Helicopter Performance Improvement by Variable Rotor Speed and Variable Blade Twist

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Variable rotor speed and variable blade twist are combined to reduce rotor power and improve helicopter performance. Two modeling methods are respectively utilized. One is based on an empirical aerodynamic model and the other is based on CFD (computational fluid dynamics). The flight data of the UH-60A helicopter is used to validate the methods. The predictions of the rotor power by the empirical method are in good agreement with the test data and the CFD method, which verifies the application of present methods in analyzing helicopter performance. The analyses indicate that significant rotor power reduction can be achieved by decreasing rotor speed. It is not appropriate to decrease the rotor speed too much in high forward flight. More power reduction can be attained by varying rotor speed than by variable blade twist. The individual variation of rotor speed or blade twist can reduce the rotor power by 17.8% or 10.4%, at a forward speed 250 km/h and weight coefficient of 0.0065. A combination of rotor speed reduction and blade twist can save 20.9%. The maximum power reduction increases with forward speed and then decreases. The optimal performance improvement occurs at the medium to high forward speed. With increasing takeoff weight, the benefit in power saving decreases. Variable blade twist has the potential in reducing blade loads introduced by variable rotor speed.

Keywords: helicopter; performance; variable rotor speed; variable blade twist

1. Introduction

Helicopters are essentially low speed, low altitude, short range aircraft [1]. Improving helicopter efficiency, endurance, range, forward speed, and ceiling are therefore important topics in helicopter design. The objective of this paper is to investigate rotor power reduction and therefore increase the available engine power. Usually, the total power consumed by helicopters is primarily composed of main rotor induced power, main rotor profile power, tail rotor power and fuselage parasite power. Rotor morphing technologies provide possible effective solutions for reducing the main rotor induced and/or profile power [2]. Potential methods to be investigated include variable rotor speed, variable rotor diameter, active blade twist, trailing edge flaps and so on.

Among the potential rotor morphing technologies, the application of variable speed rotors in the V-22, X2 and A160 aircraft has demonstrated significant performance improvements, especially regarding long endurance, high speed and larger range. Decreasing rotor speed can effectively reduce rotor power at cruise in low altitude and light weight conditions, though the power reductions diminish with increasing altitude and/or gross weight, and in low speed flight [3]. This is due to the effective reduction of rotor profile power by decreasing rotor speed. In hover, and low forward flight, the rotor induced power dominates the total helicopter power. Varying rotor speed usually attains limited power savings. In fast forward flight, the angles of attack of blades have to be increased to generate enough thrust to trim the helicopter due to the reduction of rotor speed, which aggravates the stall area and decreases the power reduction ability. Some limited power reduction may be attained in high speed. However, varying rotor speed in flight may lead to dynamics issues [4, 5]. With lower rotor speeds, and higher forward speeds, larger rotor advance ratios are attained, and this can introduce high blade loads and vibration problems. Wind tunnel test of a variable speed model rotor indicated the general increase of the root bending moments and higher harmonic pitch link loads with the reduction of rotor speed [6]. To retain the benefits in performance for variable speed rotors, and reduce or avoid excessive loads and vibration issues is a challenging task that is worthy of investigation.

Active twist rotors change the blade twist distribution according to the flight state of the vehicles, and this can be utilized to improve helicopter performance. Increasing blade twist in hover and decreasing it in high forward flight is well recognized in helicopter rotor design. The wind tunnel tests confirmed that highly twisted rotors provided better hover performance, but higher forward flight blade loads and vibratory fixed frame hub loads [7]. The initial idea of active blade twist was utilized for rotor vibration reduction. In 1990s, Chen and Chopra conducted the hover and forward flight wind tunnel tests of smart model rotors with individual blade twist control using embedded piezoceramic materials [8, 9]. These experimental results indicated that tip twist amplitudes on the order of 0.5 degrees were obtainable, which was less than the target value 1 to 2 degrees. However, they demonstrated that induced-strain actuation of blade twist was a feasible concept for rotor vibration control. The NASA/ARMY/MIT active twist rotor tested in the NASA Langley Transonic Dynamics Tunnel demonstrated rotor vibratory loads reduction in the fixed frame [10, 11]. The active twist rotor of Sikorsky Aircraft also demonstrated 1% to 2% rotor power reduction in wind tunnel tests [12]. Cheng and Celi showed that the two-per-revolution input could be used to reduce rotor power [13]. Thakkar and Ganguli showed that shear induced piezoceramic actuation could be used for twisting the rotor blade which can reduce vibration, delay flow separation and alleviate dynamic stall [14, 15]. The benefit studies of the active twist rotor using weak fluid-structure coupling clearly showed that the application of active twist control could reduce the rotor vibrations and power simultaneously [16]. The coupled computational fluid dynamics and computational structural dynamics analysis of the full-scale UH-60A Blackhawk helicopter rotor showed that the rotor lift to effective drag ratio increased by 7.3% and the corresponding power decreased by 3.3% by a 4-degree dynamic twist for the high forward flight (C8534) [17]. In this case, the pitch link loads increased by about 2%, and the other blade loads or rotor vibratory loads remained unchanged or decreased [18]. Experimental results in German Aerospace Center (DLR) suggested that the active twist blades incorporating MFCs (Macro Fiber Composite) were capable of generating sufficient twist deformation under full centrifugal loads at different higher harmonic excitations [19, 20]. It is therefore possible that active twist rotors can be used for reducing vibratory loads and at the same time decreasing rotor power.

This work is focused on the application of variable rotor speed in conjunction with variable blade twist to obtain reductions in the required rotor power and the vibratory loads introduced by the decrease of rotor speed. The rotor can change its speed independently by varying the transmission ratio or the shaft speed of the engine without the variation of the blade twist. The rotor blades can change the twist according to the flight state but not with the azimuth. Two helicopter models to predict helicopter performance are utilized. One is based on an empirical aerodynamic model and the other is based on CFD (Computational Fluid Dynamics). To demonstrate the benefits in power reduction, a baseline rotor, aerodynamically approximating the UH-60A main rotor is used. The parametric analyses of different rotor speeds and blade twists are investigated to explore how much power reduction can be achieved. The optimal combined rotor speed and blade twist is analyzed to illustrate the selection of these variables for different flight states. The vibratory loads of variable speed rotors are also analyzed.

2. Modeling Methods

2.1 Empirical Model

To analyze helicopter performance, an empirical aerodynamic model is used. It includes a main rotor model, a fuselage model, a tail rotor model and a propulsive trim method. The rotor modeling follows [21, 22]. A moderate deflection beam model is employed to describe the elastic deformations of the rotor blades. The rigid rotations associated with the blade hinges and the blade rotation about the rotor shaft are introduced as generalized coordinates [23]. Look-up aerofoil aerodynamics is used. The induced velocity over the rotor disk is captured by the Pitt-Peters inflow model [24]. Assembling the structural, kinetic, and aerodynamic terms yields the equations of motion based on the generalized force formulation. The implicit Newmark integration method is utilized to calculate the steady responses in the time domain. 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 aerodynamic forces and moments. The thrust of the tail rotor is determined by the main rotor torque divided by the distance from the hub center of the tail rotor to the main rotor shaft. Given the thrust and forward speed, the power of the tail rotor is determined by momentum theory in hover and forward flight.

Given initial three pitch controls (collective and cyclic pitches) and two rotor shaft attitude angles (longitudinal and lateral tilt shaft angles), the periodic response of the rotor 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 is derived from the rotor torque and fight state. These component forces and moments constitute the equilibrium equations of the helicopter, which 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.

2.2 CFD Model

CFD is nowadays used as the primary tool for analyzing the aerodynamics of helicopter rotors, propellers, or wind turbines. All CFD calculations shown here were performed using the Helicopter Multi-Block Method (HMB2) taking advantage of its ability to perform steady-state periodic or fully unsteady computations [25] using the RANS and URANS approach or even SAS [26] and DES [27]. For this work, fine multi-block grids were used with the sliding plane method [28]. The grids had approximately 12 million cells per blade for the isolated cases. It was assumed that the blades were rigid. For the cases presented in this paper, the Reynolds Averaged Navier-Stokes (RANS) method was used with the $k-\omega$ turbulence model.

HMB2 solves the Navier-Stokes equations in integral form using the arbitrary Lagrangian Eulerian formulation for time-dependent domains with moving boundaries:

$$\frac{d}{dt}\int_{V(t)} \vec{\omega}\, dV + \int_{\partial V(t)} \left(\vec{F}_i(\vec{\omega}) - \vec{F}_v(\vec{\omega})\right) \vec{n}\, dS = \vec{S}. \tag{1}$$

The above equations form a system of conservation laws for any time-dependent control volume $V(t)$ with boundary $\partial V(t)$ and outward unit normal $\vec{n}$. The vector of conserved variables is denoted by $\vec{\omega} = [\rho, \rho u, \rho v, \rho w, \rho E]^T$, where ρ is the density, u, v, w are the Cartesian velocity components and E is the total internal energy per unit mass. $\vec{F}_i$ and $\vec{F}_v$ are the inviscid and viscous fluxes, respectively. For hovering rotors, the grid is fixed, and a source term,$\vec{S} =$

$[0, -\rho\vec{\omega} \times \vec{u}_h, 0]^T$, is added to compensate for the inertial effects of the rotation. $\vec{u}_h$ is the local velocity field in the rotor-fixed frame of reference.

The non-inertial frame of reference used here has two benefits over a rotating frame of reference: firstly, the energy equation is unchanged by the rotation vector $\vec{\omega}$ and, secondly, a vanishing 'undisturbed' velocity field occurs in contrast to the position-dependent 'undisturbed' velocity field in the rotating frame of reference, which is given by $-\vec{\omega} \times \vec{r}$.

Equations 1 are discretized using a cell-centered finite volume approach on structured multiblock grids. The spatial discretisation leads to a set of equations in time,

$$\frac{\partial}{\partial t}\left(\vec{\omega}_{i,j,k} V_{i,j,k}\right) = -\vec{R}_{i,j,k}\left(\vec{\omega}_{i,j,k}\right), \tag{2}$$

where $\vec{\omega}$ and $\vec{R}$ are the vectors of cell variables and residuals, respectively. Here, i, j, k are the cells indices in each of the grid blocks, and $V_{i,j,k}$ is the cell volume. The convective terms are discretized using Osher's upwind scheme [29], MUSCL variable interpolation is used to provide high order accuracy and the Van Albada limiter [30] is employed to prevent spurious oscillations near steep gradients. Boundary conditions are set using ghost cells on the exterior of the computational domain. For viscous flow simulations, ghost values are extrapolated at solid boundaries ensuring that the velocity takes on the solid wall velocity. Implicit time integration is employed, and the resulting linear system of equations is solved using a pre-conditioned Generalized Conjugate Gradient method. For unsteady simulations, an implicit dual time stepping method is used, based on the pseudo-time integration approach by Jameson [31]. The HMB2 method has been validated for a range of rotorcraft applications and has demonstrated good accuracy and efficiency for very demanding flows. Examples of work with HMB2 can be found in references [28, 32, and 33]. Several rotor trimming methods are available in HMB2 along with a blade-actuation algorithm that allows for the near-blade grid quality to be maintained on deforming meshes [28].

The HMB2 solver has a library of turbulence closures including several one- and two- equation turbulence models and even non-Boussinesq versions of the $k - \omega$ model that is used for this work. Turbulence simulation is also possible using either the Large-Eddy or the Detached-Eddy approach. The solver was designed with parallel execution in mind and the MPI library along with a load-balancing algorithm are used to this end. For multi-block grid generation, the ICEMCFD Hexa commercial meshing tool is used and CFD rotor grids with 10-30 million points and thousands of blocks are commonly used.

For forward flying rotors, the HMB2 solves the compressible-flow Reynolds-Averaged Navier-Stokes equations in an inertial frame of reference. The employed finite-volume discretisation accounts for moving and deforming meshes in time-accurate simulations. Consequently, a rotor in forward flight is modeled in a 'helicopter-fixed frame of reference', where the forward flight velocity is introduced through the definition of the 'free-stream' conditions. For isolated rotors, as well as, rotor/fuselage or rotor/wind-tunnel cases, the rotor and rotor blade motions are then accounted for using mesh velocities. For rotor/fuselage or rotor/wind-tunnel cases, the relative motion of the rotor and the fixed fuselage or tunnel is accounted for the sliding-plane approach [32].

3. Validation of the Employed Methods

The flight data of the UH-60A helicopter [34] is utilized to validate the methods adopted in this work. A baseline helicopter aerodynamically approximating the UH-60A helicopter is used. The parameters of the baseline main and tail rotors are listed in Tables 1 and 2. The distributions of the airfoil and blade twist of the main rotor are given in [35]. 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 [34]

$$D/q(ft^2) = 35.83 + 0.016(1.66\alpha_s^2),$$

(3)

where, D is fuselage drag, q is dynamic pressure, and α_s is aircraft pitch angle. The distance from the hub center of tail rotor to the rotor shaft is 9.9263 m. The vertical distance from the mass center of the helicopter to the rotor hub is 1.77546 m. Since the structural properties of rotor blades have little influence on helicopter power, the blades are assumed to have uniform mass and stiffness distribution. In the present work, the rotor speed can be reduced by 30%, instead of 16% adopted in [3]. Articulated rotors can't support lower rotor speeds due to the smaller centrifugal forces and larger blade flapping. The type of the baseline rotor is assumed to be a rigid rotor design like the X2 or A160 aircraft. The fundamental flap, lag and torsion frequency ratios of the baseline rotor at the full rotor speed are taken as 1.15, 1.50 and 6.72, respectively.

Table 1: Main rotor parameters

Main Rotor Radius	8.1778 m
Nominal Main Rotor Speed	27.0 rad/s
Blade Chord Length	0.5273 m
Blade Twist	Nonlinear
Blade Airfoil	SC 1095/SC 1094R8
Number of Blades	4
Flap Hinge Offset	0.381 m
Blade Mass per Unit Length	13.92 kg/m
Longitudinal Shaft Tilt	3°

Table 2: Tail rotor parameters

Tail Rotor Radius	1.6764 m
Nominal Tail Rotor Speed	124.62 rad/s
Tail Rotor Blade Chord	0.2469 m
Tail Rotor Blade Twist	-18°
Airfoil	SC 1095
Number of Blades	4

The comparisons of the prediction of the rotor power by the empirical method with the flight test data for different takeoff weights are shown in Figure 1. The weight coefficients C_W in the four flight states are 0.0065, 0.0074, 0.0083 and 0.0091, respectively. It is obvious that the predictions are in good agreements with the flight test data for these takeoff weights, which verifies the application of this method in the analysis of helicopter performance.

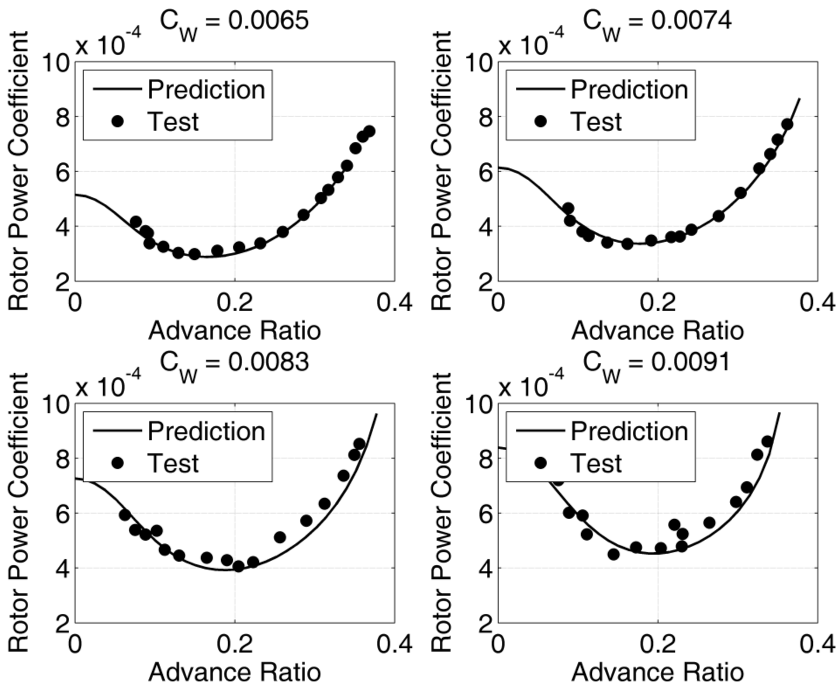


Figure 1: Comparison of the prediction with the flight data [34].

4. Performance Improvements

The individual effects of variable rotor speed and variable blade twist on the rotor power reduction are first investigated. Then, their combined effect of both is analyzed. The power reduction is defined to be the power without rotor morphing minus the power with rotor morphing divided by the power without rotor morphing. A positive value means the reduction of the rotor power and corresponding helicopter performance improvement. A minus sign means increase of the power. The takeoff weight was set to 8322.4 kg, and the corresponding weigh coefficient was 0.0065.

The rotor power with increasing forward speed for different rotor speeds is shown in Figure 2, and the corresponding power reduction is shown in Figure 3. With decreasing rotor speed, the rotor power usually deceases and the power reductions in Figure 3 are all positive. At a speed of 150 km/h, the rotor power decreases by 7.36%, 12.8% and 16.9% with 5%, 10% and 15% rotor speed reduction, respectively. It is obvious that decreasing rotor speed can significantly reduce the rotor power, especially in medium to high forward flight. Varying rotor speed is an effective means to improve helicopter performance. The power reduction increases with increasing forward speed for the cases with 5% and 10% rotor speed reduction. With 15% rotor speed reduction, the power reduction increases first smoothly and then decreases rapidly. At a speed of 210 km/h, the maximum power reduction 20.3% is achieved. At a speed of 250 km/h, the power is reduced by 15.2%. It is not appropriate to decrease the rotor speed too much in high speed forward flight, since this lowers the Mach number in the retreating side, introduces larger stall area, and worsens the aerodynamic environment of advancing and retreating sides of rotor blades. This can adversely lower the benefit in power reduction achieved by further reduction of rotor speed.

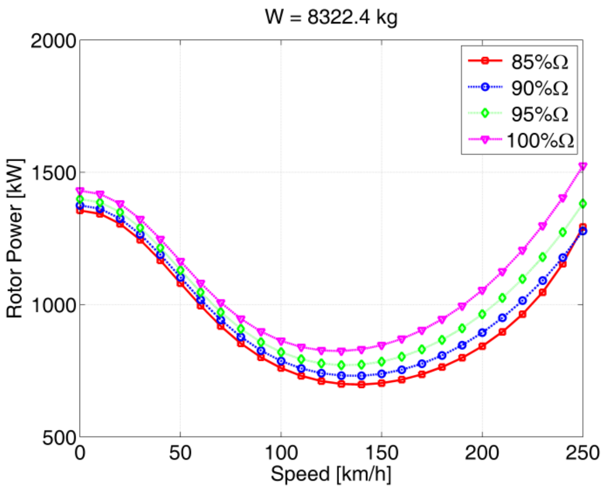


Figure 2: Rotor power variation with rotor speed.

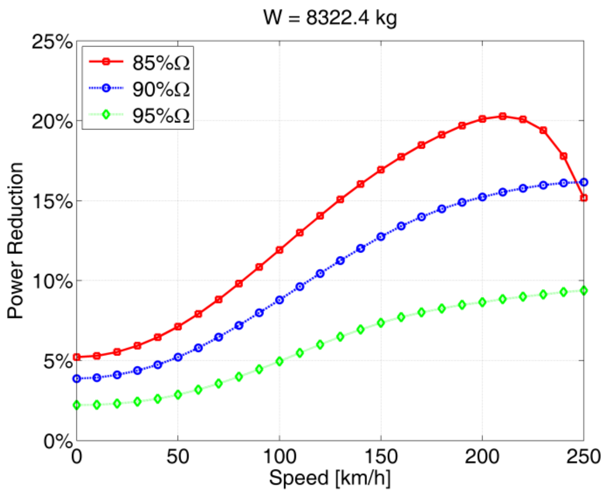


Figure 3: Rotor power reduction variation with rotor speed.

The rotor power with increasing forward speed for different blade twists is shown in Figure 4, and the corresponding power reduction is shown in Figure 5. In hover, the power increases with decreasing blade twist. As the blade twist changes from -16º to -12º, -8º, -4º, 0º, the power increases by 0.53%, 2.85%, 5.38% and 10.2%, respectively. Large blade twist is preferred in hover. With increasing forward speed, the benefit in power reduction with larger blade twist decreases. At a speed of 250 km/h (advance ratio μ=0.315), the power decreases by 6.59%, 10.1%, 9.46% and 2.86% for the corresponding blade twists. The reduction first increases with blade twist and then decreases. An optimal value of blade twist exists for each forward speed. In high speed forward flight, moderate blade twist is preferred for better rotor performance.

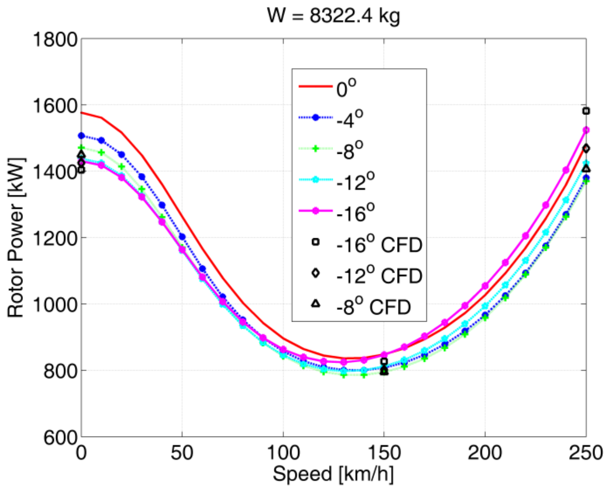


Figure 4: Rotor power with blade twist.

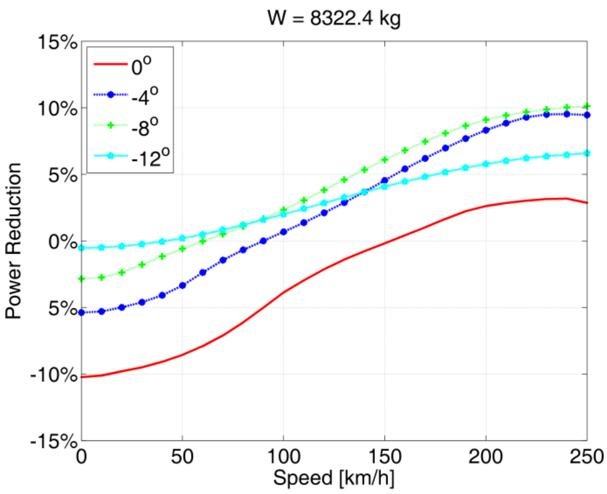


Figure 5: Percentage of rotor power reduction with blade twist.

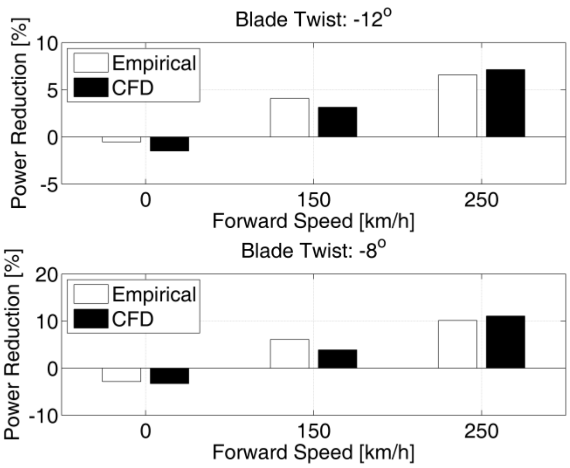


Figure 6: Power reduction comparison.

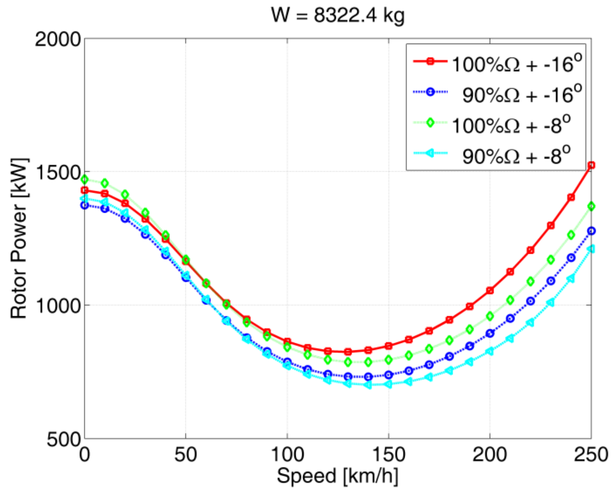


Figure 7: Influence of rotor speed and blade twist on the required rotor power.

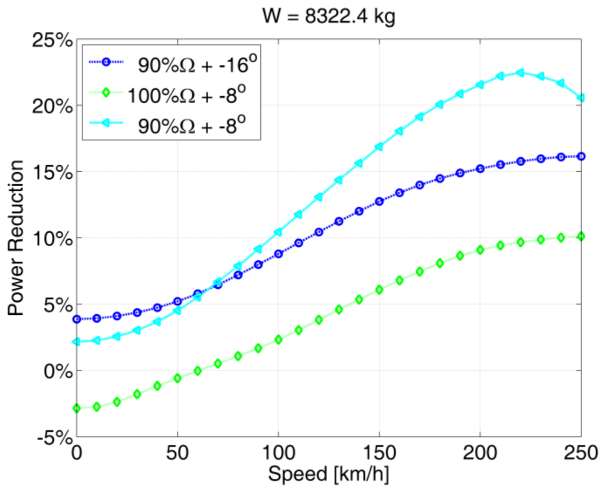
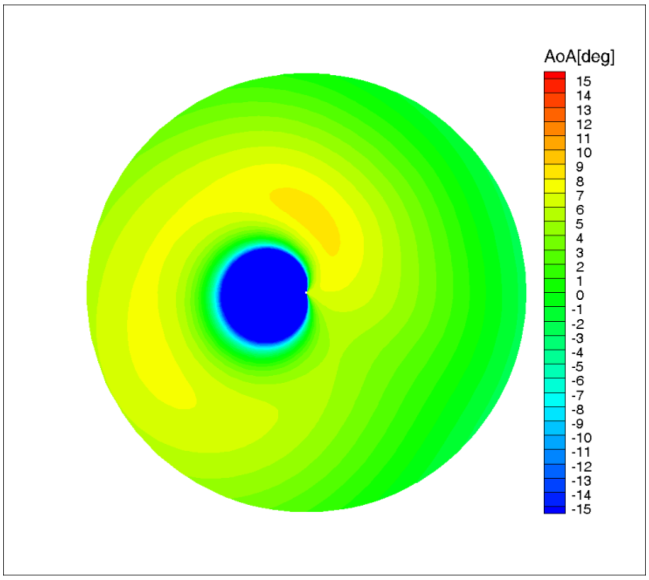


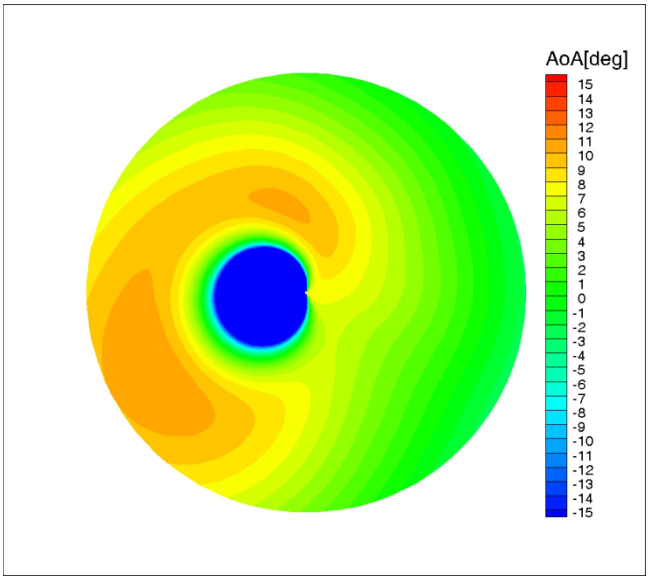
Figure 8: Comparison of rotor speed and blade twist on the required rotor power.

Figure 6 shows the comparison of the power reduction predicted by the empirical and CFD methods at speeds of 0, 150 and 250 km/h, and the absolute values are shown in Figure 4. The predictions of the power reduction by the methods are in good agreements. In hover or high speed flight, the differences of the percentage of power reduction between the two methods are not larger than 1%. At a speed of 150 km/h, the value is 2.23% with the twist -8°. This indicates excellent consistency of the two methods to analyze helicopter performance improvement.

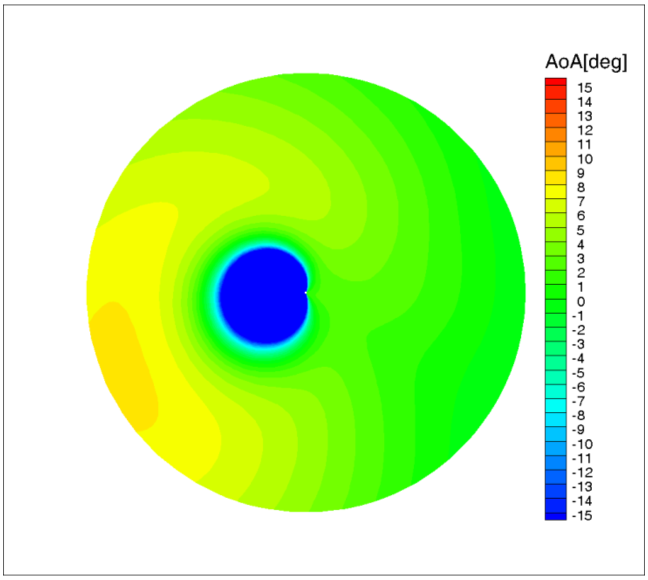
The rotor power with increasing forward speed for different combined rotor speed and blade twist is shown in Figure 7, and the corresponding power reduction is shown in Figure 8. It is obvious that 10% reduction of the rotor speed can attain better performance improvement than 8° reduction of the blade twist, which indicates that varying rotor speed is a more effective means to improve helicopter performance than variable blade twist. The combination of varying rotor speed and blade twist can achieve better power reduction than the individual variation of rotor speed, when the forward speed is larger than 70 km/h. The smaller reduction in hover and low forward flight is due to the reduction of blade twist, which can adversely increase the rotor power. At a speed of 250 km/h, the power decreases by 16.2%, 10.1% and 20.6% with 10% reduction of rotor speed, 8° reduction of blade twist and combination of both. This verifies the advantage of using the combined rotor morphing technologies over individual one. Figure 9 shows the angles of attack for these cases. The angles of attack increase due to the reduction of rotor speed and the corresponding asymmetry between the advancing side and retreating side increases. This indicates the increase of blade loads. The reduction of blade twist decreases the asymmetry of the distribution of the angle of attack and decreases the blade loads. It can be deduced that variable blade twist has the potential to decrease the blade loads introduced by the variable rotor speed.



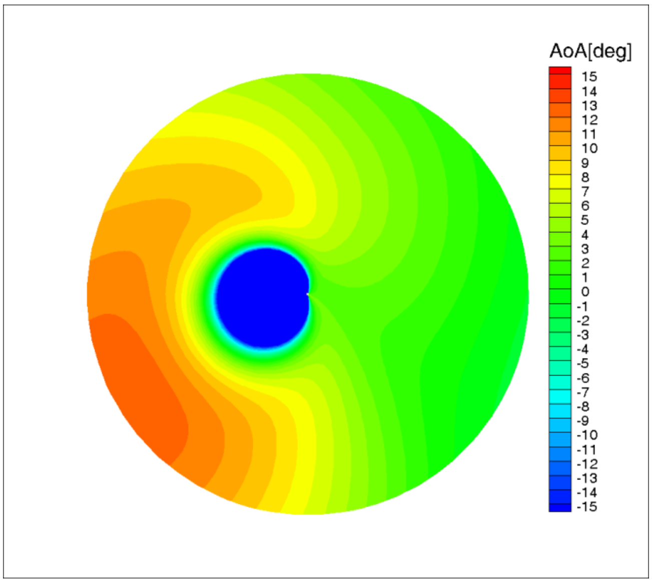
(a) Full rotor speed and -16° blade twist



(b) 90% full rotor speed and -16° blade twist



(c) Full rotor speed and -8° blade twist



(d) 90% full rotor speed and -8° blade twist

Figure 9: Angle of attack distribution at 250 km/h.

5. Optimal Performance

The maximum reduction of rotor power is explored for different forward speeds to evaluate the potential in performance improvement. The rotor speed was varied with discrete intervals of 1% of the full rotor speed. The blade twist can be changed from -16° to 0° with intervals of 1°. At a speed of 125 km/h, the rotor power with rotor speed and blade twist is shown in Figure 10. The rotor power first decreases with the rotor speed and then increases. It also decreases with the blade twist and then increases. It is therefore obvious that maximum rotor power reduction exists. The power reductions for different limits of the variation of rotor speeds are shown in Figure 11. It is obvious that a larger variation of rotor speed can lead to better power reduction. The benefit in power saving is smaller than 1.5%, if the speed is limited to change from

20% to 30%. This benefit becomes more than 5.5% with the change from 20% to 10%. Therefore, excessive reduction of the rotor speed seems unnecessary. The power reduction just increases and then decreases with increasing forward speed. Better performance improvement can be achieved at medium to high forward speed. The power reduction 23.7% is obtained at a speed of 200 km/h. The corresponding rotor speed is 86% full rotor speed and blade twist of -9°. The rotor speed and blade twist for the maximum power reduction at different forward speeds are shown in Figures 12 and 13. Larger reduction of rotor speed is preferred in hover or slow forward flight. For higher forward flight, higher rotor speed is preferred. The variation of blade twist exhibits a different trend. In hover and low forward flight, larger negative blade twist is preferred. With increasing forward speed, the preferred blade twist decreases and then increases.

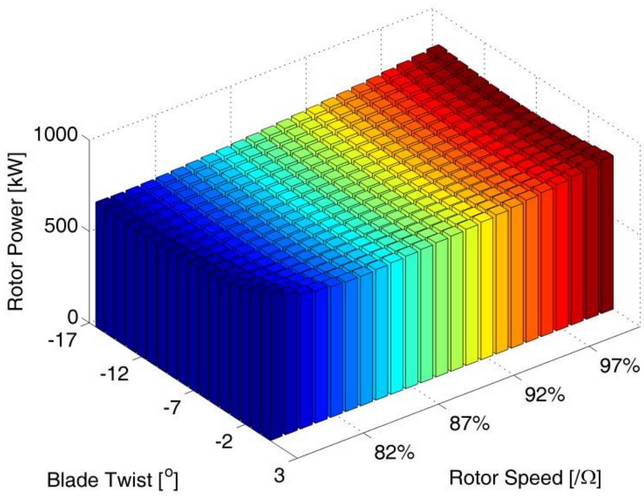


Figure 10: Rotor power variation with rotor speed and blade twist at a speed of 125 km/h.

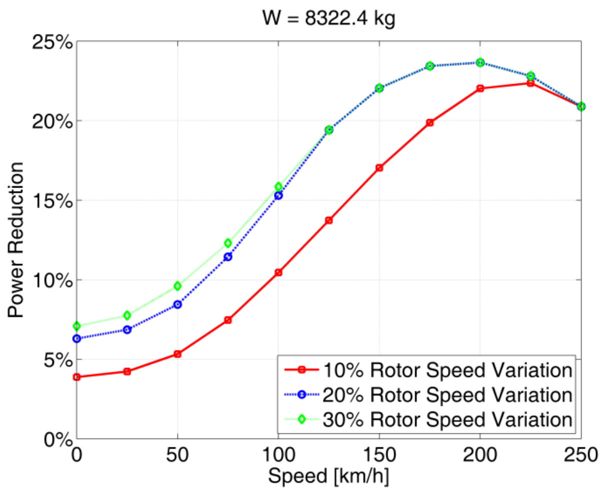


Figure 11: The optimal power reduction for the helicopter weight 8322.4 kg.

Figure 14 shows the power reductions with three rotor morphing strategies: variable rotor speed, variable blade twist and combination. Individually varying rotor speed can obtain larger power reduction than individually varying blade twist in the whole range of forward speeds studied. Variable rotor speed is a better technology than variable blade twist for helicopter performance improvement. At lower speeds, the power saving is primarily due to the reduction of rotor speed, and the effect of variable blade twist seems very small. This is partly due to the initial large twist -16°. If a smaller initial blade twist is prescribed as the baseline, changing blade twist can achieve some power saving. However, generally speaking, varying rotor speed can achieve better performance improvement than variable blade twist. At high forward speed, the combination can obtain more power reduction than individually varying rotor speed or blade twist. At a speed of 250 km/h, varying the rotor speed results in 17.8% power reduction, and varying blade twist results in 10.4%. With both, the value is 20.9%. The optimal power reduction increases with forward speed and then decreases. The maximum improvement occurs at the medium to high forward speed. The optimal rotor speed and blade twist corresponding to the maximum power reduction adopted in these three rotor morphing strategies are listed in Table 3. It is obvious that simultaneously varying rotor speed and blade twist decreases the required magnitudes of individually varying rotor speed or blade twist.

Table 3: Rotor speed and blade twist for different morphing strategies.

Speed (km/h)	0	25	50	75	100	125	150	175	200	225	250
Individually Varying Rotor Speed	72%	70%	72%	74%	77%	79%	80%	82%	84%	85%	87%
Individually Varying Blade Twist (°)	-16	-16	-13	-11	-9	-8	-8	-7	-6	-6	-7
Rotor Speed	72%	70%	72%	75%	77%	80%	82%	84%	86%	88%	90%
Blade Twist (°)	-16	-16	-16	-14	-11	-8	-9	-9	-9	-9	-10

The increase of takeoff weight decreases the reduction of rotor power by varying rotor speed [3]. The weight of the helicopter may have a strong effect on the optimal performance achieved by the combination of varying rotor speed and blade twist. In the previous analyses, the helicopter takeoff weight was 8322.4 kg (C_W=0.0065). With the takeoff weight of 10627.0 kg (C_W=0.0083), the optimal power reduction and the corresponding rotor speed and blade twist are shown in Figure 15. The trends of the rotor speed, blade twist and optimal power reduction are the same as before. The maximum benefit is 10.0% at a forward speed of 175 km/h, and the corresponding rotor speed ratio and blade twist are 92% and -12°. The range of the obtained power reduction decreases distinctly. With increasing takeoff weight, smaller variations of the rotor speed and blade twist is needed for optimal performance improvement.

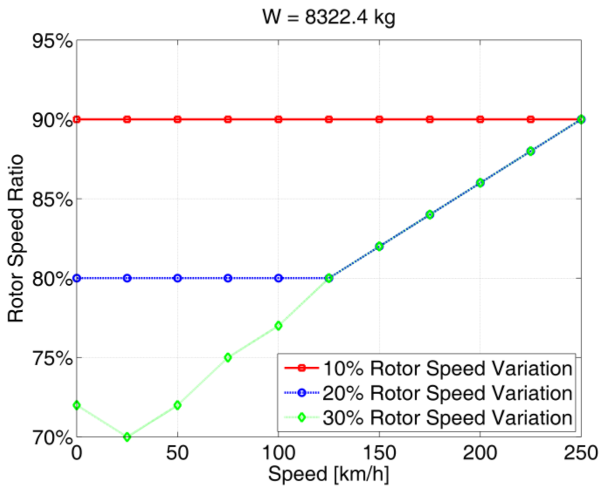


Figure 12: Rotor speed for optimal performance.

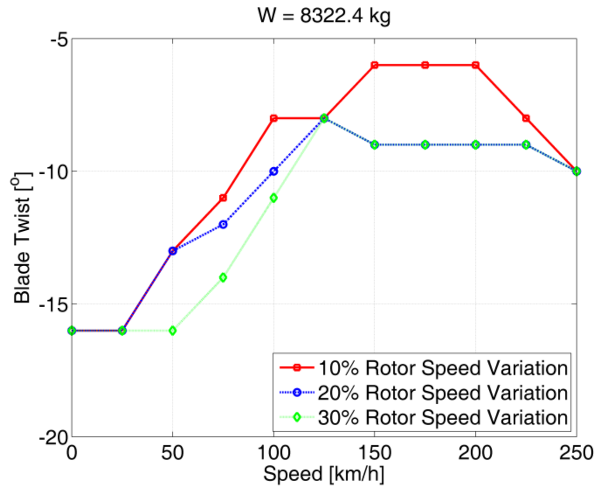


Figure 13: The blade twist corresponding to the optimal performance.

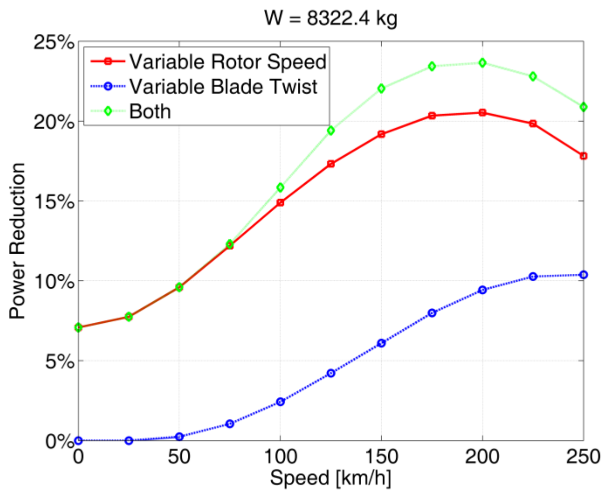


Figure 14: Power reduction for different rotor morphing strategies.

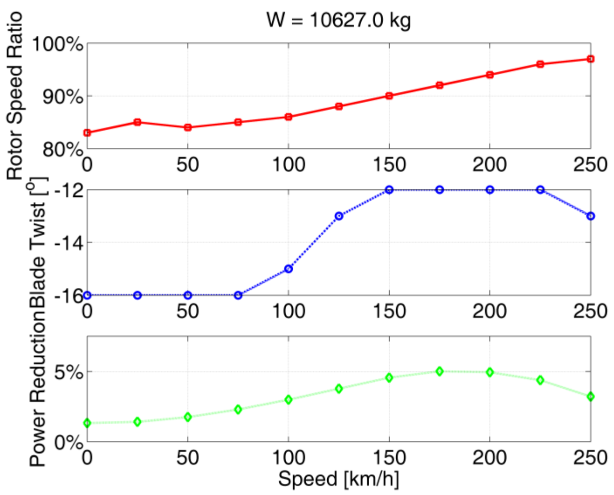


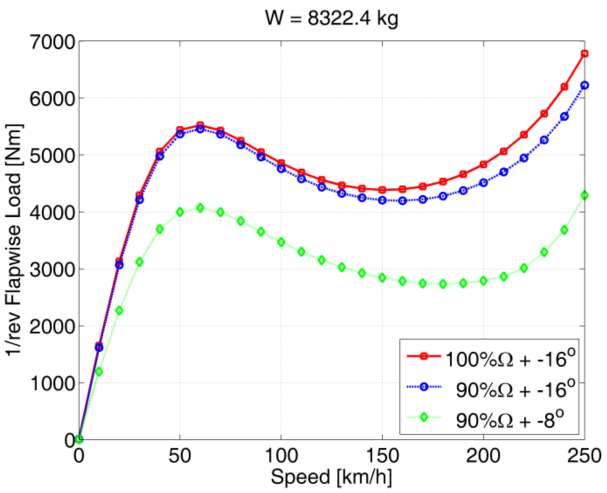
Figure 15: Optimal performance for the weight 10627.0 kg.

6. Loads Analysis

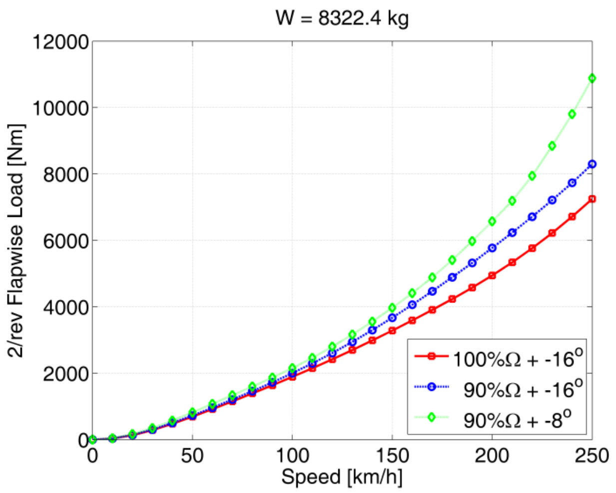
For the analysis of the influence of variable rotor speed and variable blade twist on the blade loads, this work concentrates on the flapwise, lagwise and torsional loads at the blade root. Figure 16 shows the 1/rev (per revolution) to 4/rev flapwise loads. The reduction of the rotor speed causes the overall decrease of the 1/rev and 4/rev loads, and the increase of the 2/rev and 3/rev loads. With the reduction of the blade twist, the 1/rev and 4/rev flapwise loads decrease and the 2/rev and 3/rev increase. The variation of the loads increases significantly with increasing forward speed. At high forward speeds, the difference is distinct.

Figure 17 shows the 1/rev to 4/rev lagwise loads. The reduction of the rotor speed causes the overall decrease of the 1/rev and 4/rev loads, and the overall increase of the 2/rev and 3/rev loads. With the reduction of the blade twist, the 1/rev to 4/rev lagwise loads generally decreases, except the 3/rev load at high speed and 4/rev at low to medium forward speed. This indicates the benefit of variable blade twist to reduce the loads introduced by the variable rotor speed.

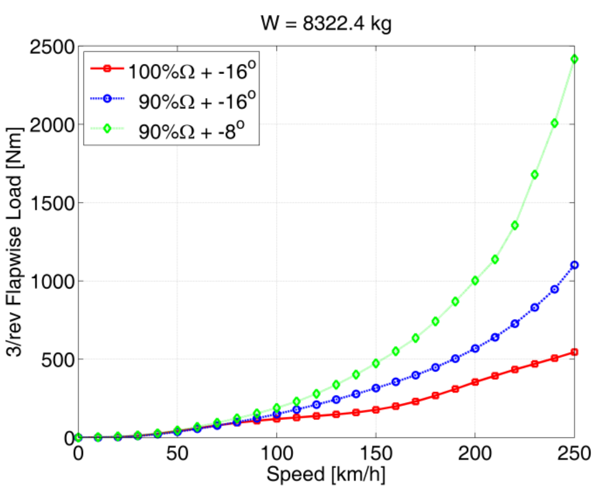
Figure 18 shows the 1/rev to 4/rev torsional loads. The reduction of the rotor speed causes the overall increase of the 1/rev to 4/rev loads. These loads generally decrease with the reduction of blade twist, except the 2/rev and 4/rev loads at high speed fight. Changing blade twist can achieve the overall decrease of the torsional loads.



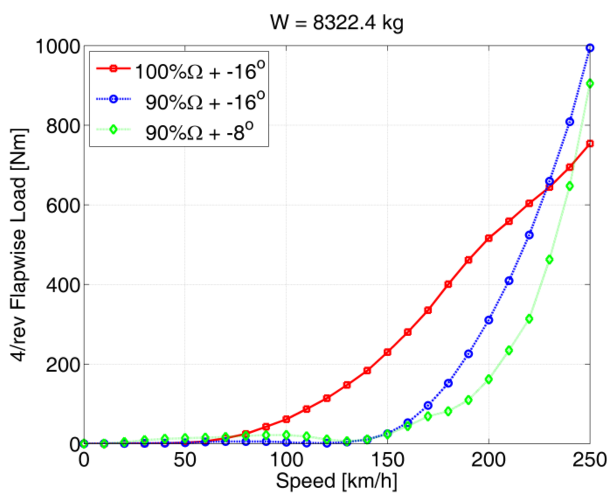
(a) 1/rev



(b) 2/rev

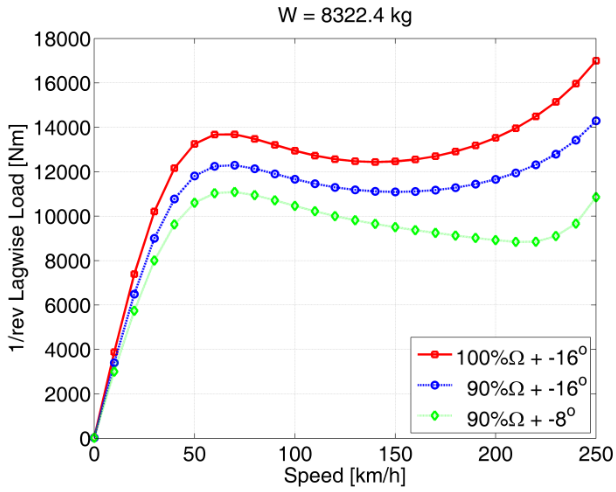


(c) 3/rev

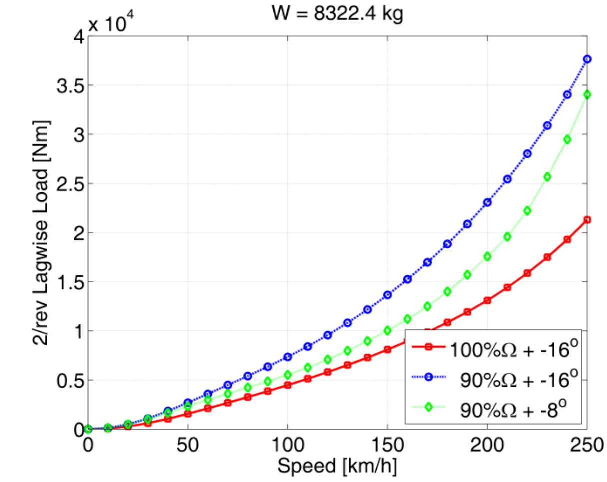


(d) 4/rev

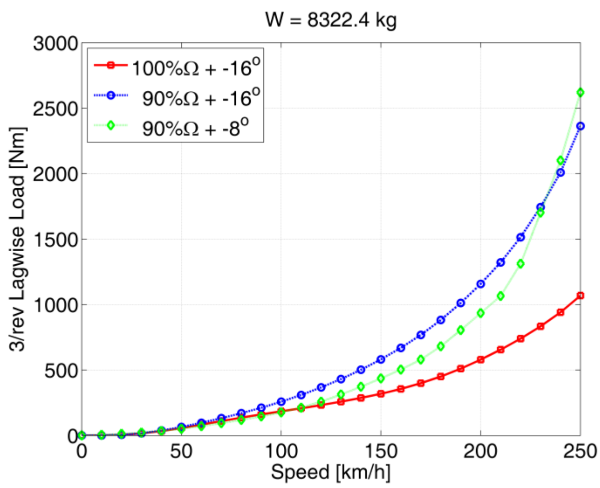
Figure 16: Flapwise loads.



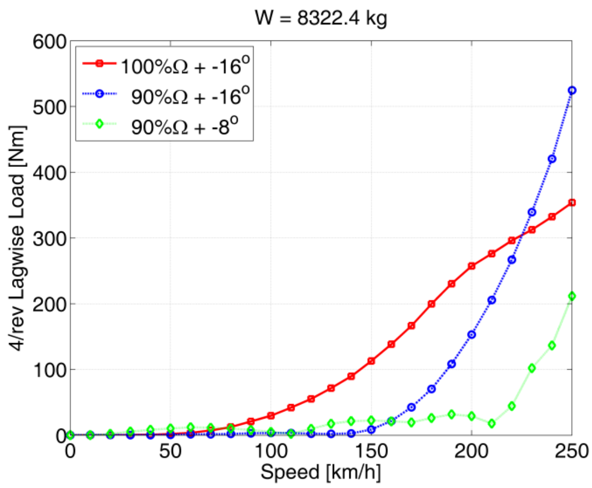
(a) 1/rev



(b) 2/rev

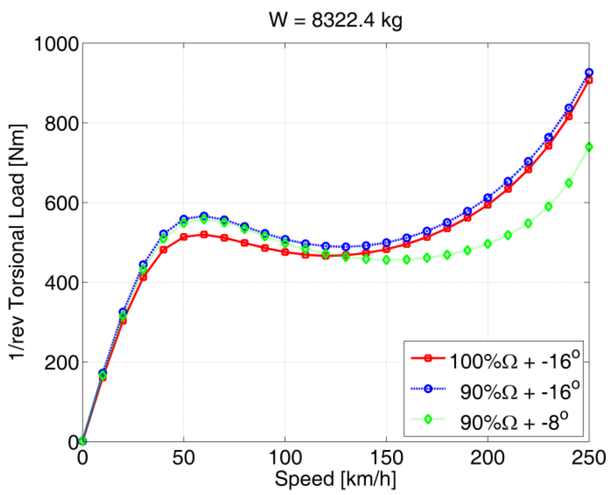


(c) 3/rev

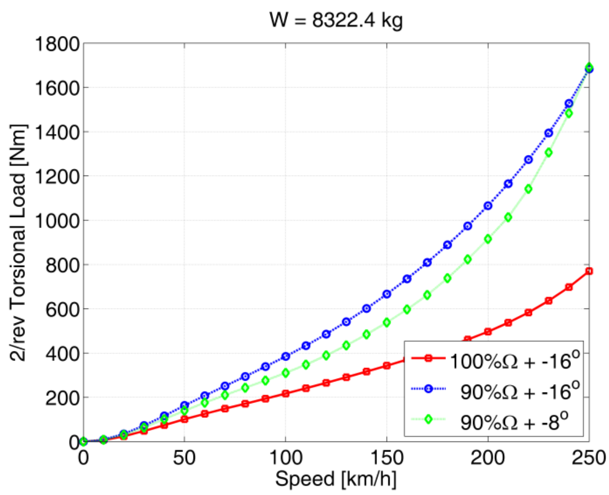


(d) 4/rev

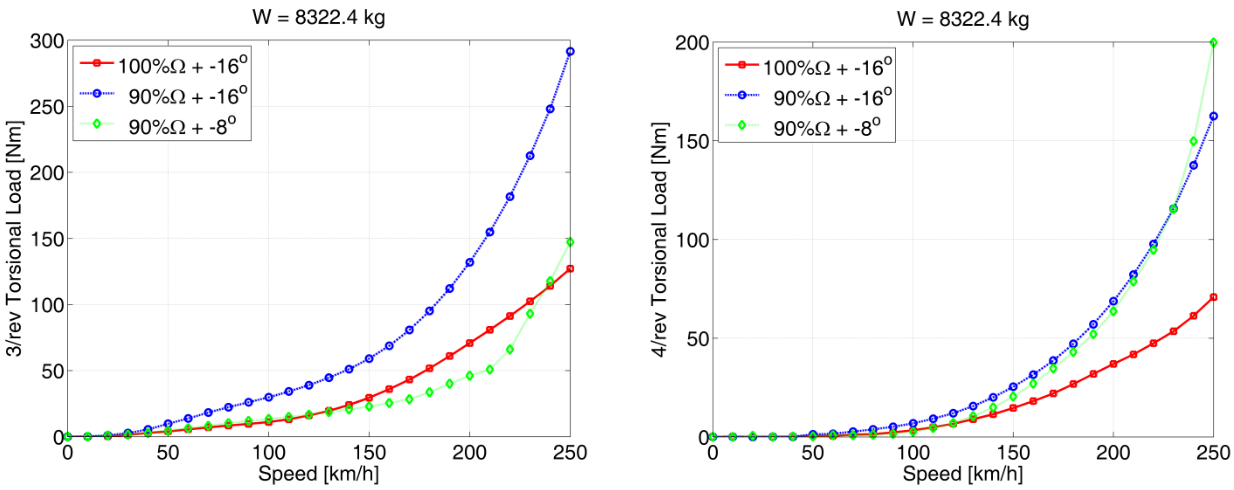
Figure 17: Lagwise loads.



(a) 1/rev



(b) 2/rev



(c) 3/rev

(d) 4/rev

Figure 18: Torsional loads.

7. Conclusions

Variable rotor speed and variable blade twist are combined to reduce rotor power and improve helicopter performance. Two modeling methods are utilized. One is based on an empirical aerodynamic model, which includes a main rotor model, a fuselage model, a tail rotor model and a propulsive trim method. The other is the Helicopter Multi-Block Method (HMB2), which is based on computational fluid dynamics. The analyses of the rotor power yielded the following conclusions:

1. The predictions of the rotor power by the empirical method are in good agreement with the flight data of the UH-60A helicopter and the CFD method, which verifies the application of these methods in the analysis of helicopter performance.

2. Varying rotor speed is an effective means of reducing rotor power and improving helicopter performance. At a speed of 250 km/h, the rotor power decreases by 20.3% with 15% rotor speed reduction. It is not appropriate to decrease the rotor speed too much in high forward speed.

3. Large blade twist in hover and moderate blade twist in high speed forward flight are preferred for better rotor performance.

4. Generally, varying rotor speed can achieve better performance improvement than changing blade twist. The combination of variable rotor speed and variable blade twist can obtain more power reduction than individually varying rotor speed or blade twist.

5. The optimal power reduction increases with forward speed and then decreases. The maximum improvement occurs at the medium to high forward speed, which is corresponding to the 23.7% power reduction ($C_w = 0.0065$).

6. With increasing takeoff weight, smaller variations of the rotor speed and blade twist are needed for optimal performance. The benefit in power saving decreases.

7. Variable blade twist has the potential in reducing blade loads introduce by variable rotor speed, especially for the lagwise and torsional blade loads.

In summary, combining variable rotor speed with variable blade twist can significantly improve helicopter performance than individually varying rotor speed or blade twist. Variable blade twist can be utilized to control the blade loads introduced by variable rotor speed.

Acknowledgments

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