Influence of Pre-twist Distribution at the Rotor Blade Tip on Performance during Hovering Flight*

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In this paper, optimization of blade twist distribution to maximize the performance of a rotor during hovering flight is described. The Japan Aerospace Exploration Agency has been developing a hybrid method coupled with computational fluid dynamics (CFD) and a prescribed wake model to reduce the computational cost. In this study, as a first step for the application of this method to optimize the blade configuration, the influence of the blade twist distribution variation on the figure of merit is investigated. The Hover Tip Vortex Structure Test (HOTIS) experiment is used as a calculation model, and the tip Mach number is 0.641. It is found that the result of using the hybrid method for the baseline blade configuration corresponds well with the full CFD of the rotor performance and figure of merit. For the influence of the blade twist on the figure of merit, high figures of merit are obtained when the difference of the blade twist at r/R=0.875 from the baseline \( \Delta \theta \) is around 1–3 deg and the difference of the blade twist at r/R = 1.0 from the baseline \( \Delta \theta \) is of negative value. Particularly, in the case of \( \Delta \theta_1 = 2.0 \) and \( \Delta \theta_2 = -3.7 \) deg, a maximum value of figure of merit of about 1.5% higher than the baseline design is achieved.

Key Words: Helicopter, Hover, CFD, Prescribed Vortex Wake Model, Optimization

Nomenclature

\( U \): conservative variables vector
\( F \): physical flux vector
\( V(t) \): moving control volume
\( n \): unit normal vector
\( S(t) \): boundary surface
\( v \): velocity vector
\( x \): velocity vector of the blade boundary
\( \rho \): air density
\( e \): total energy
\( p \): pressure
\( x \): x component of vortex wake position
\( y \): y component of vortex wake position
\( z \): z component of vortex wake position
\( R_0 \): rotor radius
\( R_i \): radial position of each vortex filament
\( \omega_i \): induced velocity
\( \Phi \): azimuth angle
\( \Omega \): angular velocity
\( C_T \): thrust coefficient
\( T \): thrust
\( \kappa \): wake contraction coefficient
\( g \): dumping coefficient
\( \Gamma \): circulation
\( U \): local velocity
\( F_i \): local lift
\( \sigma \): solidity
\( Q \): torque

Subscripts
\( v \): vortex wake
\( i \): vortex wake filament number
\( b \): blade number
\( n \): blade element number

1. Introduction

Helicopters have so various flight conditions such as forward and hovering flights and therefore require extensive parametric studies to design the rotor blades. Thus, simplified theories have been mainly used; for example, blade element momentum theory, lifting line theory, vortex theory and so on. Since these theories cannot compute the three-dimensional flow field around a complex blade configuration, only simple geometries such as rectangular shape with twist or with blade tip modifications have been employed so far. Recently, the computation of complex blades using computational fluid dynamics (CFD) methods has become possible due to the improvement of computer performance, and the number of complex-shaped rotor blades has increased. However, the designing of rotary wings using CFD has high computational cost. Thus, several hybrid methods that couple CFD with some potential theories such as lifting line theory, the free wake model or the prescribed wake model have been developed. The Japan Aerospace Exploration Agency (JAXA) has been developing a hybrid method of CFD and the prescribed wake model, which empirically defines rotor wake trajectories. Validation of this hybrid method had been...
already performed using HART II workshop data.\textsuperscript{2,3} However, validation has only been conducted using forward flight conditions; hovering cases have not been validated yet.

In this study, the hybrid method is evaluated using the Hover Tip Vortex Structure Test (HOTIS) data obtained by DLR data,\textsuperscript{4} and as a first step for the application of this method to optimizing blade configuration, the influence of blade twist distribution variation on the figure of merit is investigated.

2. Numerical Method

2.1. CFD solver: rFlow3D

In this study, the “rFlow3D” code, a finite-volume CFD solver based on the moving overlapped grid method developed at JAXA is utilized.\textsuperscript{5} Governing equations of the three-dimensional flow space field are described in an arbitrary Lagrangian Eulerian formulation since a rotor blade rotates with elastic deformation, the conservative variables vector, \(\rho\) is air density, \(\mathbf{v}\) is a velocity vector for the cell volume, \(e\) is total energy, \(\mathbf{n}\) is the normal vector on the boundary surface. Components of \(\mathbf{U}\) and \(\mathbf{F}\) are expressed as

\[
\mathbf{U} = \begin{pmatrix} \rho \\ \rho \mathbf{v} \\ \rho e \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} (\mathbf{v} - \mathbf{x}) \cdot \mathbf{n} \\ (\mathbf{v} - \mathbf{x}) \cdot \mathbf{n} \rho \mathbf{v} + p \mathbf{n} \\ (\mathbf{v} - \mathbf{x}) \cdot \mathbf{n} \rho e + p \mathbf{v} \cdot \mathbf{n} \end{pmatrix}
\]

In the numerical flux, the modified simple low-dissipation AUSM (mSLAU) scheme\textsuperscript{6,6} is employed. The fourth-order compact Monotonic Upstream-centered Scheme for Conservation Lows (MUSCL) Total Validation Diminishing (TVD) (FCMT) scheme\textsuperscript{7} is used to improve spatial accuracy. A dual-time stepping method is used for time integration to keep the time accuracy while allowing a relatively large time step since the flow field around the rotary wing is unsteady. The first-order backward Euler method is selected, and in “pseudo time” integration, the Lower-Upper Symmetric-Gauss-Seidel (LU-SGS) method\textsuperscript{8} is used.

2.2. Prescribed wake model

A rotor blade is divided into several elements where vortex wakes are emitted from the boundaries between the blade elements. Equations of the wake trajectories are written as follows,

\[
x_v = r_i \cos \psi_v
\]

\[
y_v = r_i \sin \psi_v
\]

\[
z_v = v_0 \frac{\Delta \psi}{\Omega}
\]

\[
v_0 = R_0 \Omega \sqrt{\frac{C_T}{2}}
\]

where \(x_v, y_v, z_v\) are vortex wake coordinates, \(R_i\) is the radial position of each vortex filament emitted from the blade, \(\psi_v\) is the azimuth angle of the rotor blade, \(\psi_e\) is the azimuth angle of the wake position, \(v_0\) is the induced velocity, \(C_T\) is the thrust coefficient, \(\Omega\) is the angular velocity of the blade, \(\kappa\) is the wake convection coefficient and \(g\) is the dumping coefficient. Equations (9)–(11) are empirical models that express the contraction of the wake trajectory proposed by Landgrebe.\textsuperscript{9}

Circulations of each vortex \(\Delta \Gamma_i\) are based on the lifting line theory, and the expression can be written as

\[
\Delta \Gamma_i = (\Gamma_{n-1} - \Gamma_n) \sqrt{\frac{C_{T_{pro}}} {C_{T_{ref}}}}
\]

\[
\Gamma_n = \frac{F_{\text{loc}}}{\rho \mathbf{U}_b} \frac{\mathbf{U}_b}{\mathbf{U}_b}
\]

\(\Gamma_n\) is circulation of the blade element, \(C_{T_{pro}}\) is the thrust coefficient calculated by pressure distribution using the CFD part of the hybrid method, \(C_{T_{ref}}\) is the thrust coefficient computed using the momentum theory, \(F_i\) is the local lift, \(\rho\) is the density and \(U\) is the local flow speed to the blade element. Figure 1 shows a sample of the configurations of CFD and multi-trailer prescribed wake model. Eight trailers are employed in the present prescribed wake model.

Coupling between CFD and the prescribed wake model is carried out by imposing the induced velocity calculated using Biot-Savart’s law from the whole trailing vortices wake on the CFD grid boundaries. Details are described in Sugiura et al.\textsuperscript{2,3}

\[
C_T = \frac{T}{\rho \pi R_0^2 (R_0 \Omega)^2}
\]

\[
\Delta \Psi = \Psi_b - \Psi_e \quad (\Delta \Psi < 0)
\]

\[
r_i = R_i [\kappa + (1 - \kappa) \exp(g \Delta \Psi)]
\]

\[
\kappa = 0.78
\]

\[
g = 0.145 + 27 C_T
\]

\(C_T\textsuperscript{40\circ}2015\text{JSASS}\)
3. Calculation Model

HOTIS data is utilized to verify the computational accuracy of this hybrid method. The experiment setup is shown in Fig. 2. Tables 1 and 2 summarize the blade specifications and test conditions.

4. Results and Discussion

4.1. Rotor performance

First, the hybrid method is compared to the full CFD and the experiment. Figure 3 shows a comparison of the rotor performance for the experiment, full CFD and hybrid method. The solid line with circles is HOTIS experiment data, the dotted line with squares is the full CFD result and the dashed line with triangles is the hybrid method result. The hybrid method result is close to both the experiment and full CFD.

The relationship between $C_T / \sigma$ and the figure of merit is shown in Fig. 4. The hybrid method result is close that of the full CFD with respect to rotor performance. However, the hybrid method and full CFD both overestimate the figure of merit when compared to the experiment.

Figure 5 shows the relationship between the collective pitch and thrust coefficient; the result of the hybrid method is close to that of full CFD. However, those numerical results generally overestimate the thrust coefficient.

The relationship between the collective pitch and torque coefficient is shown in Fig. 6. The hybrid method corre-
sponds well with full CFD, but the results of the hybrid method and full CFD overestimate the torque coefficient when compared to the experiment. When the pitch angle is small, the hybrid method and full CFD are close to the result of the experiment. Although an actual blade has elastic deformation which tends to cause a negative twist, the present numerical simulations do not consider elastic deformation. This is suggested as the cause of the overestimation of thrust versus the collective pitch angle. Additionally, the possible effects of flow circulation and ground effect accompanying the HOTIS experiments are not considered.

Figure 7 shows spanwise airload coefficient distributions. The hybrid method basically corresponds well with full CFD, but it underestimates at the blade tip and the local airload distributions are noticeably different. Different wake models specifically designed for hovering conditions such as Landgrebe and Kocurek & Tangler’s models have been tested, but the improvements were found to be quite limited. However, as can be seen from Figs. 3–6, performances for the whole rotor are satisfactorily predicted in good agreement with the full CFD method, which confirms that agreeable results can be expected by applying the current efficient hybrid method for rotor blade performance estimation in hovering flight instead of the cost consuming full CFD method.

4.2. Optimal blade twist modification

As an application of the hybrid method, optimal blade twist is investigated. Design parameters are shown in Table 3 and Fig. 8. In this study, two parameters \( \Delta \theta_1 \) and \( \Delta \theta_2 \) are used, which are pitch angle differences from the baseline blade. The evaluation function is a figure of merit, which is thrust efficiency under hovering conditions and is expressed as follows,

\[
FM = \frac{P_{\text{ideal}}}{P_{\text{actual}}} < 1
\]  
(14)

\[
P_{\text{ideal}} = \frac{T_{\text{vfx}}}{Q\Omega}
\]  
(15)

\[
P_{\text{actual}} = Q\Omega
\]  
(16)

where, \( P_{\text{ideal}} \) is the ideal power required to hover, \( P_{\text{actual}} \) is the actual power required to hover, and \( x_0, x_1 \) and \( x_2 \) are the blade twist points. For the interpolation among \( x_0, x_1 \) and \( x_2 \), cubic spline formulation is used.

Following the optimization procedure utilizing a Kriging model to accelerate the optimal design variables search process, 20 samples based on the improved hypercube sampling method are computed as initial sample points. Then, a Kriging model is built and the optimal design point is searched.

Figure 9 shows a figure of merit distribution based on the Kriging model constructed when \( \Delta \theta_1 \) and \( \Delta \theta_2 \) are swept from \(-10\) to \(+10\) deg, respectively. From Fig. 9, it is found that the figure of merit is slightly larger than the baseline configuration when \( \Delta \theta_1 \approx 2.0 \) deg and \( \Delta \theta_2 \approx -3.7 \) deg. The blade twist distribution for these design values is shown in Fig. 10. The airload coefficient distribution for this optimal case is shown in Fig. 11. It can be seen that the maximum airload coefficient point moves to the inner side and is stronger than the baseline. In addition, the airload around the blade tip is weaker than the baseline. These results indicate that the circulations on the inner side are stronger and the tip vortex circulation is weaker than the baseline. This delivers more efficient performance than the baseline linear twist distribution design. This feature is proven by comparing the tip vortex intensity between the optimal design and baseline as shown in Fig. 12. A much weaker blade tip vortex is observed in the optimal design case.

| Table 3. Design parameters. |
|-----------------------------|
| \( x_0 \) \((r/R)\) | 0.75 |
| \( x_1 \) \((r/R)\) | 0.875 |
| \( x_2 \) \((r/R)\) | 1 |
| \( \Delta \theta_1 \) [deg] | \(-10\) to \(+10\) |
| \( \Delta \theta_2 \) [deg] | \(-10\) to \(+10\) |

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Figure 13 shows the comparison of the figure of merit between the baseline and the blade twist modification case ($\Delta \theta_1 = 2.0$ and $\Delta \theta_2 = -3.7$ [deg]). The figure of merit in the modified case is slightly larger (about 1.5%) than that of the baseline.

4.3. Computing efficiency

A desktop computer with an Intel® Core™ i7-3770 (4 cores) CPU was used in this study. For the hybrid method, one case needs about a day for computation using a CPU core. Yet for full CFD, one case takes over one week using a core. We therefore conclude that the hybrid method has a computational efficiency seven-fold that of the full CFD. Calculation at the inner background grids requires a lot of time using full CFD, but the hybrid method doesn’t compute inner background grids. It is considered that this makes a major contribution to the improvement in calculation efficiency.

5. Conclusion

The computational accuracy of the hybrid method was evaluated for hovering flight conditions, and the influence of the blade twist distribution on the figure of merit was investigated using HOTIS experimental data. The following results were obtained.

1. The results of the rotor performance and the figure of merit using the hybrid method correspond well with those using the full CFD computations.
2. The thrust and torque coefficients of the hybrid method are close to that of full CFD, but they are overestimated compared to the experimental data due to the omission of blade elasticity, which tends to cause negative twist and possible effects of flow circulation and ground effect accompanying the HOTIS experiments.

3. The airload distribution of the hybrid method is basically close that of full CFD, but it is underestimated around the blade tip. The effect of discrepancy of airload distribution at the blade tip is not considered to be significant to the overall rotor performance estimations.

4. Optimal modification of the twist distribution at the blade tip portion of the baseline blade was studied. It was found that the figure of merit can be improved up to 1.5% from the baseline. This is due to the fact that the tip vortex strength of the modified blade twist is weaker than that of the baseline.

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