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Effect of Rotor Blade Deflections on Blade-Vortex Interaction Noise Prediction

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ABSTRACT

Blade-vortex interaction (BVI) noise is a main noise source from a rotorcraft and has been a barrier to wide acceptance for applications of rotorcrafts. In order to predict the noise accurately, it is required to consider characteristics of rotor blades having high aspect ratio as well as flow-unsteadiness around blades. Therefore a numerical analysis of BVI needs a prediction method using an aerodynamic and structural coupling, and it is required to investigate the effect of blade deflections on BVI noise prediction as a preliminary study for development of the coupled method. In this study, deflections of rotor blades were divided into flapping, lead-lag and torsional deflections and the effect of variations of those deflections on the noise prediction was investigated. In order to predict the noise, Farassat's Formulation 1A and free-wake panel method using CVC (Constant Vorticity Contour) and VLM (Vortex Lattice Method) were used. For the validation of the noise prediction, the predicted result was compared with the experimental result of HART II (Higher Harmonic Control Aeroacoustics Rotor Test) rotor. The result demonstrated that the blade air-load, acoustic pressure time history and noise contour were well predicted. Based on the validation, noise predictions through variations of the blade deflections were performed, and the effect of each blade deflection on the noise prediction was analyzed.

1. INTRODUCTION

A rotorcraft has played an important role for civil and military missions because it has unique flying abilities like hovering, vertical take-off and landing, and sideway flights. However, flow-unsteadiness around blades arising from flow asymmetry of rotating blades generates several noises, and that has become a barrier to wide use of rotorcrafts [1].

Blade-vortex interaction (BVI) noise is the most annoying noise source among several noise sources generated by a rotorcraft. This phenomenon is the result of the interaction between a shed tip vortex and a following blade, and this noise source becomes dominant during low speed descent and maneuvering flight. Especially, during an approach to a landing site, the impulsive BVI noise annoys people near the site highly and is propagated to relatively large distances. Consequently, the BVI noise has been a significant barrier to wide acceptance for civil applications of rotorcrafts [2].

During the last three decades, many researchers have focused the BVI noise, and significant progress has made in the understanding of the generation of this noise source [3-5]. Especially, many research efforts for the numerical prediction of BVI noise have indicated that an accurate prediction model requires consideration for the aerodynamic and structural interaction of rotor blades [6-7]. Because the distance between a rotor blade and a tip vortex is a major factor for airload fluctuations and noise generated by BVI, a noise prediction using only aerodynamic analysis without any consideration of blade deflections is limited to predict BVI noise accurately. Therefore, consideration of blade deflections arising from high aspect ratio and flow-unsteadiness of blades is

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In this study, deflections of rotor blades were divided into flapping, lead-lag and torsional deflections and the effect of variations of those deflections on the noise prediction was investigated. In order to predict the noise, Farassat's Formulation 1A and free-wake panel method using CVC (Constant Vorticity Contour) and VLM (Vortex Lattice Method) were used. For the validation of the noise prediction, the predicted result was compared with the experimental result of HART II (Higher Harmonic Control Aeroacoustics Rotor Test) rotor. The result demonstrated that the blade air-load, acoustic pressure time history and noise contour were well predicted. Based on the validation, noise predictions through variations of the blade deflections were performed, and the effect of each blade deflection on the noise prediction was analyzed.

2. Methodology

2.1 Airloads prediction

For the aerodynamic analysis, the free-wake vortex lattice method (free-wake VLM) is used. In the case of moderate advance ratio and tip Mach number, the continuity equation for the flow field around rotor blades reduces to the Laplace's equation in terms of the total velocity potential.

$$\Phi^* = \frac{1}{4\pi}\int_{\text{body+wake}} \gamma \mathrm{n} \cdot \nabla\left(\frac{1}{\mathrm{r}}\right) \mathrm{dS} + \Phi_\infty \tag{1}$$

Applying the small disturbance assumption, rotor blades are replaced with flat plates, and then those are expressed by vortex sheets that are general solutions for the Laplace's equation [8]. The Neumann boundary condition is applied to each sub-divided panel on the sheets, and then vortex strength on each panel is calculated by solving a linear equation as follows:

$$a_{i,j}\Gamma_j = -U_\infty n_j - w_{wake} n_j \tag{2}$$

The force generated by a vortex sheet is computed by using the Kutta-Joukowski theorem [8].

$$L_i = \rho V_i \Gamma_i \tag{3}$$

For the computational efficiency of a free wake calculation, the constant vorticity contour (CVC) model [9] is used for the wake modeling. In this model, wake filaments having the same strength are distributed by the circulation distribution of the trailing edge and release points where wake filaments are released are changed with the azimuthal change of the circulation distribution. The CVC wake model reduces the computing cost for the free wake calculation because it generally needs a half of filaments than vortex lattice wake model in which the span-wise and azimuthal variations of the bound circulation are represented by the trailed component and the shed component, respectively [9]. The strength of wake filaments and release points are determined as follows:

$$\Gamma = \frac{1.5\max(\Gamma(r,\psi))}{0.5N} \tag{4}$$

$$r_n = r_a + [(n+0.5)\Gamma - \Gamma(r_a)]\frac{(r_b - r_a)}{\Gamma(r_b) - \Gamma(r_a)} \tag{5}$$

For a free wake analysis, the velocities induced on those wake filament points released from blades are calculated and each wake filament point is moved using those velocities every time step.

In order to predict BVI airloads with blade deflections, a structural analysis method is coupled with the aerodynamic analysis method. The finite element method based on Euler beam assumption is used to obtain the flap bending, twist and extension displacements of rotor blades. The blade is divided into finite elements, and then stiffness properties and mass distribution are applied to each element in order to define the stiffness and mass matrices. By using the resulting stiffness and mass matrices, the eigenvalue problem is derived, and it gives the mode shapes. Applying the nodal force from the aerodynamic analysis, the modal responses are driven. These responses are used to obtain the displacements and velocities of the blade segments [10]. In the aerodynamic and structural coupled methodology, information between the free-wake vortex lattice method and the finite element method is exchanged every one-revolution.

2.2 Noise prediction

The Farrasat's Formulation 1A [11] is used to predict the BVI noise. This is the retarded time formulation of the Ffowcs Williams-Hawkings (FW-H) equation [12]. In this formulation, the acoustic pressure is represented as a sum of thickness and loading noise term as follows:

$$p'(\vec{x},t) = p'_T(\vec{x},t) + p'_L(\vec{x},t) \tag{6}$$

$$4\pi p'_T(\bar{x},t) = \int_{f=0} \left[\frac{\rho_0 \dot{v}_n}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[\frac{\rho_0 v_n \left(r\dot{M}_i \hat{r}_i + c_0 M_r - c_0 M^2 \right)}{r^2 (1-M_r)^3} \right]_{ret} dS \tag{7}$$

$$\begin{aligned} 4\pi p'_L(\bar{x},t) &= \frac{1}{c_0} \int_{f=0} \left[\frac{\dot{l}_i \hat{r}_i}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0} \left[\frac{l_r - l_i M_i}{r^2 (1-M_r)^2} \right]_{ret} dS \\ &+ \frac{1}{c_0} \int_{f=0} \left[\frac{l_r \left(r\dot{M}_i \hat{r}_i + c_0 M_r - c_0 M^2 \right)}{r^2 (1-M_r)^3} \right]_{ret} dS \end{aligned} \tag{8}$$

where p'_T and p'_L represent the thickness and loading noise term, respectively. In addition, the subscript *r* means the vector component of the radiation direction to an observer point and the dot on $\dot{M}_i$ and $\dot{l}_i$ means the rate of variation with respect to retarded time. The airloads and blade motion obtained from the flow analysis are used for the input of acoustic analysis and the sound pressure level is obtained by using the Fourier transformation of the acoustic pressure obtained by the acoustic analysis.

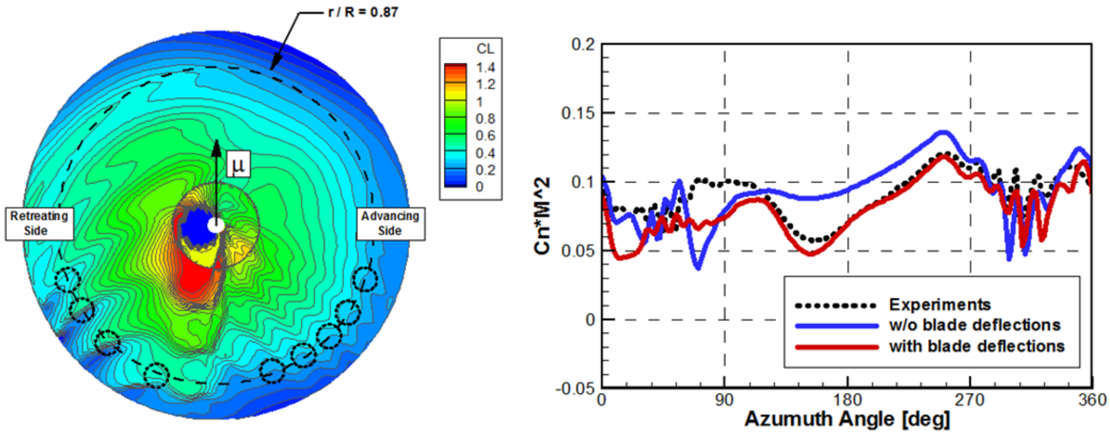
3. Results and discussions

The predicted results were compared with the experimental result of the baseline condition for the HART II (Higher Harmonic Control Aeroacoustics Rotor Test) rotor [13]. The HART II rotor is a 4-bladed hingeless rotor and Table 1 shows the specification of the rotor and the operation condition for baseline condition.

Airfoil	NACA23012mod	Advance ratio	0.15
Twist	-8.0 deg. (linear)	Shaft angle	5.3 deg.
Radius	2.0m	C_T/σ	0.0055
Chord	0.121m (rectangular)	M_{tip}	0.641

Table 1 – Dimensions of blades and operation conditions

Fig. 1 shows the predicted airloads for the baseline condition of HART II rotor. Fig. 1 (a) and (b) show predicted C_l contour with blade deflections and predicted $C_n M^2$ at r/R=0.87, respectively. The airload fluctuations generated by BVI are shown in Fig. 1 (a). In Fig. 1 (b), the impulsive airload fluctuations generated by the BVI events are observed on the advancing (azimuth angle 0 to 90 deg.) and retreating (azimuth angle 270 to 360 deg.) side of the rotor. This rapidly changing airloads are the noise source of BVI phenomenon. As shown in this figure, although rigid blade case also shows the airload fluctuations, the magnitude of these fluctuations is overestimated. Moreover, this case has some discrepancy in the region for 90~270 deg.



(a) Predicted C_l contour (b) Predicted C_nM^2 at r/R=0.87

Figure 1 – Predicted airloads for the baseline condition of HART II rotor

The rate of change of airloads is one of the primary parameters for the noise prediction. Using the azimuth angle as the time variable, the time derivative of the airloads is shown in Fig. 2. Some discrepancies on the advancing side are observed, but the BVI airloads predicted with blade deflections on the retreating sides are well captured in amplitude, number, and location. In the case of the prediction without blade deflections, the magnitude of fluctuations is overestimated.

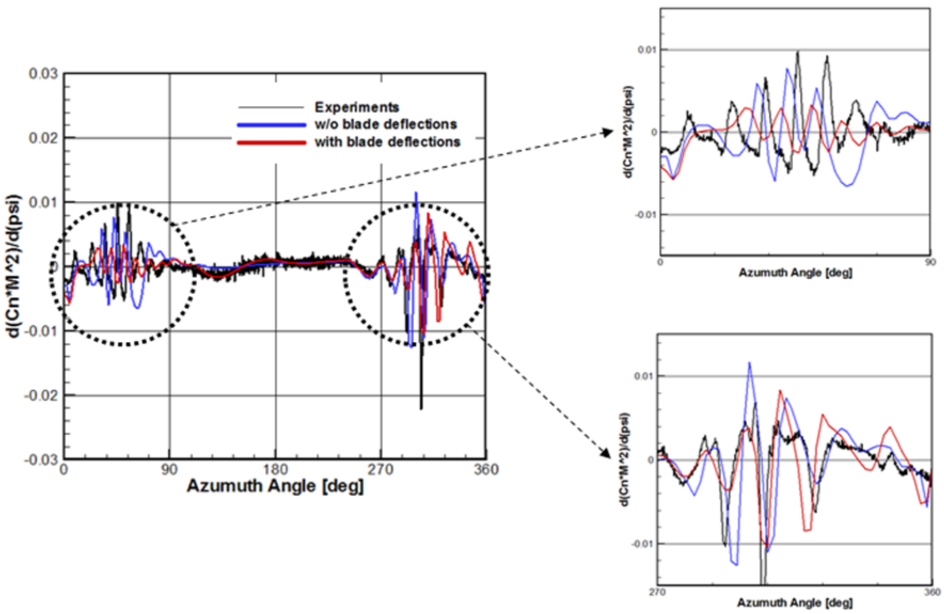
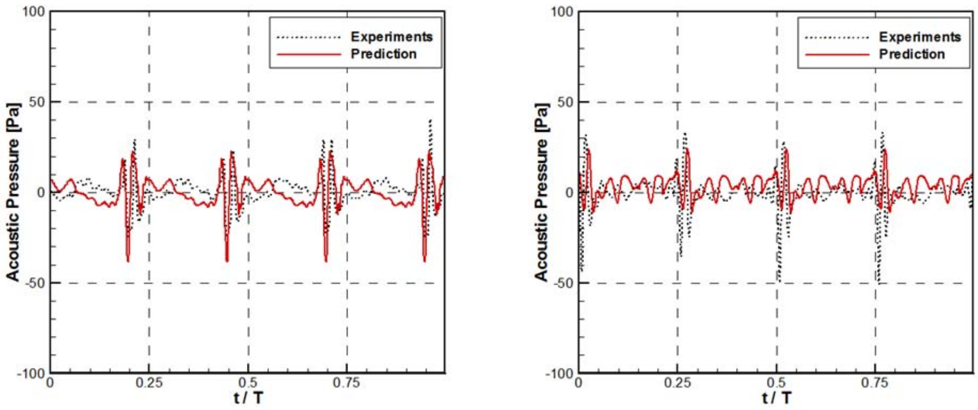


Figure 2 – $dC_NM^2/d\psi$ for the baseline condition of HART II rotor

For a validation of the acoustic time history and noise contour, the predicted results are compared with the acoustic measurements for the HART-II baseline condition. In the HART-II test, the vertical position of the acoustic array was 2.2m below the rotor hub. Predicted acoustic time histories with the measurements are shown in Fig. 3. The general shapes of the acoustic time history are captured quite well. At the retreating side, the peak acoustic pressure of the predicted result approaches that of the measurement. However, at the advancing side, the peak noise is under-predicted because the airload fluctuations on the advancing side generated by the BVI is under-predicted as shown in figure 2.



(a) Retreating side (b) Advancing side

Figure 3 – Comparison of the predicted acoustic time history with the HART II experiments

Comparisons of the measured and predicted noise contours are shown in figure 4. In the predictions without blade deflections, the BVI noise is over-predicted and the noise directivity is not seen in the noise contour. However, the noise level and directivity pattern from the predictions with blade deflections are similar to the measurements except some regions. Some differences appear in the advancing side region, and those are due to the under-prediction of airload fluctuations at the advancing side of the rotor. The spot occurred by the high noise level near the aft side arises from the rapid drop in the airloads near the aft side as shown in figure 1.

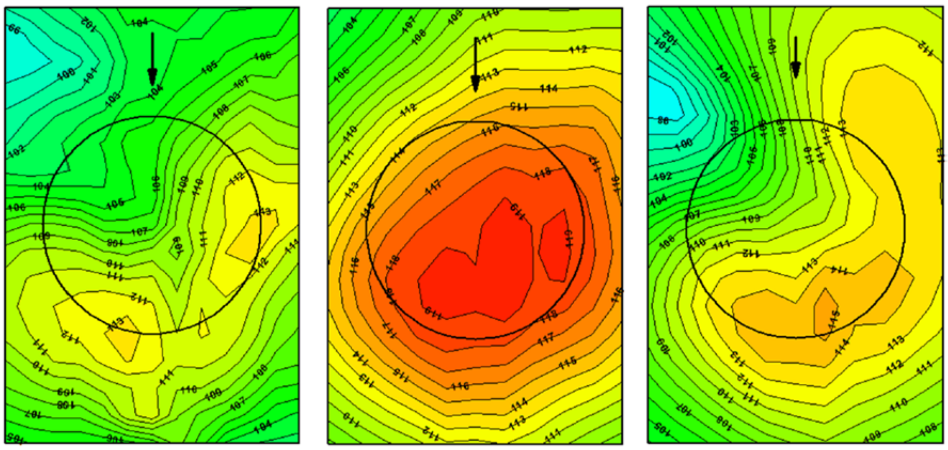


Figure 4 – Comparison of predicted noise contours with the HART II experiments (OASPL)

(Left: Measurements, Mid: Predictions without blade deflections, Right: Predictions with blade deflections)

4. CONCLUSIONS

In this study, the effect of variations of blade deflections on the noise prediction was investigated. In order to predict the noise, Farassat's Formulation 1A and free-wake panel method using CVC (Constant Vorticity Contour) and VLM (Vortex Lattice Method) were used. For the validation of the noise prediction, the predicted result was compared with the experimental result of HART II (Higher Harmonic Control Aeroacoustics Rotor Test) rotor. The result demonstrated that the blade air-load, acoustic pressure time history and noise contour were well predicted. Based on the validation, noise predictions through variations of the blade deflections were performed, and the predicted results with blade deflections showed better agreement with measurements than those without blade deflections.

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