-60A helicopter [11]. The parameters of the main and tail rotors are listed in Tables 1 and 2 [16-18]. The fuselage drag force is given by [11],

$$\frac{D}{q}\ (\mathrm{ft}^2) = 35.83 + 0.016 \times (1.66\alpha_s^2) \tag{3}$$

The vertical distance from the mass center of helicopter to the rotor hub is 1.78 m. The main and tail rotor power predictions are compared to the flight test data of the UH-60A at two weight coefficients in Figure 1 including the comparison with the data for off nominal rotor speed analysis (11% rotor speed reduction) in [5]. The predictions of the main and tail rotor powers are in good agreement with the flight test data.

Table 1

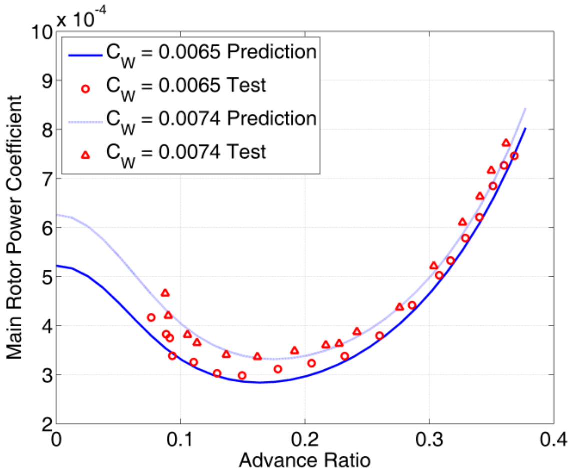
Main rotor parameters[16-18]

Parameter	Value
Main Rotor Radius	8.18 m
Nominal Main Rotor Speed	27.0 rad/s
Blade Chord Length	6.45% *R*
Blade Twist	Nonlinear
Blade Airfoil	SC1095/SC1094R8
Number of Blades	4
Flap Hinge Offset	4.66% *R*
Blade Mass per Unit Length	13.9 kg/m
Longitudinal Shaft Tilt	3^{o}

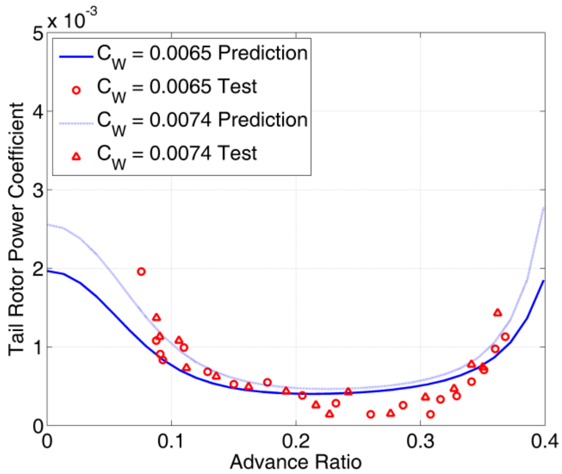
Table 2

Tail rotor parameters[16-18]

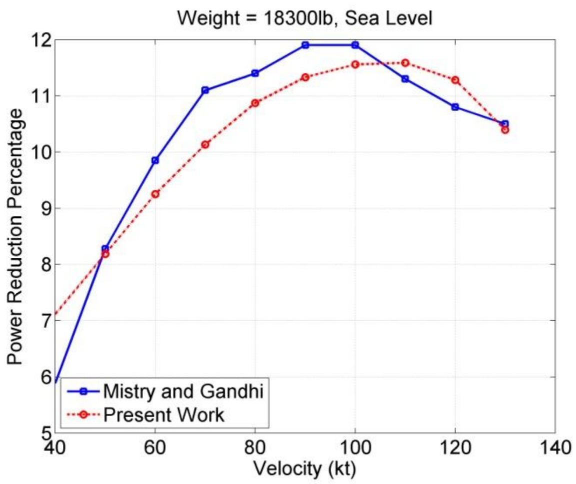
Parameter	Value
Tail Rotor Radius	1.68 m
Nominal Tail Rotor Speed	124.6 rad/s (4.62 Ω_{MR})
Tail Rotor Blade Chord	0.25 m
Tail Rotor Blade Twist	-18^o
Airfoil	SC1095
Number of Blades	4
Tail Rotor Torque Arm	9.93 m



(a) comparison of main rotor power with fight test[11]



(b) comparison of tail rotor power with flight test [11]



(c) comparison with the data for off nominal RPM analysis [5].

Figure 1 Comparison with test data.

3.0 FLIGHT PERFORMANCE ANALYSIS

The tail rotor power has contributions from profile power, associated with viscous drag, and induced power, associated with lift. The profile power dominates the tail rotor power in medium to high speed forward flight. Reducing the tail rotor speed may have a strong impact on the tail rotor power in these fight conditions. The power reduction percentage is defined as

$$\eta = (1 - P/P_b) \times 100\% \tag{4}$$

In this work, the helicopter power means the sum of the main rotor and tail rotor power. In the following analysis, three strategies of the tail rotor speed are investigated. 'Fixed Ω_{TR}' means that the tail rotor speed remains unchanged. 'Following Ω_{MR}' means that the transmission ratio is fixed so that the tail rotor speed varies with the main rotor speed. 'Optimal Ω_{TR}' denotes that the tail rotor speed can vary independently and operates at the speed corresponding to the minimum tail rotor power. To seek the optimal speed, the rotor speed was varied in 1% increments until minimum power is determined. The weight coefficient at the nominal main rotor speed is 0.0065.

3.1 HOVER

The main rotor power, and the corresponding power reduction as functions of the main rotor speed in hover, are shown in Figure 2. The maximum main rotor power reduction is 8.0% at 73% rotor speed, however, the additional power reduction below 80% rotor speed is small. Below 70% rotor speed, the reduction in power reduces.

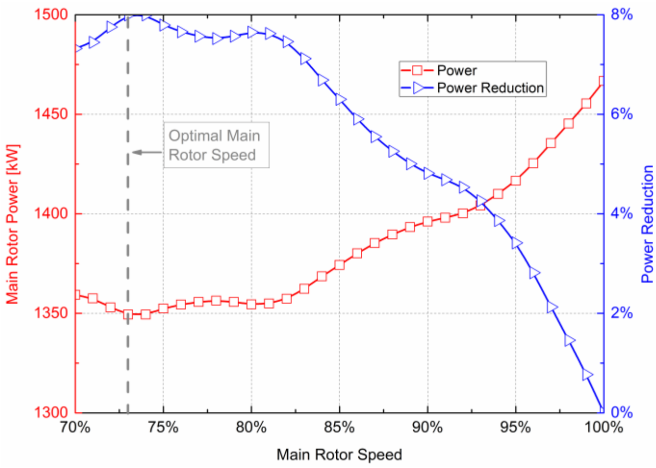


Figure 2 Main rotor power versus main rotor speed in hover.

The tail rotor power and corresponding power reductions for the different strategies of tail rotor speed versus main rotor speed are shown in Figure 3. The tail rotor power increases with decreasing main rotor speed, which is due to the increase of tail rotor thrust and therefore increased tail rotor induced power. Optimizing tail rotor speed in hover has a small potential for decreasing the tail rotor power. The largest reduction to tail rotor power occurs for 100% of the nominal main rotor speed and 81% of the nominal tail rotor speed resulting in 3.15% of the tail rotor power reduction or just 0.375% of the helicopter power. There is no significant performance improvement from tail rotor speed optimization in hover due to the small expected power savings.

The helicopter power, and the corresponding power reductions at different main rotor speeds in hover, are shown in Figure 4. The optimal main rotor speed changes from 73% for the minimum main rotor power to 82% for the minimum helicopter power for all tail rotor speed strategies. This is due to the increase of the tail rotor thrust and the corresponding increase of the induced power, and the slow decrease of the main rotor profile power with decreasing main rotor speed. For the optimal speed main rotor, it is necessary to consider the power changes of the tail rotor. The reduced rotor speed range required for minimum power (73% to 82%) implies a simpler transmission and is an important design consideration.

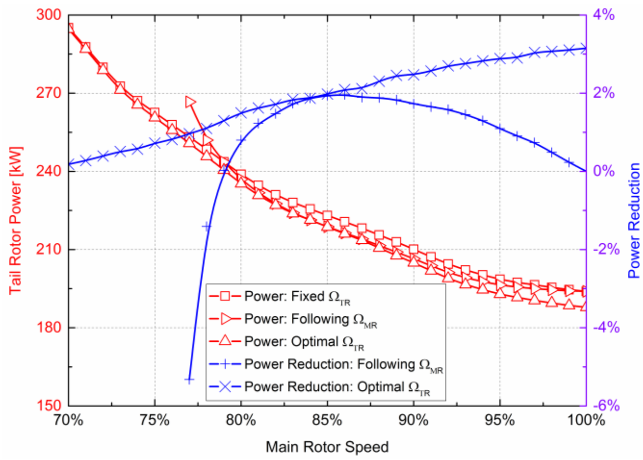


Figure 3 Tail rotor power versus main rotor speed in hover.

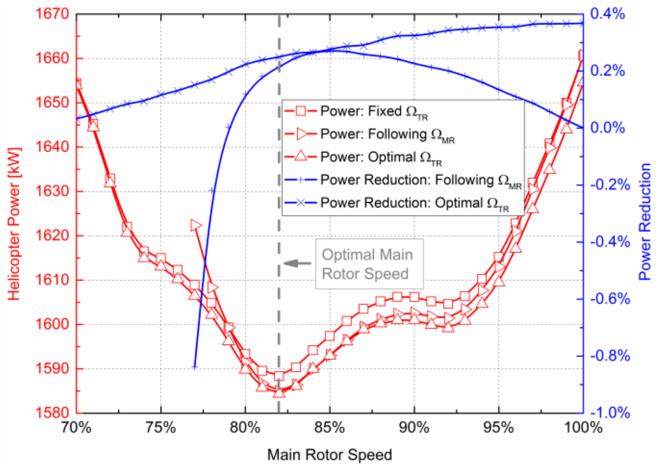


Figure 4 Helicopter power versus main rotor speed in hover.

Figure 5 shows the required tail rotor thrust corresponding to the reduction in main rotor speed. The required tail rotor thrust increases with decreasing main rotor speed. Figure 5 includes the maximum thrust capability of the three tail rotor speed variation strategies. 1) For a fixed tail rotor speed, a large margin is maintained. 2) For the tail rotor speed operating following the change of main rotor speed, the maximum tail rotor thrust decreases dramatically with decreasing main rotor speed. At 76% of the nominal main rotor speed (i.e. 76% of the nominal tail rotor speed), the tail rotor cannot provide enough thrust to counter the main rotor torque. 3) For a tail rotor operating at the speed corresponding to the minimum power, the maximum tail rotor thrust degrades dramatically compared with the maximum thrust generated at the nominal speed. The yaw control margin for maneuvers decreases accordingly.

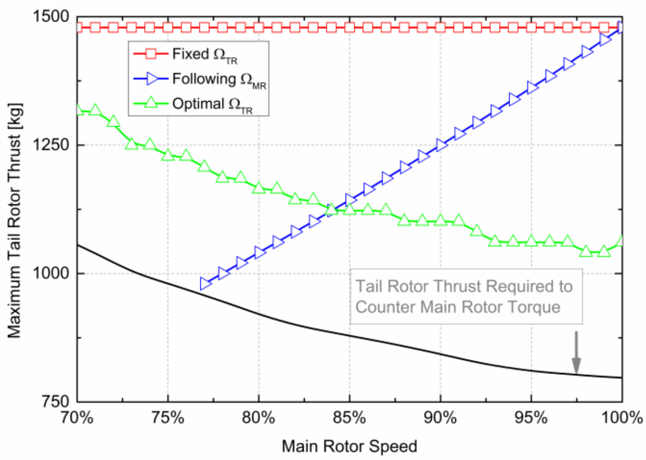


Figure 5 Tail rotor thrust versus main rotor speed in hover.

The tail rotor speeds for the different strategies in hover are shown in Figure 6. The optimal tail rotor speed generally increases with decreasing main rotor speed. At low or high main rotor speeds, a tail rotor speed that follows the main rotor speed is far from optimal, and the tail rotor cannot obtain the maximum possible power reduction.

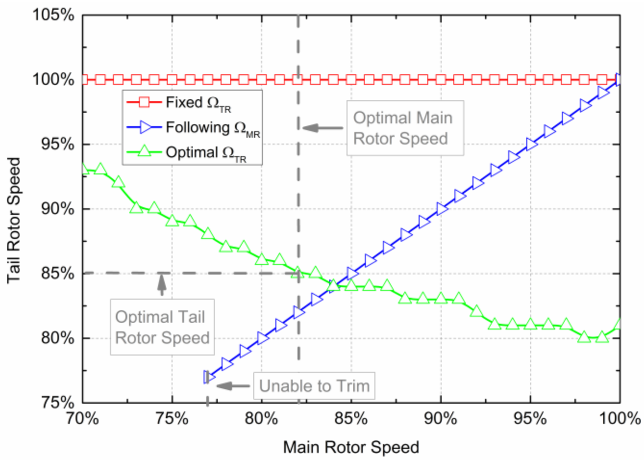


Figure 6 Tail rotor speed versus main rotor speed in hover.

3.2 CRUISE CONDITION

Figure 7 shows the main rotor power at different rotor speeds at a cruise speed of 130 km/h ($\mu = 0.164$ at $100\%\Omega_{MR}$). The main rotor speed for the minimum main rotor power is 81% of the nominal speed, corresponding to a power reduction of 12.7% of the main rotor power. Reducing the main rotor speed in cruise leads to larger power savings than in hover (8.0%).

For the different strategies of tail rotor speed, the tail rotor power and the corresponding power reduction versus the main rotor speed are shown in Figure 8. For the fixed tail rotor speed or the optimal tail rotor speed, the tail rotor power increases with decreasing the main rotor speed. For a tail rotor following the main rotor speed, the tail rotor power generally decreases. The optimization of the tail rotor speed can obtain significant additional power savings. At 100% main rotor speed, the tail rotor power can be reduced by 15.6 kW (37% reduction) compared to 6.1 kW in hover. In cruise, the induced power decreases due to the decrease of the required tail rotor thrust, while the profile power increases due to the higher forward speed, with the profile power dominating the tail rotor power. Optimizing the tail rotor speed to reduce the profile power can therefore have a stronger influence on the tail rotor power than in hover.

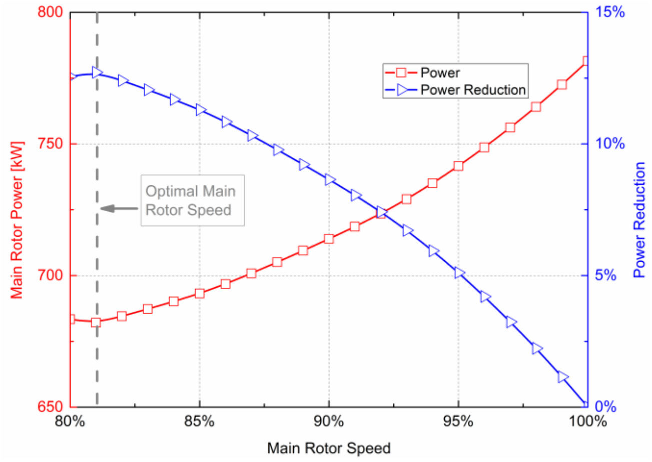


Figure 7 Main rotor power versus main rotor speed in cruise.

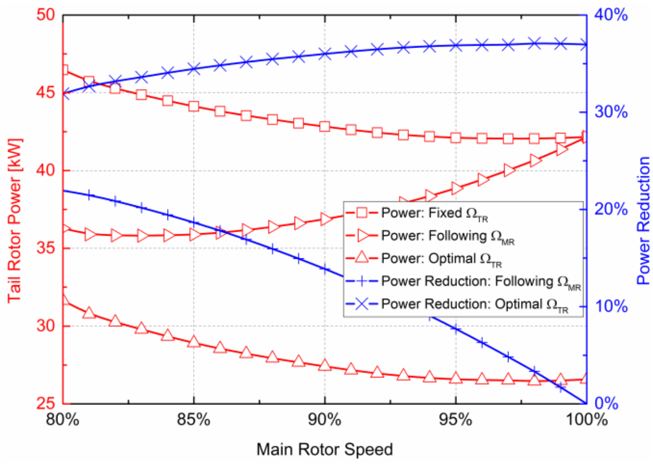


Figure 8 Tail rotor power versus main rotor speed in cruise.

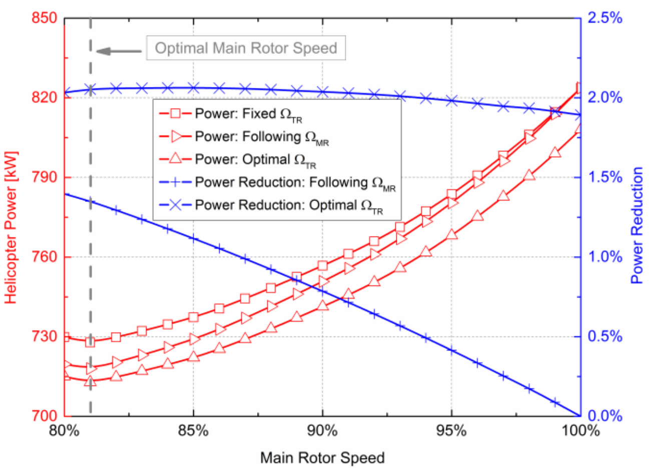


Figure 9 Helicopter power versus main rotor speed in cruise.

The helicopter power, and the corresponding tail rotor power reductions for different main rotor speeds in cruise are shown in Figure 9. With the consideration of the change of tail rotor power, the optimal main rotor speed remains at 81%.

The maximum helicopter power reduction is 13.5% by optimizing both main and tail rotor speeds. The main rotor contributes to the power reduction by 12.1%, and the tail rotor contributes 1.4%. Optimizing the tail rotor speed at 100% main rotor speed can reduce the total power by 1.9%. The decrease of the main rotor speed causes an increase of tail rotor thrust and power. This shrinks the power reduction from 1.9% to 1.4%. Optimizing the tail rotor speed in cruise may be worth pursuing in helicopter design, if the savings in fuel weight are larger than the weight penalty for implementing the variable rotor speeds.

The required tail rotor thrust to counter the main rotor torque and the maximum tail rotor thrusts for the different strategies of tail rotor speed, are shown in Figure 10. The required tail rotor thrust increases with decreasing main rotor speed. However, these values are much smaller than those in hover due to the decrease of the main rotor power in cruise. The tail rotor is probably sized to provide adequate performance in hover and high speed flight (high power), and may be inefficient in cruise. For the cases of fixed tail rotor speed or for following the main rotor speed, the maximum tail rotor thrusts are much larger than the required thrust to counter the main rotor torque. With the optimal tail rotor speed, the maximum tail rotor thrust reduces significantly, which is due to the reduced tail rotor speed. This corresponds to a minimum of the tail rotor power.

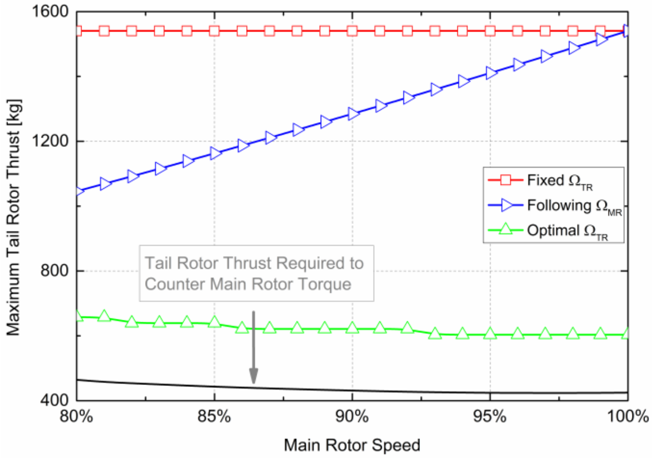


Figure 10 Tail rotor thrust versus main rotor speed in cruise.

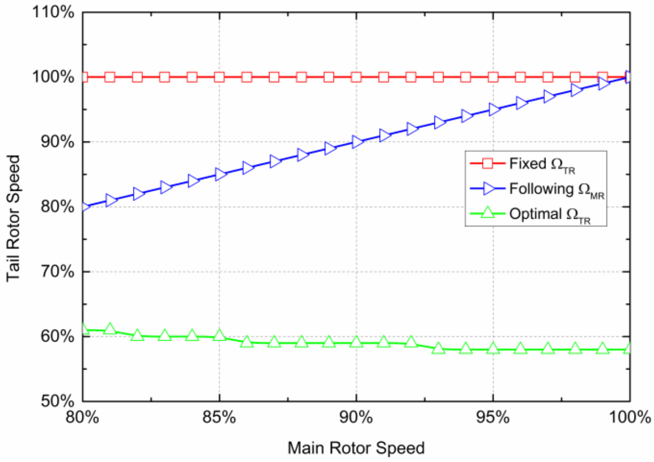


Figure 11 Tail rotor speed versus main rotor speed in cruise.

The tail rotor speeds for the different strategies in cruise are shown in Figure 11. The optimal tail rotor speeds are significantly smaller than the values in hover, and the values following the main rotor speed. The optimal tail rotor speed increases slightly with decreasing the main rotor speed.

3.3 HIGH SPEED FLIGHT

At a speed of 300 km/h, the main rotor power levels at different rotor speeds are shown in Figure 12. Varying the main rotor speed cannot achieve significant power reduction in high speed flight. For the different strategies of tail rotor speed, the tail rotor power and the corresponding power reductions versus main rotor speed are shown in Figure 13. The tail rotor power increases with decreasing main rotor speed. With 5% reduction of the main rotor speed, the tail rotor power increased by 35.8% of the tail rotor power at the 100% speed for the fixed speed tail rotor. Optimizing the tail rotor speed is ineffective in obtaining power savings at high speed flight, and it does not affect the optimized main rotor speed.

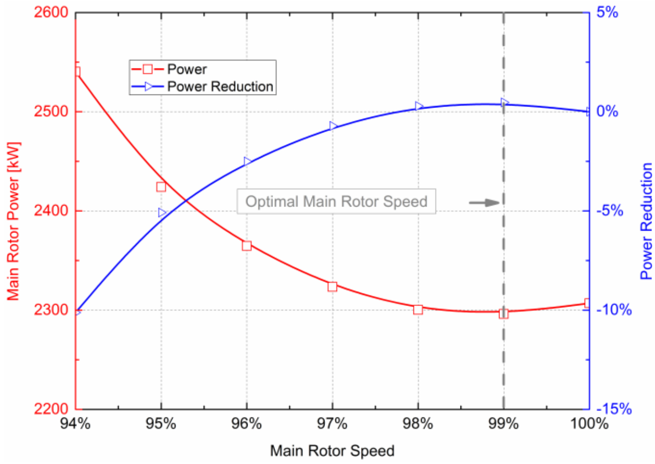


Figure 12 Main rotor power versus main rotor speed in high speed flight.

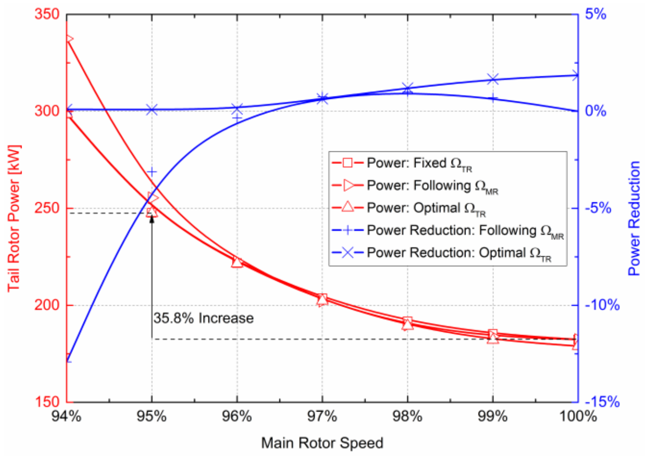


Figure 13 Tail rotor power versus main rotor speed in high speed flight.

3.4 HIGH THRUST

To show the effect of the main rotor thrust on the tail rotor speed optimization, the helicopter weight coefficient is now increased to 0.0074. The helicopter powers for the baseline and the different strategies of tail rotor speed are shown in Figure 14 for a sweep of air speeds. The largest potential for reducing power through optimizing the main and tail rotor speeds is in cruise. The power reduction first increases with forward speed and then decreases. The corresponding power reductions are shown in Figure 15. In hover, the reductions are about 2.0% for the three strategies analysed here. The percentages increase to the maximum values 6.9%, 7.7% and 8.3% for the fixed, following and optimal strategies respectively at a speed of 140 km/h. The maximum power reduction is smaller than the value at the weight coefficient of 0.0065. Optimizing the tail rotor speed results in 1.4% larger power reduction than the fixed tail rotor speed.

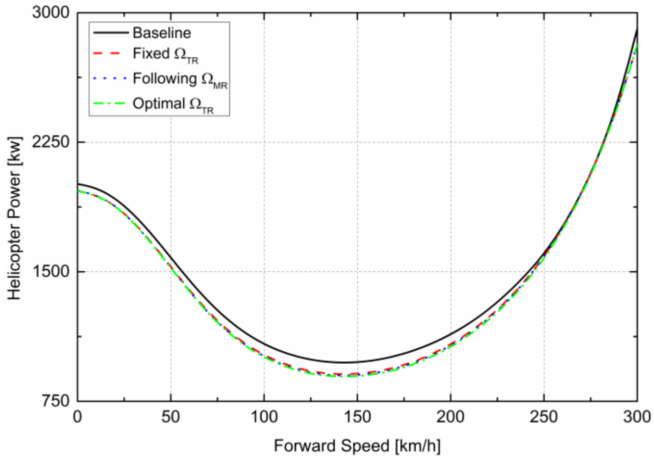


Figure 14 Total power with forward speed at the weight coefficient 0.0074.

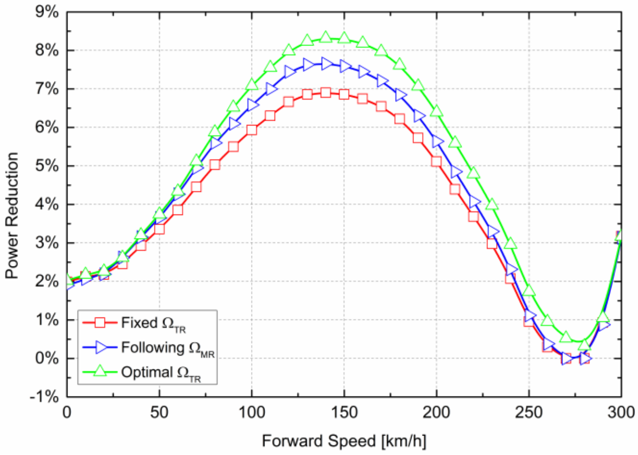


Figure 15 Power reductions with forward speed.

The main and tail rotor speeds for different minimum powers are shown in Figure 16. These speeds are overall larger than the values at the lower weight coefficient 0.0065. In hover and low speed forward flight, the optimal main rotor speed for minimum main rotor power is lower than the main rotor speed for the minimum helicopter power, which is similar to the lower weight coefficient. The optimal tail rotor speed decreases with forward speed until cruise. In cruise, the tail rotor speed drops to 65%, and then increases to 100% at high speed flight. This trend is not in sync with the optimal main rotor speed, which indicates that a tail rotor speed that follows the main rotor speed will not maximize power savings.

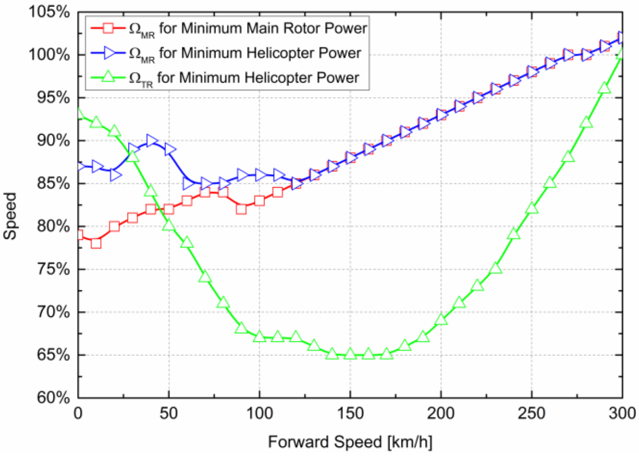


Figure 16 Rotor speed with forward speed.

4.0 CONCLUSIONS

A helicopter model based on the UH-60A was used to investigate potential helicopter performance improvements by varying the tail rotor speed for helicopters with variable speed main rotor. The flight test data of the UH-60A helicopter was used to validate the analysis. The predictions of the main and tail rotor power are generally in good agreement with the flight tests, verifying the application of the present method in analyzing main rotor and tail rotor performance. Key conclusions of this study are:

1) The tail rotor thrust required to counter the main rotor torque in hover increases with decreasing main rotor speed due to the increase of the main rotor torque.
2) In hover, the maximum tail rotor thrust decreases significantly with decreasing main rotor speed, until the tail rotor cannot provide enough thrust to counter the main rotor torque. Including the tail rotor power in the total helicopter power results in a higher optimal main rotor speed. The reduced range of main rotor speed may be beneficial for the design of variable speed main rotors.
3) In cruise, optimizing the tail rotor speed can lead to greater power savings than in hover or high speed flight. The maximum power reduction is over 30% of the baseline tail rotor power, or about 2% of the total helicopter power. The optimal main rotor speed for the minimum main rotor power is the same as the optimal main rotor speed for the minimum helicopter power.
4) In high speed flight, optimization of the tail rotor speed provides no significant improvement.
5) The power reduction by varying the main and tail rotor speeds becomes smaller as the helicopter weight increases.
6) The optimal tail rotor speed is close to the nominal speed in hover, drops in cruise, and increases in high speed flight.
7) Optimizing the tail rotor speed provides larger power savings than a tail rotor speed that follows the main rotor speed.

Finally, it is noted that the precise numbers given here are specific to the helicopter model used in this work. For a rotor with different planform, airfoils, diameter, etc., the optimum deployment and performance improvement levels may vary. Nevertheless similar trends are expected. An optimization that includes more parameters e.g. chord, twist, etc. may result in greater power savings.

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