



Han, D., Dong, C. and Barakos, G. N. (2017) Performance Improvement of Variable Speed Rotors by Gurney Flaps. In: 43rd European Rotorcraft Forum, Milan, Italy, 12-15 Sep 2017.

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# Performance Improvement of Variable Speed Rotors by Gurney Flaps

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## Abstract

Gurney flaps are used for improving the performance of variable speed rotors. An analytical model able to predict helicopter rotor power is first presented, and the flight data of the UH-60A helicopter is used for validation. The predictions of the rotor power are in good agreement with the flight test data, justifying the use of this tool in analyzing helicopter performance. A fixed Gurney flap can enhance the performance of variable speed rotors and expand the corresponding flight envelop, especially near stall and high speed flight. A retractable Gurney flap at 1/rev yields more power savings than a fixed Gurney flap or a retractable one with higher a harmonic prescribed motion. At a speed of 200km/h, the retractable Gurney flap at 1/rev can obtain 3.22% more power reduction at a rotor speed of 85% nominal rotor speed, and this value is 8.37% at a speed of 220km/h. The height corresponding to the minimum power increases slowly in low to medium speed flight, and increases dramatically in high speed flight. With increasing take-off weight (i.e. rotor thrust), the retractable Gurney flap at 1/rev can obtain more rotor power savings.

Keywords: Performance; Variable Speed Rotor; Gurney Flap; Harmonic Motion

## 1. INTRODUCTION

Reducing rotor speed in hover and forward flight, has been extensively investigated to save helicopter power and improve helicopter performance [1-9]. Kang et al. analyzed several rotor morphing concepts, and the comparisons showed that a reduced rotor speed could yield more power savings than other investigated concepts [10]. Varying rotor speed, primarily changes the rotor profile power. At high thrust and/or high speed, the rotor induced power and/or fuselage parasitic power dominate the helicopter power. The potential of the variable rotor speed in decreasing rotor power diminishes significantly in these flight states [6, 8].

The Gurney Flap (GF) is a lift enhancement device, invented by the race car driver Dan Gurney in 1960s [11]. GF attracted much attention not only due to its efficiency and simplicity, but also due to its lower power consumption than a plain-flap configuration[12]. It has been extensively explored to

improve helicopter rotor performance. The investigations by Kentfield indicated that GFs could enhance helicopter rotor performance under many circumstances [13], which is primarily due to the increase of the maximum lift coefficient, and lift-to-drag ratio in the retreating side of rotor blades. Kinzel et al. utilized deployable GFs (Miniature Trailing-Edge Effectors, MiTEs) to obtain helicopter power savings [14]. The analysis showed that MiTEs were most effective for increasing performance at high altitude, large payloads, high flight speeds, or any combination of these, which is because of their better performance near stall. Pstrikakis et al. investigated the potential effect of a GF on the performance of W3 Sokol blade in hover and forward flight [15, 16]. The results showed an increase in the aerodynamic performance by GFs, especially for high thrust conditions. GFs can also be utilized to reduce vibrations in helicopter rotors. Min et al. calculated the performance of a rotor equipped with a GF in forward flight, and descent using a hybrid Navier-Stokes/free-wake solver [17]. Their

investigations indicated that GFs had the potential to reduce rotor vibratory loads, and the GF with fixed height could decrease the descent rate needed to maintain autorotation. Liu et al. used microflaps (deployable GFs) for vibration reduction [18]. Their open-loop phase-sweep studies showed more than 80% 4/rev vertical shear reduction at high-vibration BVI (blade vertex interaction) flight condition, and the closed-loop control analysis showed over 90% reduction in the combined vibration objective function. Min et al. used a dynamically deployed GF to conduct rotor vibration control [19]. The CFD-CSD (Computational Fluid Dynamics - Computational Structural Dynamics) coupled analysis showed that more than 80% 4/rev vertical vibratory hub load could be reduced with an optimized GF schedule, and the individual control of multiple segments of flaps along the blade span could be used to conduct multiple signal controls. It is obvious that GF can be used to improve helicopter rotor performance, especially in high thrust, high speed and/or high altitude, and may simultaneously reduce rotor vibratory loads.

With decreasing rotor speed, helicopter rotors have to increase the blade pitch angles to maintain balance due to the decrease of the dynamic pressure. This enlarges the stall area, and decreases the power savings obtained by the reduced rotor speed. To compensate this reduction of performance improvement, retractable GFs of variable height are utilized to improve the performance of variable speed rotors. A helicopter rotor power prediction model, which includes a blade model, aerofoil table look-up method, the Pitt-Peters inflow model [20], a fuselage model and a propulsive trim method [21], is used here. The flight data of the UH-60A helicopter [22] is utilized to validate the model. Parametric analyses of different retractable GFs were investigated with the validated model to explore how much power savings can be achieved further based on the power reduced by variable rotor speed.

## 2. MODELING AND VALIDATION

To determine the parameters of GF for minimum rotor power, a parameter sweep for each flight state is conducted. This process has to be repeated for several rotor power settings. If a single computation requires one minute of CPU time, to find the minimum power can span dozens of hours. Since the objective of this work is to explore the potential of GF in reducing the power of variable speed rotors, an analytical model to predict the helicopter rotor power is used. This model estimates the rotor power within less than a second using a standard personal computer.

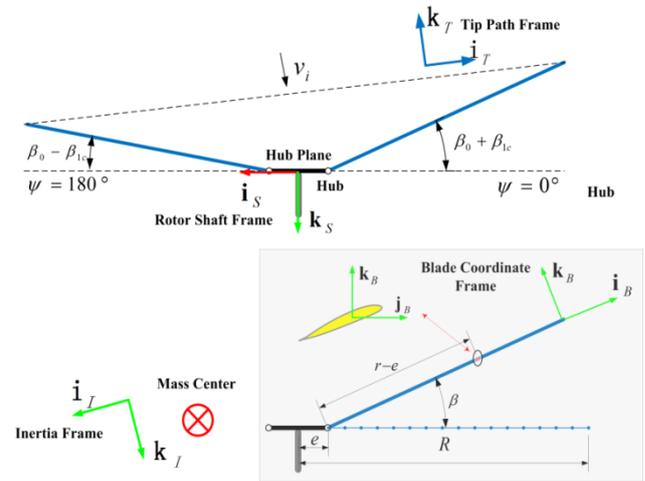


Figure 1 Coordinate frames.

The blade model is based on a rigid beam with a hinge offset and a hinge spring, used to match the fundamental flapwise blade frequency. For the analysis of the performance of variable speed rotors, using a rigid blade model and omitting the change of blade twist were indubitably acceptable [6]. GFs attached to rotor blades not only change the lift and drag coefficients, but also the moment coefficients. This can introduce the change of blade twist. Since advanced helicopters with variable speed rotors, such as X2 and A160, usually adopt the design of rigid rotors, the higher torsional stiffness can significantly reduce the change amplitude of blade twist. The inability in predicting the influence of the change of blade twist on the performance, lowers the prediction precision. However, it still renders

acceptable predictions for rotor performance analysis and comparisons [14, 23, 24].

The velocity vector of an arbitrary point on the pitch axis in the rotor tip path plane with respect to the local airflow is

$$\begin{Bmatrix} U_R \\ U_T \\ U_P \end{Bmatrix} = [T_{SB}]^T \begin{Bmatrix} \dot{r}_x \\ \dot{r}_y \\ \dot{r}_z \end{Bmatrix} - [T_{SI}]^T \begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix} - [T_{ST}]^T \begin{Bmatrix} 0 \\ 0 \\ v_i \end{Bmatrix} \quad (1)$$

where,  $\dot{r}_x$ ,  $\dot{r}_y$  and  $\dot{r}_z$  are the velocity components in the rotor shaft coordinate system of the arbitrary point on the pitch axis.  $V_x$ ,  $V_y$  and  $V_z$  are the components of local air velocity in the inertia frame.  $v_i$  is the induced velocity.  $[T_{BS}]$  denotes the transformation matrix from the rotor shaft frame to the blade airfoil frame.  $[T_{ST}]$  denotes the transformation matrix from the rotor tip path plane to the rotor shaft frame.  $[T_{SI}]$  denotes the

transformation matrix from the inertial frame to the rotor shaft frame, as shown in Figure 1. The induced velocity over the rotor disk is predicted by the Pitt-Peters inflow model [20], which captures the first harmonic variation of induced velocity in azimuth as following

$$\frac{v_i}{\Omega R} = \lambda_0 + \lambda_c \frac{r}{R} \cos\psi + \lambda_s \frac{r}{R} \sin\psi \quad (2)$$

where,  $\Omega$  is rotor speed,  $R$  rotor radius,  $\psi$  azimuth angle, and  $\lambda$  rotor inflow ratio,  $r$  radial position. The angle of attack and resultant velocity are derived from the velocity vector. Look-up table aerofoil aerodynamics is used to calculate the lift and drag coefficients of the blade elements according to the local resultant air flow and angle of attack.

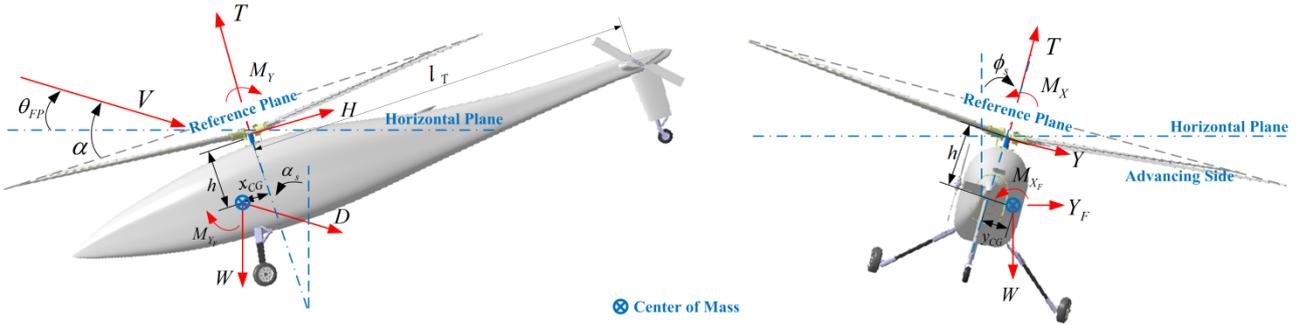


Figure 2 Forces and moments on a helicopter.

The hub forces and moments of the main rotor are derived from the resultant root forces and moments of the blades. The fuselage is treated as a rigid body with specified aerodynamic forces and moments. For simplicity, the thrust of the tail rotor is determined by the main rotor torque divided by the distance between the hub center of the tail rotor and the main rotor shaft. The power and collective pitch of the tail rotor are determined by the blade element theory with uniform inflow.

Given three pitch controls (collective and two cyclics) and two rotor shaft attitude angles (longitudinal and lateral tilts), the periodic response

of the rotor in steady forward flight can be obtained for a prescribed forward speed. The hub forces and moments of the main rotor are balanced by the forces and moments acting on the fuselage and tail rotor. The forces and moments on the fuselage are determined by the flight state and attitude angles. The thrust and power of the tail rotor are derived from the rotor torque and flight state. These force and moment components, as shown in Figure 2, constitute the equilibrium equations of the helicopter

$$\begin{cases} T - W = 0 \\ D + H - T\alpha_s = 0 \\ Y + Y_F + T\phi_s = 0 \\ M_Y + M_{Y_F} + W(h\alpha_s - x_{CG}) - hD = 0 \\ M_X + M_{X_F} + W(h\phi_s - y_{CG}) + hY_F = 0 \end{cases} \quad (3)$$

where,  $T$ ,  $H$ ,  $Y$ ,  $M_Y$  and  $M_X$  are the rotor thrust, drag force, side force, pitching moment and roll moment;  $D$ ,  $Y_F$ ,  $M_{Y_F}$  and  $M_{X_F}$  are fuselage drag, side force, pitching moment, and roll moment;  $W$  is helicopter weight;  $x_{CG}$ ,  $y_{CG}$  and  $h$  are the longitudinal, lateral and vertical distance from the mass center of the helicopter to the rotor hub center;  $\alpha_s$  and  $\phi_s$  are the longitudinal and later tilt angles of the rotor shaft. The equations are solved to update the pitch controls and rotor attitude angles for the next iteration. After several iterations of the periodic rotor responses and solutions of the equilibrium equations, the converged or trimmed pitch controls and rotor attitude angles can be obtained. Then, the main rotor power and related information of the helicopter can be derived.

The flight data of the UH-60A helicopter [22] is utilized to validate the model used in this work. The parameters of the main and tail rotors are listed in Tables 1 and 2 [25-28]. For the performance analysis, only the aerodynamic drag force is considered in the fuselage model. The fuselage drag equation utilized in the present analysis is [22]

$$\frac{D}{q} \text{ (ft}^2\text{)} = 35.83 + 0.016 \times (1.66\alpha_s^2) \quad (4)$$

where,  $D$  is the fuselage drag,  $q$  is the dynamic pressure, and  $\alpha_s$  is the aircraft pitch angle. The distance from the hub center of tail rotor to the rotor shaft is 9.93 m. The vertical distance from the mass center of the helicopter to the rotor hub is 1.78 m. The comparisons of the prediction of the rotor power with the flight test data for the takeoff weight coefficients 0.0065, 0.0074, 0.0083 and 0.0091 are shown in Figure 3. It is obvious that the predictions by the present method are generally in good agreement with the flight test data for the weights

considered. This justifies the use of present method for the analysis of helicopter performance.

|                            |                 |
|----------------------------|-----------------|
| Main Rotor Radius          | 8.18m           |
| Main Rotor Speed (100%)    | 27.0 rad/s      |
| Blade Chord Length         | 0.527m          |
| Blade Twist                | Nonlinear       |
| Blade Airfoil              | SC1095/SC1094R8 |
| Number of Blades           | 4               |
| Flap Hinge Offset          | 0.381 m         |
| Blade Mass per Unit Length | 13.9 kg/m       |
| Longitudinal Shaft Tilt    | 3°              |

Table 1: Main rotor parameters

|                        |             |
|------------------------|-------------|
| Tail Rotor Radius      | 1.68 m      |
| Tail Rotor Blade Chord | 0.247 m     |
| Tail Rotor Speed       | 124.6 rad/s |
| Tail Rotor Blade Twist | -18°        |
| Blade Airfoil          | NACA0012    |
| Number of Blades       | 4           |

Table 2: Tail rotor parameters

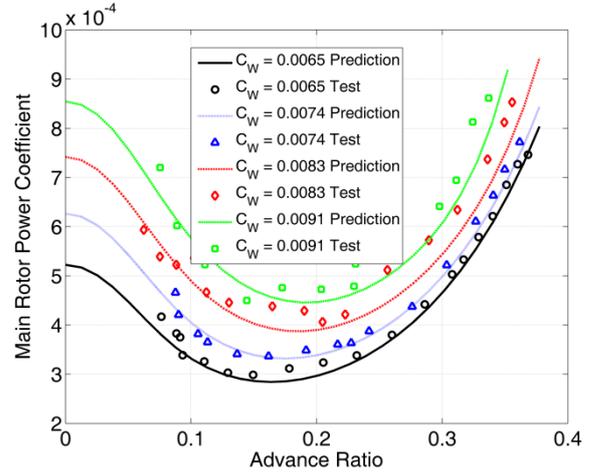


Figure 3 Comparison of predictions with flight test data.

The methodology in Ref. 13 to capture the change of the aerodynamic characteristics of NACA 0012 airfoil is utilized. The comparisons of the lift coefficients between the test in Ref. 29 and the prediction based the C81 airfoil table are shown in

Figure 4, which shows the prediction is generally in good agreement with the test data. In the following analysis, the rotor blade airfoil is changed to the airfoil NACA 0012. The parameters of the GF are shown in Figure 5. where,  $d$  is the height of GF,  $c$  chord length. For a retractable GF, the mounting angle  $\beta$  is  $90^\circ$ , and the height is given as a prescribed value. In the following analysis, the maximum height ratio  $d/c$  is limited to be less than 5.0% and the GF extends from 70% to 90% of the rotor radius.

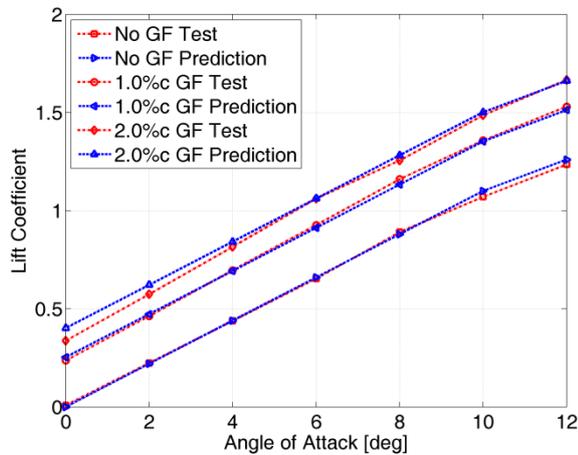


Figure 4 Comparison between test and prediction data.

The power reduction ratio is defined to determine the benefit in rotor power savings as

$$\eta = (1 - P/P_b) \times 100\% \quad (5)$$

where,  $P$  is the rotor power to be compared with, and  $P_b$  is the baseline rotor power. The baseline power is defined as the rotor power at sea level at  $100\% \Omega$  and without any GF. In the following analysis, the baseline weight is 8322.3kg, and the corresponding weight coefficient at  $100\% \Omega$  is 0.0065.

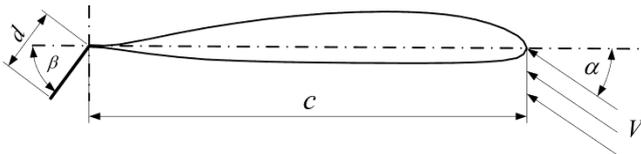


Figure 5 Configuration of a GF.

### 3. GF WITH FIXED HEIGHT

For different rotor speeds and GF heights, the helicopter rotor power is shown in Figure 6. The power for the fixed-height GF has a minimum for heights ranging  $0 \leq d/c \leq 5\%$ . To determine the minimum power, a parameter sweep with 0.1% increment of height ratio at a prescribed forward flight speed is conducted. With decreasing rotor speed, the rotor power generally decreases. On the other hand, the rotor power at  $85\% \Omega$  is larger than the value at  $90\% \Omega$ , when the forward speed is larger than 240 km/h. So, for high speed forward flight, an excessive decrease of the rotor speed is not necessary. Compared with the clean blade, the power with GF decreases by 3.67, 6.67, 14.2 and 30.6 kW, at a forward speed of 200 km/h and rotor speeds of  $100\%$ ,  $95\%$ ,  $90\%$  and  $85\%$ , respectively. It is obvious that, at lower rotor speeds, larger power savings can be obtained, and the GF can enhance the performance of variable speed rotors.

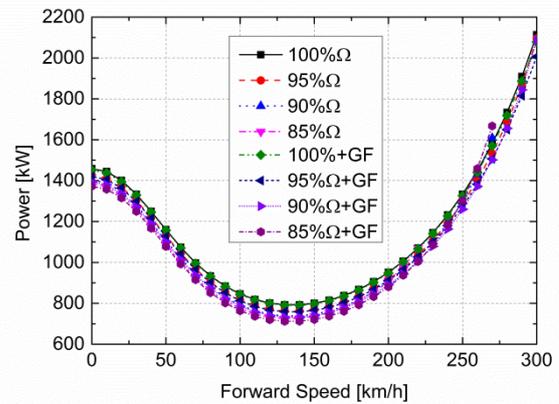


Figure 6 Helicopter power for different rotor speeds and GF heights.

The corresponding power reductions are shown in Figure 7. At full rotor speed, the rotor power with the GF decreases by 0.499% in hover, and varies smoothly with flight speed. At a speed of 250 km/h, the reduction begins to increase distinctly with forward speed, and touches the maximum value 1.66% at a speed of 300 km/h. The GF exhibits better performance at high speed flight. For rotor speeds of  $95\% \Omega$ ,  $90\% \Omega$ , and  $85\% \Omega$ , the power

reduction increases first and then decreases. With decreasing rotor speed, the attainable maximum forward speed decreases. When the rotor speed is reduced to  $85\% \Omega$ , the helicopter cannot fly faster than 220 km/h. With the GF, the maximum speed extends to 270 km/h. At a rotor speed of  $90\% \Omega$ , the difference between the power reductions with and without GF is 0.63%, 0.67%, 1.49%, 2.92% and 6.77% at 0, 100, 200, 250, and 270 km/h, respectively. Since the GF does not change the blade tip Mach number, the better airfoil performance with the GF, especially near stall, is responsible for the power reduction. It is obvious that the GF can enhance the performance of variable speed rotors and expand the corresponding flight envelop, especially near stall and a high speed flight.

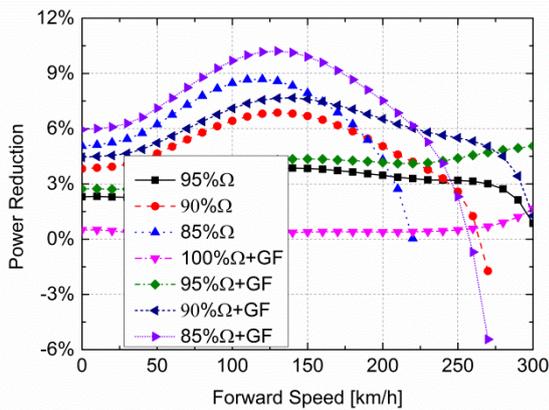


Figure 7 Power reduction for different rotor speeds and GF heights.

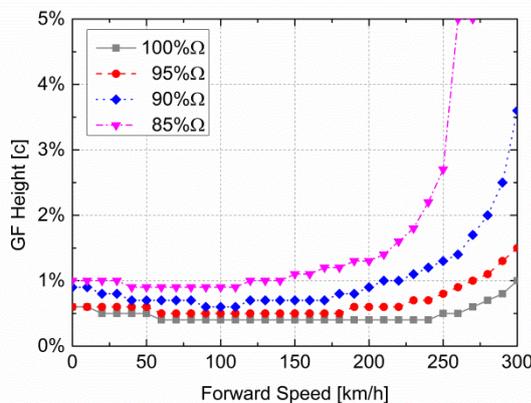


Figure 8 GF height corresponding to minimum power.

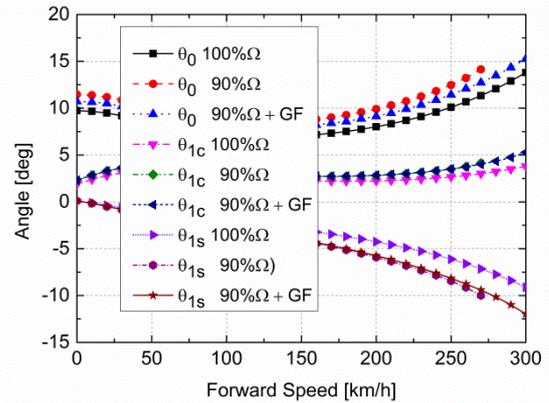


Figure 9 The collective, longitudinal and lateral cyclic pitches for the fixed height GF.

The GF heights corresponding to minimum power are shown in Figure 8. With the forward speed, the height first decreases slightly, and then increases. At high speed flight, it increases dramatically. With decreasing rotor speed, the required GF height increases. At a speed of 260 km/h and rotor speed of  $85\% \Omega$ , the height ratio is 5.0%. It can therefore be anticipated that, larger maximum forward speed can be obtained with larger GF height.

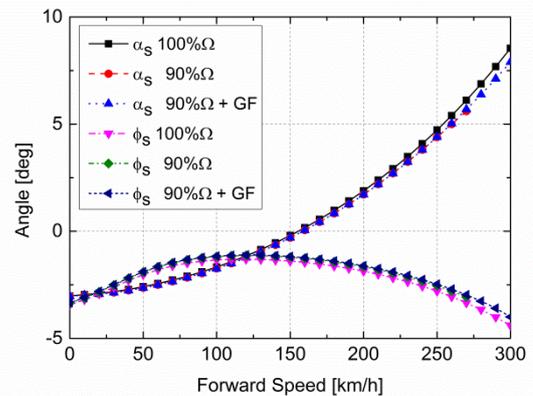


Figure 10 The longitudinal and lateral tilts of rotor shaft for the fixed height GF.

The collective pitch  $\theta_0$ , longitudinal cyclic pitch  $\theta_{1c}$ , and lateral cyclic pitch  $\theta_{1s}$  at a rotor speed of  $90\% \Omega$  with and without GF compared with the values at  $100\% \Omega$  are shown in Figure 9. With decreasing rotor speed, the absolute values of the collective and cyclic pitches increase. The decrease of the dynamic pressure results in increased pitch

angles to maintain balance of the helicopter. These trends are similar as those in Ref. 30. The deployment of the GF decreases  $\theta_0$ , and the magnitude is relatively small. The  $\theta_{1c}$  and  $\theta_{1s}$  changes slightly. The longitudinal tilt angle  $\alpha_s$  and lateral tilt angle  $\phi_s$  of rotor shaft are shown in Figure 10.  $\alpha_s$  and  $\phi_s$  decrease with decreasing rotor speed, which have the same trend as those in Ref. 30.  $\alpha_s$  and  $\phi_s$  changes little compared with the values without the GF. It is obvious that the GF primarily changes  $\theta_0$ , which is due to the lift enhancement effect.

#### 4. RETRACTABLE GF

In the following analysis, the GF height is prescribed as

$$h = A[1 + \sin(n\Omega t + \phi)] \quad (6)$$

where,  $A$  is the average GF height,  $n$  the harmonic number,  $\Omega$  the rotor speed, and  $\phi$  the phase of harmonic motion.

##### 4.1. 1/rev

Figure 11 shows the rotor power for different forward speeds and phases of the 1/rev harmonic motion of the GF. The amplitude of the GF motion is set to 2%c. At low speed flight, the change of the rotor power with the flap phase is substantially small. At high speed flight, the power changes distinctly. At a speed of 300km/h, and at 340° phase, the power increases by 3.99%. As the phase shifts to 180°, the power decreases by 3.51%. The phase of the GF motion has a significant influence on the rotor power. The phases corresponding to the minimum power for the investigated speeds was around 180°. In the following analyses related to the 1/rev GF motion, the phase was set to 180°.

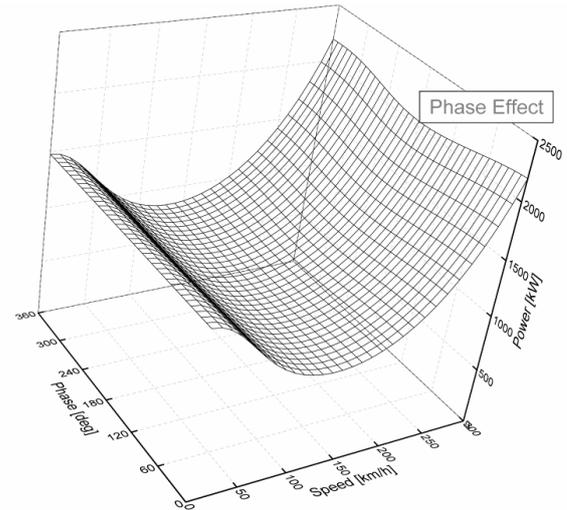


Figure 11 Rotor power for different forward speed and the phase of GF (2%c).

Figure 12 shows the power reduction for different rotor speeds. Compared to the fixed GF height, the 1/rev retractable GF yielded the larger power reduction. At a speed of 300 km/h and rotor speed of 100% $\Omega$ , the maximum power reduction was 3.51%. This value was 1.66% for the fixed height GF. As the rotor speed decreases by 5%, the two values became 7.63% and 5.06%. With increasing forward speed, the difference between the power reduction with and without the GF increases, especially for high speed flight. At a speed of 200 km/h, the differences at speeds of 95% $\Omega$ , 90% $\Omega$  and 85% $\Omega$  were 0.70%, 1.49% and 3.22%, respectively. At 220 km/h and 85% $\Omega$ , the difference was 8.37%, which is much larger than the value at the speed of 200km/h. It is obvious that the GF can achieve better performance improvement in lower rotor speeds and higher speed flight, which indicates that the GF is more effective at high thrust and speed. The maximum forward speed can be attained by deploying the GF, highlighting its potential in expanding the flight envelope of helicopters.

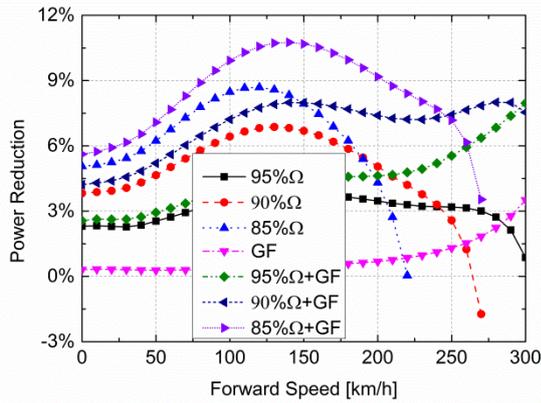
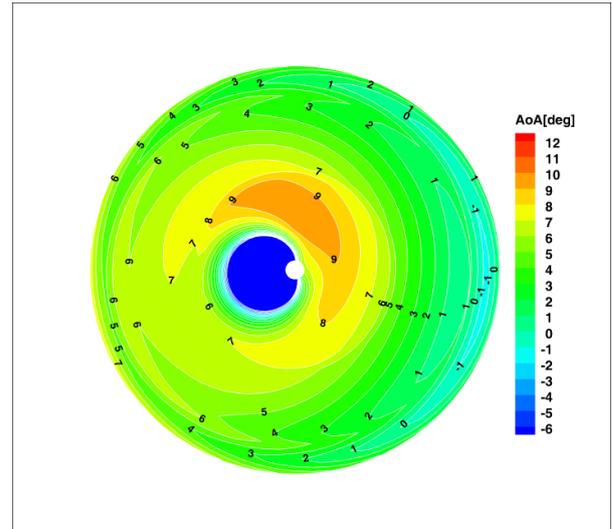
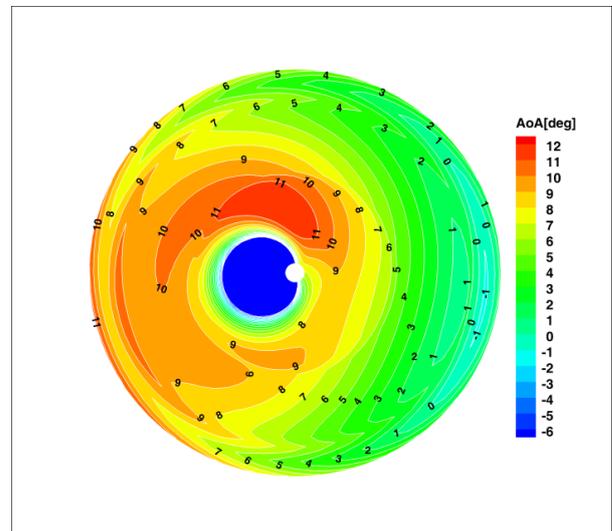


Figure 12 Power reduction for the 1/rev motion.

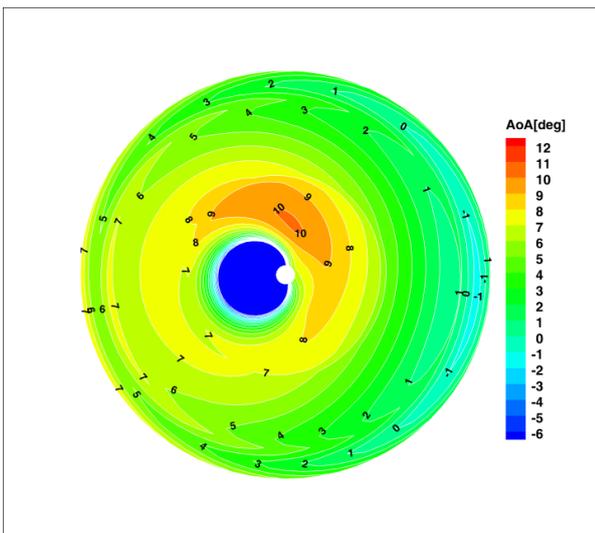
Figure 13 compares of the distributions of the angle of attack for different rotor speeds and GF heights at a flight speed of 200 km/h. Reducing the rotor speed (90%Ω), the overall angle of attack increases to provide enough thrust and maintain balance. The angle of attack in the retreating side increases distinctly. The region with larger than 10° of angle of attack expands, and a region with 11° emerges. This also indicates the deterioration of rotor loads. With the GF, the average angle of attack decreases, which is due to the lift enhancement by the GF. The radial distribution of the angle of attack becomes less abrupt, which indicates alleviation of rotor loads.



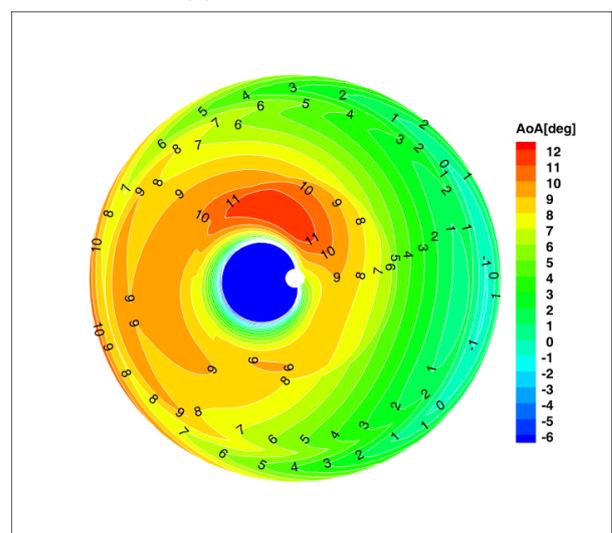
(b) 100%Ω and  $A = 2\%c$



(c) 90%Ω with  $A = 0$



(a) 100%Ω and  $A = 0$



(d) 90%Ω and  $A = 2\%c$

Figure 13 Distribution of the angle of attack at a flight speed of 200km/h.

Figure 14 shows the GF height corresponding to the minimum rotor power at the prescribed rotor and forward speeds. With increasing forward speed, the GF height increases. The trend changes smoothly at low to medium speeds. For high speed flight, the required height increases dramatically. Reducing the rotor speed, larger height is needed. At high forward speed, a GF larger than 2.5% is needed, which indicates that the maximum forward speed can be extended if a larger GF is available.

The collective pitch  $\theta_0$ , longitudinal cyclic pitch  $\theta_{1c}$ , and lateral cyclic pitch  $\theta_{1s}$  at a rotor speed of 90% $\Omega$  with and without the 1/rev GF are compared with the values at 100% $\Omega$  are shown in Figure 15. The trends are similar as those of the fixed height GF. The deployment of the 1/rev GF decreases  $\theta_0$ , and its magnitude is a slightly larger than the fixed height GF.  $\theta_0$  decreases by 1.04° for the fixed height GF, and this value is 1.46° for the 1/rev GF at a speed of 250 km/h and rotor speed of 90% $\Omega$ . The  $\theta_{1c}$  and  $\theta_{1s}$  change substantially small. Compared with the fixed height GF,  $\theta_{1s}$  decreases larger. The longitudinal tilt angle  $\alpha_s$  and lateral tilt angle  $\phi_s$  of rotor shaft are shown in Figure 16, which changes little compared with the values without the deployment of GF.

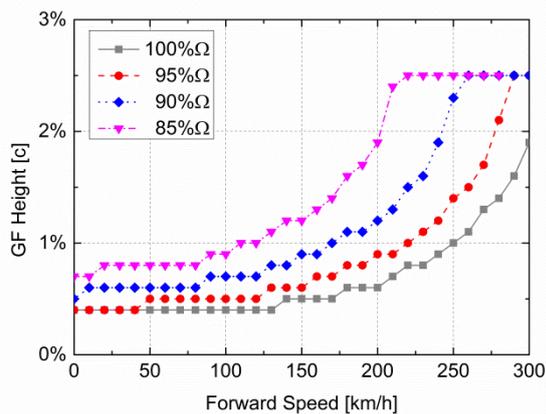


Figure 14 GF height corresponding the minimum power for the 1/rev motion.

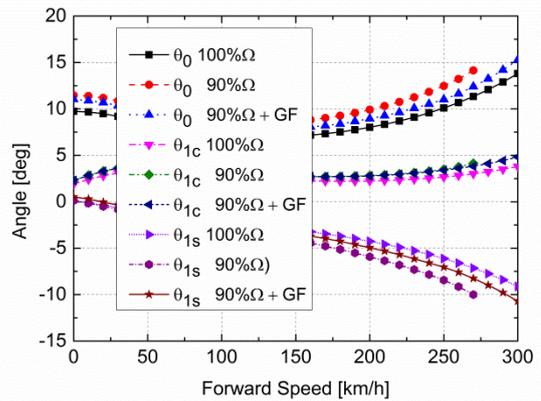


Figure 15 The collective, longitudinal and lateral cyclic pitches for the 1/rev GF.

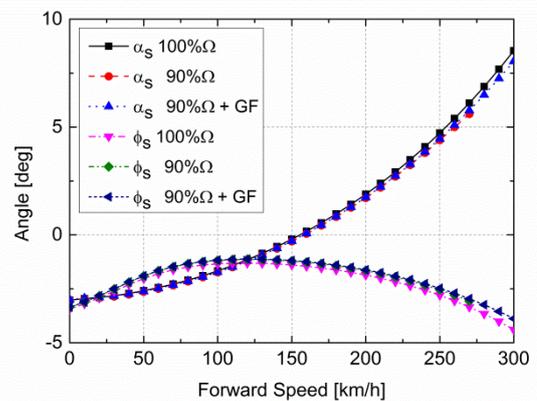


Figure 16 The longitudinal and lateral tilts of rotor shaft for the 1/rev GF.

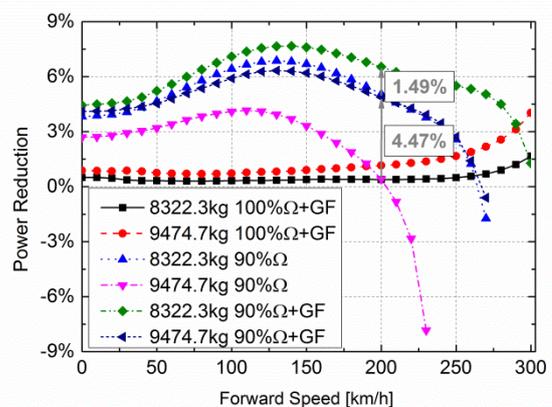


Figure 17 Power reduction for larger take-off weight.

Figure 17 shows the power reductions for

different take-off weights. With larger weight, the GF can achieve much more power savings, especially at high speed flight. At a weight of 8322.3 kg and rotor speed of 90%Ω, the 1/rev GF can yield 1.49% more power reduction than without GF. As the weight changes to 9474.7 kg (weight coefficient 0.0074 at 100%Ω), this value becomes 4.47%. It is obvious that the GF can achieve better performance improvement in high thrust cases, and the maximum forward speed can be increased. To attain larger maximum forward speeds, the rotor speed can be reduced to decrease the blade tip Mach number in the advancing side, and the 1/rev GF could be used to alleviate stall in the retreating side. This may be a practical way to achieve higher speed for high speed helicopters.

#### 4.2. 2/rev

For different forward speeds, the influence of the phase of the 2/rev retractable GF on the power is shown in Figure 18. The magnitude  $A$  is set to 2‰. At low to medium forward speed, the power changes little with the phase. At high speed flight, the variation of the power with the phase is clear. The best phase for the minimum power is around 110°. In the following analyses, this could be used.

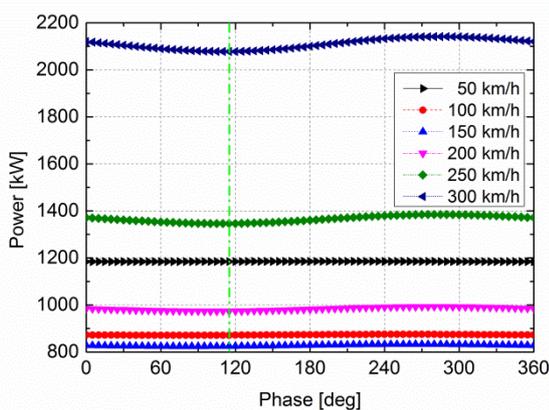


Figure 18 Power with 2/rev GF motion.

Figure 19 shows the power reduction for different forward and rotor speeds. The power is the minimum for a GF with  $h \leq 5‰$ . Compared to the

1/rev, the 2/rev GF results in smaller power reduction. At a speed of 300 km/h and rotor speed of 100%Ω, the 1/rev GF obtains 3.51% power reduction, and this value is 2.18% for the 2/rev GF. At a rotor speed of 85%Ω, the maximum power reduction with the 1/rev GF is 10.7%, and this value is 10.2%. From the point of view of power reduction, a lower harmonic GF is preferred.

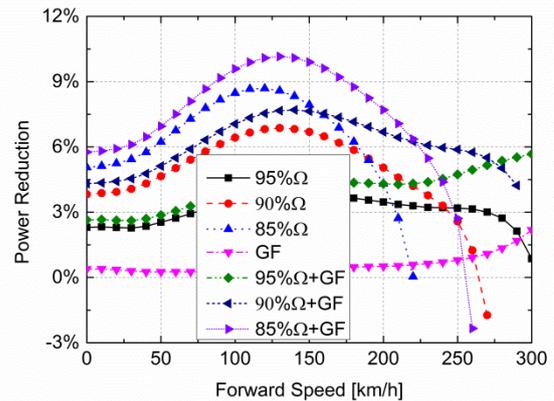


Figure 19 Power reduction for the 2/rev motion.

Figure 20 shows the height of the 2/rev GF corresponding to the minimum rotor power. With increasing forward speed, the GF height first decreases slightly and then increases. The trend changes smoothly at low to medium speed. At high speed flight, the required height increases dramatically. Lowering the rotor speed, larger height is needed. At high speed flight, a height larger than 2.5‰ is needed, which is due to the height limit set in this study. If a larger height is available, a larger power reduction in high speed flight can be obtained. At a speed of 200 km/h, the average heights for the 100%Ω, 95%Ω, 90%Ω, and 80%Ω are 0.4‰, 0.6‰, 0.9‰ and 1.2‰. For the 1/rev GF, the average heights change to 0.6‰, 0.8‰, 1.1‰ and 1.7‰, respectively. It is obvious that for larger harmonic motion, a smaller height is better.

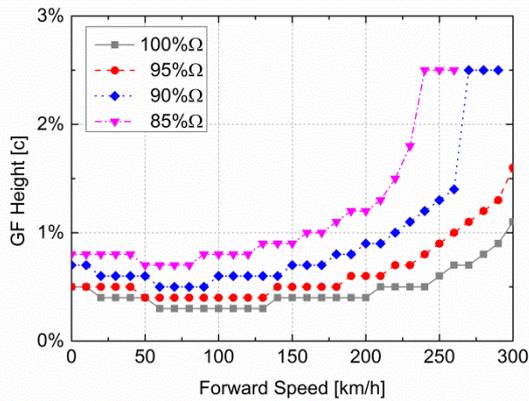


Figure 20 GF height corresponding the minimum power for the 2/rev motion.

### 4.3. Higher Harmonic GF

Figure 21 shows the power reduction for different harmonics of the GF. The average height is fixed at 2%*c*, and the phase is shifted to the value corresponding to the minimum power at the prescribed speed. It is clear that the power savings decrease with increasing harmonics. 2%*c* is the larger value investigated. In the high speed flight, power savings can be obtained. For the 1-4/rev GF, the power reductions at a speed of 300 km/h are 3.51%, 1.71%, 0.765% and 0.557%, respectively. It is obvious that 1/rev harmonic motion can achieve the best performance improvement. It is also larger than the power saved by the fixed height GF shown in Figure 4.

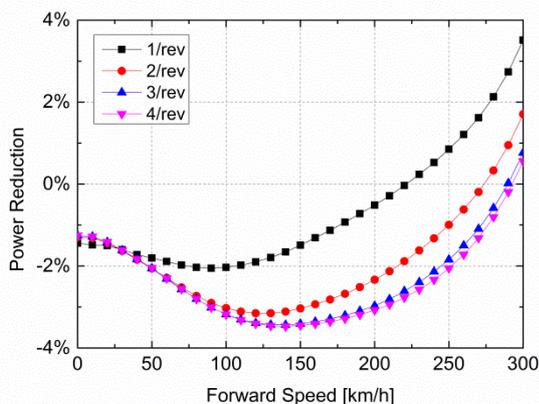


Figure 21 Higher harmonic input.

## 5. CONCLUSIONS

An empirical helicopter model was used to explore performance improvement of variable speed rotors by GFs. The flight data of the UH-60A helicopter was used to validate the model. The predictions of the rotor power were in good agreement with the flight test data, justifying the application of the present method in analyzing rotor performance. The analyses yielded the following conclusions:

1) The GF with fixed height can enhance the performance of variable speed rotors and expand the corresponding flight envelop, especially near stall, and at high speed flight. At lower rotor speeds, more rotor power can be saved. The flap height corresponding to the maximum power reduction, decreases slightly with forward speed and then increases. At high speed flight, the power reduction increases dramatically with the flap height.

2) The 1/rev retractable GF can yield more power savings than a fixed one. At a speed of 200km/h, the 1/rev GF obtained 3.22% more power reduction at a rotor speed of 85%Ω. This value was 8.37% at 220km/h. The flap height corresponding to the minimum power increases slowly at low to medium flight speed, and increases much higher at high speed flight.

3) The 1/rev GF can obtain more rotor power savings for larger weights.

4) The 2/rev retractable Gurney flap gives smaller power savings than the 1/rev GF at the same fight condition. The average height is also smaller than for the 1/rev GF.

5) The power reduction decreases with the increase of the GF harmonics. The 1/rev GF can obtain the maximum power savings, and it is also larger than the fixed height GF.

6) The deployment of the GF decreases the collective pitch by a small amount. The changes to the cyclic pitches and tilt of rotor shaft were relatively small.

Finally, it is noted that the precise numbers given above are specific to the blade utilized in this work. For a rotor with different planform, airfoils,

diameter, etc., the optimum deployment and performance improvement levels may vary.

## 6. ACKNOWLEDGMENTS

This work is supported from the National Natural Science Foundation of China (11472129), the Aeronautical Science Foundation of China (20165752048), and Science and Technology on Rotorcraft Aeromechanics Laboratory Foundation (6142220050416220002).

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