

HYBRID METHOD OF CFD AND PRESCRIBED WAKE MODEL FOR ROTORCRAFT AEROACOUSTICS AND AERODYNAMICS PREDICTION

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Abstract

This paper explains a hybrid method of computational fluid dynamics (CFD) and prescribed wake model developed at Japan Aerospace Exploration Agency (JAXA). The base CFD code herein is a structured grid Euler solver, <rFlow3D>, which has intensively been developed for helicopter applications at JAXA. The rFlow3D is a highly versatile CFD code that can numerically simulate flows around helicopter in a wide range of flow conditions, considering trimming and blade elastic deformation. In this study, several existing prescribed wake models are combined with rFlow3D. Accuracy of the hybrid method is evaluated by comparing computational results with experimental ones. Airlord coefficient on blade and blade vortex interaction noise contour computed by the hybrid method show good agreement with experiment, however, they are still overestimated since their miss distances are rather short. Thus, we plan to improve the hybrid method by utilizing initial vortex position data obtained from rFlow3D to prescribed wake models in the near future.

1. INTRODUCTION

Helicopter has been active in various situations such as emergency medical service, fire-fighting, pesticide spraying, broadcasting, and transport in mountains since it has unique flight characteristics; hovering and vertical take-off and landing.

However, helicopter noise, especially blade vortex interaction (BVI) noise, is one of environmental problems for residents around heliport. Recently, blade airfoil and blade tip geometry have been developed for noise reduction. On the other hand, rotor active control also has been expected to reduce noise since miss distance which is a vertical distance between blade and vortex can be controlled satisfactorily. Miss distance is an important factor of BVI noise since pressure fluctuations on blade depend on miss distance. When miss distance is short, pressure fluctuations on blade are large, and vice versa. Thus, for establishment of helicopter active noise reduction technology, it is necessary to predict precisely unsteady pressure fluctuations around helicopter, especially on rotor blade. It is also very important to predict accurately behaviour of vortex wake for understanding BVI noise, which is a phenomenon that vortex wake generated by preceding blade interfere with following one.

Several simplified BVI noise prediction methods have been enthusiastically developed worldwide (USA, Germany, France, and South Korea) [1]. Although their computational cost is low, there is still room for improvement in their computational accuracy. Japan Aerospace Exploration Agency

(JAXA) used to develop a practical computation method by combining CFD and prescribed wake model [2]. However, the airlord coefficient computed by the method was rather overestimated. In this study, the hybrid method of CFD and prescribed wake model is improved by accurately reflecting induced velocity of prescribed wake model to CFD and modifying circulation of prescribed wake model.

JAXA has been developing computational fluid dynamics (CFD) code "rFlow3D (rotor Flow 3D)" for rotorcraft analysis. The rFlow3D which is based on moving overlapped structured grid method can solve the flow fields around rotating blades. The rFlow3D has been validated by comparing two experimental results: one is rotor in hovering condition conducted by Caradonna etc., and the other is ROBIN (ROtor Body Interaction) model which includes fuselage [3-6]. The rFlow3D realizes high accuracy by considering following analyses; computational structural dynamics (CSD), flight dynamics, blade elastic deformation, and trim. Moreover, a comprehensive analysis tool for BVI noise has been developed by combining rFlow3D with structural analysis code "rMode (rotor Mode)" and acoustics analysis code "rNoise (rotor Noise)". Fig. 1 shows configuration of JAXA BVI noise comprehensive analysis tool.

As mentioned above, it has been found that rFlow3D has enough computation accuracy by comparing computational results with experiments. However, it's hard to say that CFD is practical for computing many BVI noise predictions, since CFD generally requires long computational time, for example, one month or

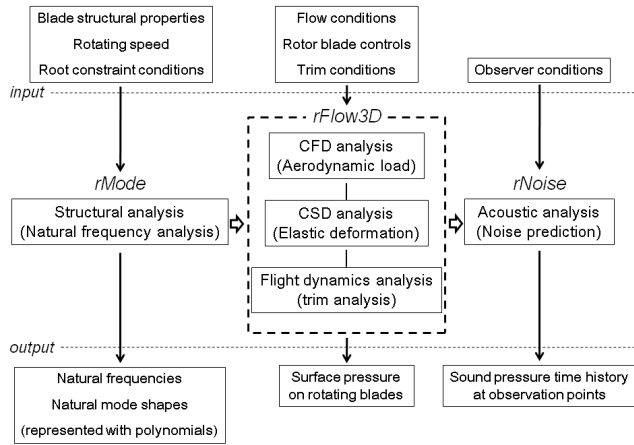


Fig. 1 Configuration of JAXA BVI noise comprehensive analysis tool

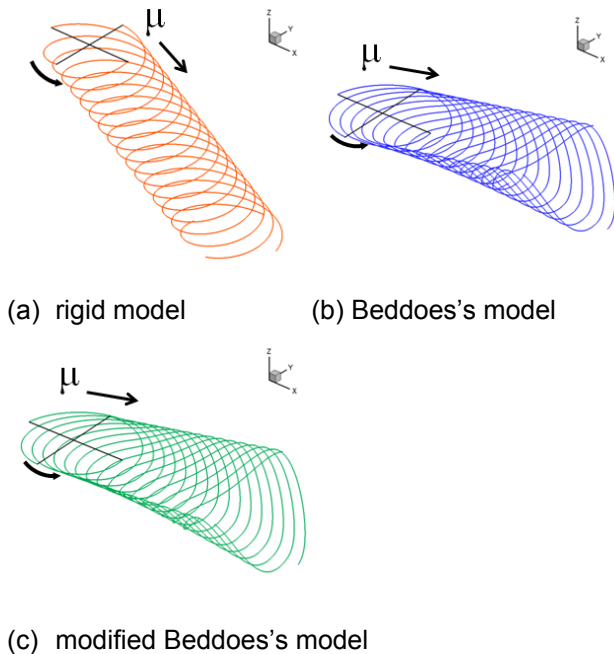


Fig. 2 Vortex wake trajectories of prescribed wake models

more for one case. On the other hand, prescribed wake model dramatically reduces computational cost, since it empirically defines blade tip vortex geometry and provides induced velocity by summing induced velocity of vortex elements based on Biot-Savart law (Fig.2).

The objective of this study is developing an effective tool for BVI noise prediction by constructing hybrid method of rFlow3D / prescribed wake model and comparing these results with HART (Higher harmonic control Aeroacoustics Rotor Test) II experimental data [7-9]. HART II is an international cooperation project of rotor active noise reduction technology.

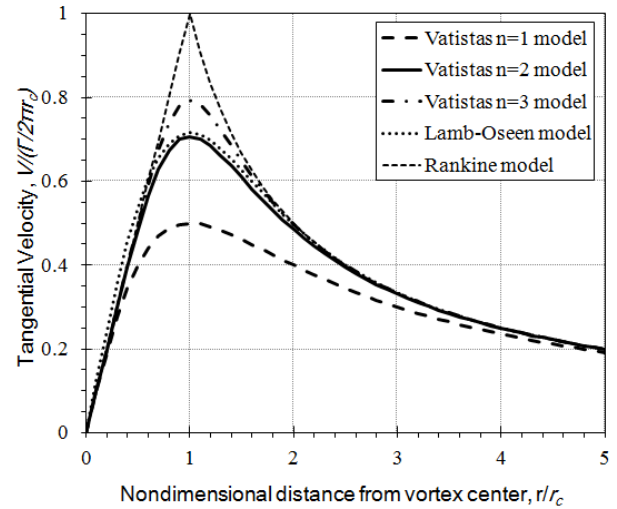


Fig. 3 Comparison of vortex wake model's tangential velocity [12]

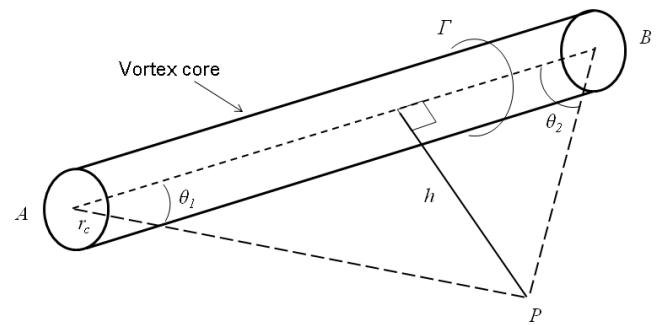


Fig. 4 Induced velocity by Biot-Savart law [12]

2. NUMERICAL METHODS

2.1. Prescribed Wake Model

2.1.1. Blade Tip Vortex Model

There are several blade tip vortex models. In this study, Vatistas $n=2$ model [10] is employed since it agrees rather well with experiments. Fig. 3 shows Vatistas model with Lamb-Oseen and Rankine models. Blade tip vortex models which include dissipation effect [11] accurately evaluate vortex even if the time is long until blade interacts with vortex. The time evolution of r_c is given as follows:

$$(1) \quad r_c(t) = \sqrt{r_{c0}^2 + 4\alpha\delta vt}$$

where t is time, r_{c0} is an initial value of vortex core radius, which is set as twenty percent of blade cord length in this study. $\alpha = 1.25643$, which is called Oseen parameter. v is dynamic viscosity coefficient, and δ is called effective diffusion constant or eddy viscosity coefficient which is determined by vortex Reynolds number.

The velocity of vortex at point P in Fig. 4 is given as follows:

$$(2) \quad V = \frac{\Gamma}{4\pi(r_c^4 + h^4)^{1/2}} (\cos\theta_1 - \cos\theta_2)$$

tangential velocity decreases as the radius of vortex core r_c increases. Here, Γ is circulation of vortex.

2.1.2. Geometry of Blade Tip Vortex

Blade tip vortex literally generated from blade tip flows backward spirally. In this process, blade tip vortex moves downward gradually by rotor downwash, and the geometry of blade tip vortex has inclination to the rotor plane (Fig. 2).

There are some models in prescribed wake model to describe three dimensional vortex geometry: rigid model, Beddoes's model [13], and modified Beddoes's model [14] (Fig. 2). Rigid model describes blade tip vortex as cylindrical spiral, Beddoes's model includes symmetrical roll-up of blade tip vortex, and modified Beddoes's model reflects asymmetrical roll-up structure of blade tip vortex. Skew angle of blade tip vortex is represented as $E = |\chi|$ in both Beddoes's model and modified Beddoes's model. However, the case of $E = |\chi|/2$ is also computed, since there is a report that computation with $E = |\chi|/2$ corresponds well with experiment [12].

Induced velocity is different among prescribed wake models, however, modified Beddoes's model is explained below since it is most realistic. Modified Beddoes's model considers conservation of momentum and asymmetry of downwash in horizontal direction.

In modified Beddoes's model, vortex trajectory projection to x-y plane is assumed as a simple epi-cycloid, and x-y coordinate is expressed as follows:

$$(3) \quad \begin{aligned} x_v &= R\cos\Psi_v + \mu_x\Delta\Psi_v \\ y_v &= R\sin\Psi_v \end{aligned}$$

where R is radius of rotor, Ψ_v is blade rotation angle when blade tip vortex is generated, $\mu_x = V\cos\alpha_{TPP}/R\Omega$, $\Delta\Psi_v = \Psi_b - \Psi_v$, α_{TPP} is rotor plane's angle of attack, Ω is blade rotation angular velocity, Ψ_b is blade rotation angle in computational time.

Z coordinate is given as integral of rotor inflow's downward component and downwash v

$$(4) \quad \begin{aligned} z_v &= (1/R\Omega) \int_{\Psi_v}^{\Psi_b} (-V\sin\alpha_{TPP} + v) d\Psi \\ &= \int_{\Psi_v}^{\Psi_b} (-\mu_z + v/R\Omega) d\Psi \\ &= -\mu_z\Delta\Psi_v + \int_{\Psi_v}^{\Psi_b} (v/R\Omega) d\Psi \end{aligned}$$

where $\mu_z = V\sin\alpha_{TPP}/R\Omega$ and downwash v is defined as follows:

(inside rotor disc)

$$(5) \quad v = v_0(1 + 8E/15\pi + Ex' - 2\mu_x y' - E|y'|^3)$$

(outside rotor disc)

$$(6) \quad v = 2v_0(1 + 8E/15\pi - 2\mu_x y' - E|y'|^3)$$

considering inhomogeneous downwash distribution to the longitudinal and lateral directions. The second term in right-hand side of eq. (4) is integrated by using eqs. (5), (6). Variables with prime in eqs. (5), (6) indicate that they are normalized by rotor radius R . v_0 is given as $v_0 = -\lambda_l R\Omega$, assuming uniform downwash inside rotor disc. λ_l is a solution of the following equation:

$$(7) \quad -C_T/2\lambda_l = [(\mu_z + \lambda_l)^2 + \mu_x^2]^{1/2}$$

Wake inclination to the longitudinal direction is expressed as $E = |\chi|$ using following skew angle:

$$(8) \quad \chi = \tan^{-1}[\mu_x/-(\mu_z + \lambda_l)]$$

2.2. CFD

2.2.1. CFD Solver

The governing equation of CFD is a three dimensional compressible Euler equation:

$$(9) \quad \frac{\partial}{\partial t} \int_{V(t)} \mathbf{U} dV + \int_{S(t)} \mathbf{F} \cdot \mathbf{n} dS = 0$$

where $\mathbf{U}$ is a solution vector, $\mathbf{F}$ is a velocity vector for x, y, z directions, $\mathbf{n}$ is a unit normal vector. Components of $\mathbf{U}$ and $\mathbf{F}$ are as follows:

$$(10) \quad \mathbf{U} = \begin{pmatrix} \rho \\ \rho\mathbf{v} \\ \rho e \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} (\mathbf{v} - \dot{\mathbf{x}}) \cdot \mathbf{n} \rho \\ (\mathbf{v} - \dot{\mathbf{x}}) \cdot \mathbf{n} \rho\mathbf{v} + p\mathbf{n} \\ (\mathbf{v} - \dot{\mathbf{x}}) \cdot \mathbf{n} \rho e + p\mathbf{v} \cdot \mathbf{n} \end{pmatrix}$$

$\mathbf{v}$ is a velocity vector for x, y, z directions, $\dot{\mathbf{x}}$ is a velocity vector of moving cell boundary, ρ is air density, p is pressure, and e is total energy.

Finite volume method and moving overlapped grid method are used in this numerical solution. mSLAU (modified Simple Low-dissipation AUSM) [4] which is modified for applying all-speed SLAU scheme to moving overlapped grid method is used for numerical velocity, and fourth spatial precision FCMT (Fourth-order Compact MUSCL TVD) scheme [15] is used for reconstruction of physical values. For time integration, fourth-order Runge-Kutta method is used in background orthogonal grid, and dual-time stepping method [16] is used in blade and fuselage grids to construct unsteady implicit method. LU-SGS/DP-LUR is used for simulated time integration. Tri-Linear interpolation method is used for exchange of values among grids.

2.2.2. Modelling of Blade Motion

It is necessary to model blade motion precisely for accurate prediction of BVI noise since fluctuations of blade position affect vortex generation point and configuration of generated vortex and blade. Pitch

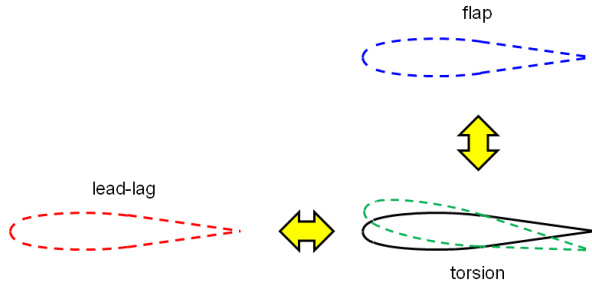


Fig. 5 Three components of blade elastic deformation

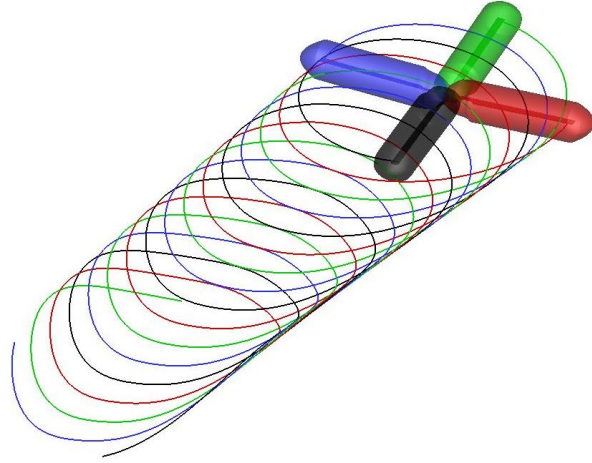


Fig. 6 Configuration of CFD computational grids and prescribed wake model

angle control and elastic deformation moves blade to vertical and horizontal directions unsteadily. Blade elastic deformation has three components, vertical deformation to blade plane (flap), horizontal movement (lead-lag), and torsion as shown in Fig. 5. Each component of blade elastic deformation is modelled in this study.

2.3. Hybrid Method of CFD and Prescribed Wake Model

This hybrid method reduces computational cost by computing only around a blade in CFD, and wake region is computed by prescribed wake model, assuming wake region is potential. Density, momentum, and energy in CFD are computed by reflecting induced velocity of blade tip vortex which is calculated by prescribed wake model. In particular, induced velocity of prescribed wake model is added to three outer layer grids in CFD to satisfy mass conservation law since the effect of compression is little in the area far from the blade [17]. Configuration of CFD computational grids and prescribed wake model is shown in Fig. 6.

At the interface of CFD and prescribed wake model, variables of flow field are calculated by following equations [17]:

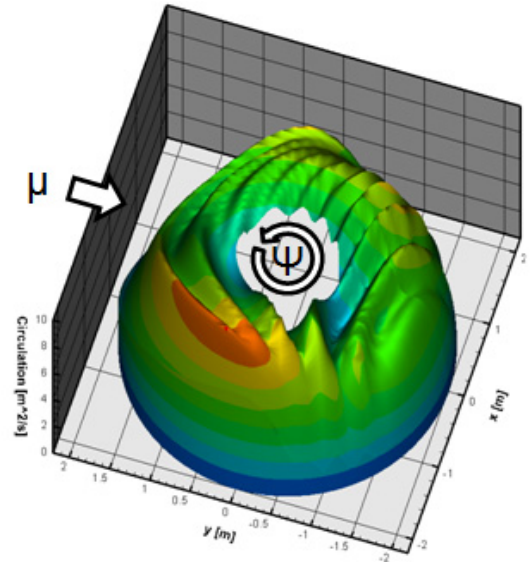


Fig. 7 Circulation distribution on blade

$$(11) \quad \begin{aligned} \begin{pmatrix} u \\ v \\ w \end{pmatrix} &= \begin{pmatrix} u_\infty + u_w \\ v_\infty + v_w \\ w_\infty + w_w \end{pmatrix} \\ \rho &= \left(\frac{a^2}{a_\infty^2} \right)^{\frac{1}{\gamma-1}} \\ e &= \rho \left[\frac{a^2}{\gamma(\gamma-1)} + \frac{u^2 + v^2 + w^2}{2} \right] \end{aligned}$$

where u, v, w is flow velocity of x, y, z directions, a is sound speed, γ is specific heat ratio, ∞ means component of uniform flow, and w means component of wake. Local sound speed is determined from the following energy equation:

$$(12) \quad a^2 = a_\infty^2 + \frac{\gamma-1}{2} [V_\infty^2 - (u^2 + v^2 + w^2)]$$

V_∞ is velocity of main stream.

Although circulation of prescribed wake model has been set constant in the previous studies, circulation fluctuates greatly according to azimuth angle (Fig. 7). In this study, circulation of prescribed wake model is varied by using circulation distribution in CFD.

2.4. Acoustic Analysis

Acoustic analysis is conducted using Farassat's Formulation 1 [18] which is a solution of sound wave equation based on Lighthill's acoustic analogy. This equation gives sound pressure fluctuation p' at any observation point as follows:

$$(13) \quad p'(x, t) = \frac{1}{4\pi} \left[\frac{\partial}{\partial t} \int \left\{ \frac{\rho v_n}{r(1-M_r)} \right\}_{ret} dS + \frac{1}{a_\infty} \frac{\partial}{\partial t} \int \left\{ \frac{p_b \cos \theta}{r(1-M_r)} \right\}_{ret} dS + \int \left\{ \frac{p_b \cos \theta}{r^2(1-M_r)} \right\}_{ret} dS \right]$$

here integration is conducted by retarded time τ and on the blade surface. Sound propagates to observation point by sound speed a_∞ at observation time t . v_n is vertical velocity on the surface cell,

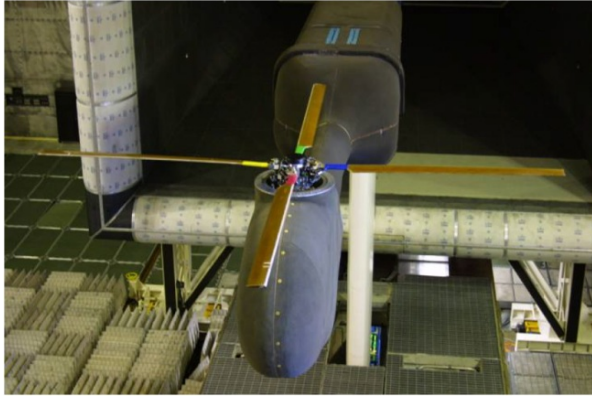


Fig. 8 HART II experiment setup [9]

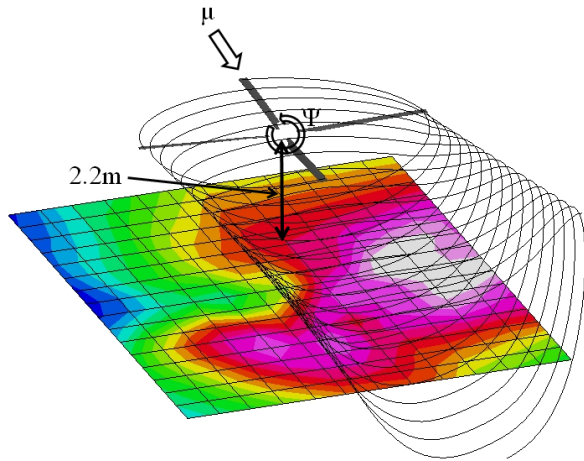


Fig. 9 Configuration of rotor and noise measurement plane

r is distance between observation point and sound source cell, and M_r is sound source cell Mach number of radiation direction at sound source time. p_b is air pressure on the blade surface, and $\cos\theta$ is cosine of crossing angle between the vertical direction of sound source cell and the direction from sound source to observation point.

The first term of right-hand side in eq. (13) is called “thickness noise” which is generated by the air pushed away by the blade motion, and the second and the third terms are called “load noise” which is generated by pressure fluctuations on the blade surface. Thickness noise belongs to monopole sound and load noise belongs to dipole sound. There are higher components than quadrupole in sound source. However, computation is conducted by using eq. (13) which excludes higher sound source than dipole since sound source lower than quadrupole is dominant in BVI noise.

3. NUMERICAL CONDITIONS

As mentioned above, the precision of the hybrid method is verified by comparing the computational

Tab. 1 Blade specifications

Number of blades	4
Rotor radius	2.0 m
Airfoil	NACA23012
Chord length	0.121 m
Twist	8.0 deg
Root cut	0.44 m

Tab.2 Baseline condition

M_∞	0.09628
M_{tip}	0.6387
μ	0.1508
C_T	4.63E-03
C_{MX}	2.81E-05
C_{MY}	-2.81E-05
θ_0	3.800 deg
θ_{1c}	1.916 deg
θ_{1s}	-1.342 deg

results with the experimental data of HART II. HART II showed that higher harmonic control of rotor can reduce noise or vibration. The rotor configuration in the experiment is shown in Figs. 8 [9], 9. The noise measurement plane was located 2.2 m below the rotor (Fig. 9). Other experimental conditions used in this numerical analysis are explained below.

The blade specifications are shown in Tab. 1. Baseline condition (Tab. 2) is employed in this study, while there are baseline, minimum noise, and minimum vibration conditions in the experiment. M_∞ is Mach number of the uniform flow, M_{tip} is Mach number of the blade tip, μ is advancing ratio, C_T is rotor thrust coefficient, C_{MX} is rotor hub rolling moment coefficient, C_{MY} is rotor hub pitching moment coefficient, and θ is pitch angle of the blade which is expressed as the following first harmonic oscillation :

$$(14) \quad \theta(\Psi) = \theta_0 + \theta_{1c}\cos\Psi + \theta_{1s}\sin\Psi$$

where Ψ is azimuth angle, θ_0 is collective pitch angle, θ_{1c} is lateral cyclic pitch angle, and θ_{1s} is longitudinal cyclic pitch angle.

Blade elastic deformation is given as a function of blade spanwise distance and azimuth angle, which is an average of four measured blades' deformation (Fig. 10).

4. NUMERICAL RESULTS AND DISCUSSIONS

Pressure fluctuations on the blade surface computed

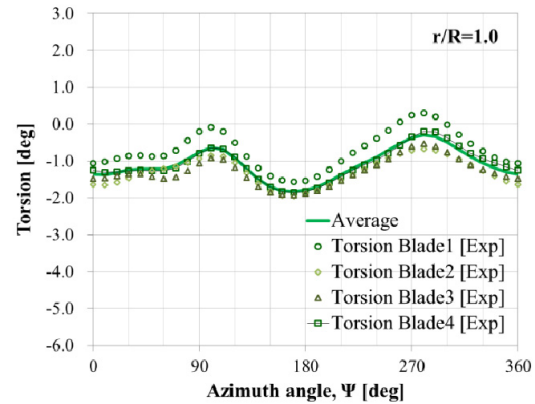
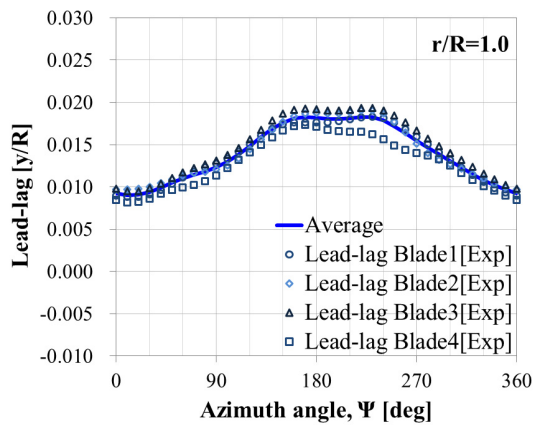
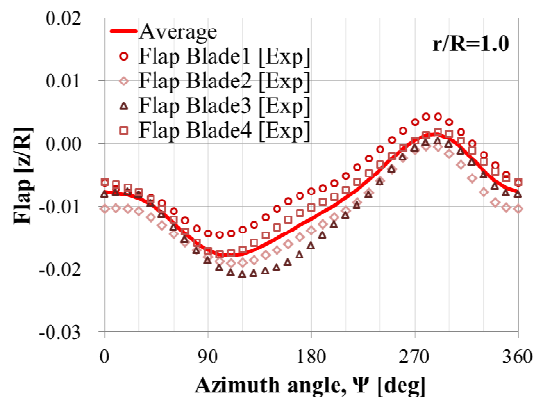
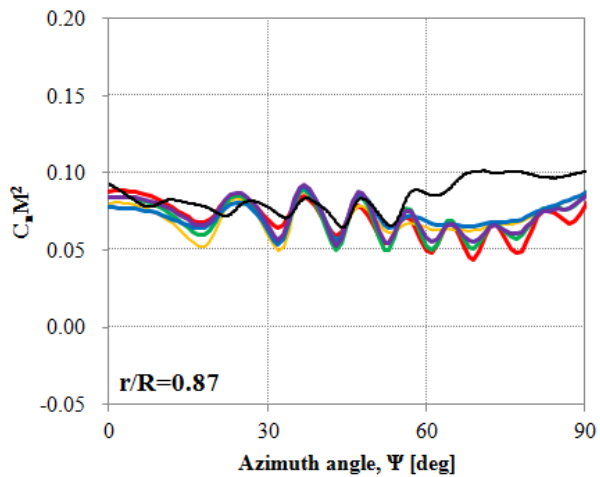
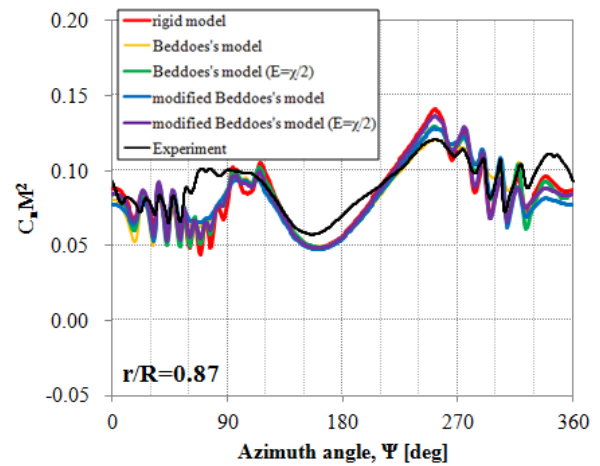
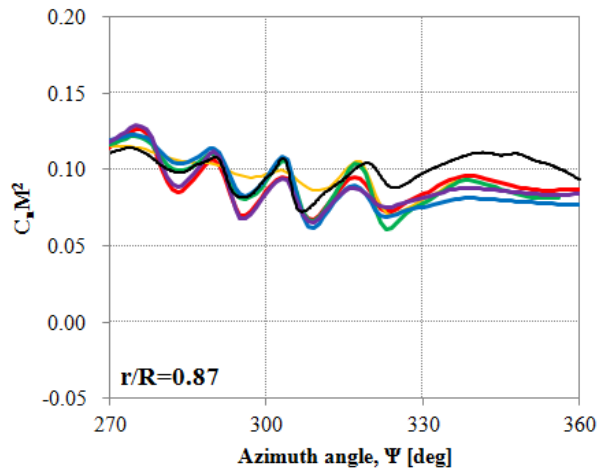


Fig. 10 Blade deformation in HART II experiment

by the hybrid method are verified since BVI noise is generated by the pressure fluctuations on the blade surface when the blade interferes with the blade tip vortex. Fig. 11 shows time variation of airload coefficient ($C_n M^2$) at 87% span based on pressure distribution on the blade surface, and Fig. 12 shows time derivative of that. From Figs. 11, 12, it is found that the hybrid method predicts blade vortex interference position precisely, though it still overestimates pressure fluctuations a little on the advancing side. It is also observed from Figs. 11, 12 that modified Beddoes's model is best estimate for



(a) Advancing side

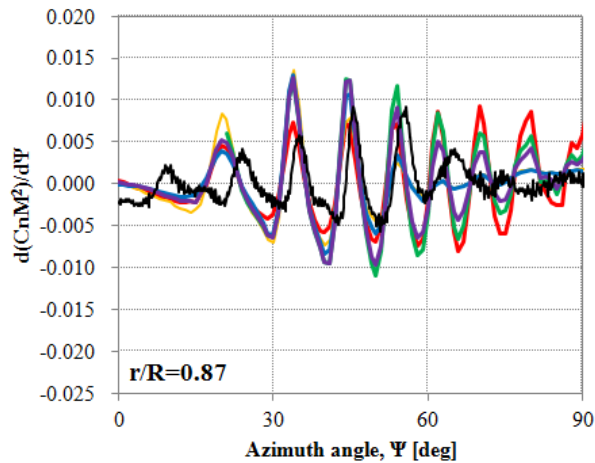
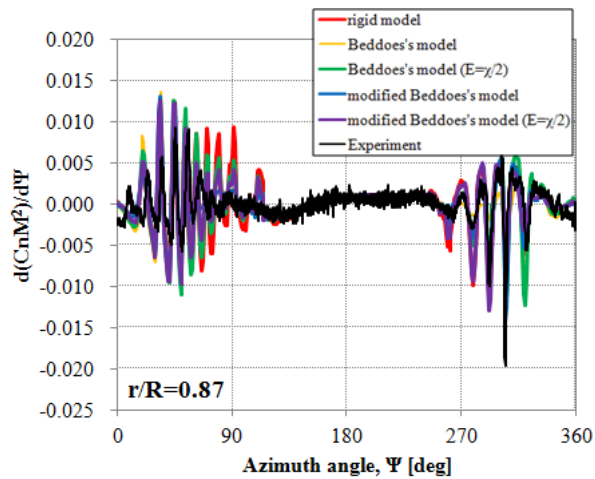


(b) Retreating side

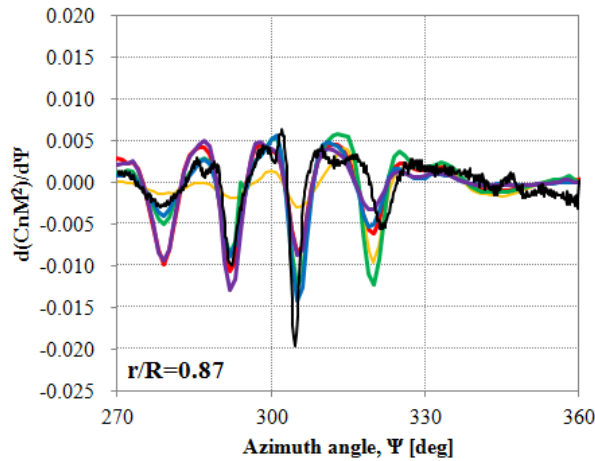
Fig. 11 Airload coefficient on blade

airload prediction, though the differences between prescribed wake models are small.

BVI noise distribution computed by pressure fluctuations around the rotor is also shown in Fig. 13. HART II experimental result and computational result by only using rFlow3D are also shown to compare. It



(a) Advancing side



(b) Retreating side

Fig. 12 Time derivative of airload coefficient on blade

is found that the hybrid method predicts noise peak position precisely though it overestimates sonic pressure level globally. Modified Beddoes's model (f) is found to be closest to experimental data in terms of noise peak position and noise distribution pattern too.

Fig. 14 shows comparison of maximum BVI noise. Maximum BVI noise of the hybrid method is about 2 dB larger than that of experiment. On the contrary to that, that of CFD is about 3 dB smaller. The reasons are considered that prescribed wake model locates vortex near the blade (Fig. 15) and vortex interferes with the blade without decay. On the other hand, vortex decays numerically in CFD since grid size is not small enough to resolve a vortex.

5. CONCLUDING REMARKS

In this study, a hybrid method of CFD and prescribed wake model is constructed and its computational accuracy is evaluated by using HART II experimental data. From Figs. 11-13, it is observed that the hybrid method shows good agreement with experiment, though there are some regions overestimating BVI noise and differences of noise peak positions. The reason that the hybrid method overestimates BVI noise is considered that vortex is located near the blade by prescribed wake model (Fig. 15) and interferes with the blade without decay. On the other hand, computational time of the hybrid method reduces to several days which are one-tenth of that of CFD (one month). Parallel computing number of the hybrid method increases since memory usage decreases. Thus, it can be said that the hybrid method is computationally effective in terms of computational time and memory usage. However, there is still room to improve computational accuracy of the hybrid method. We'd like to increase computational accuracy by reflecting generated vortex position from CFD to prescribed wake model, and by constructing vortex decay model in the near future.

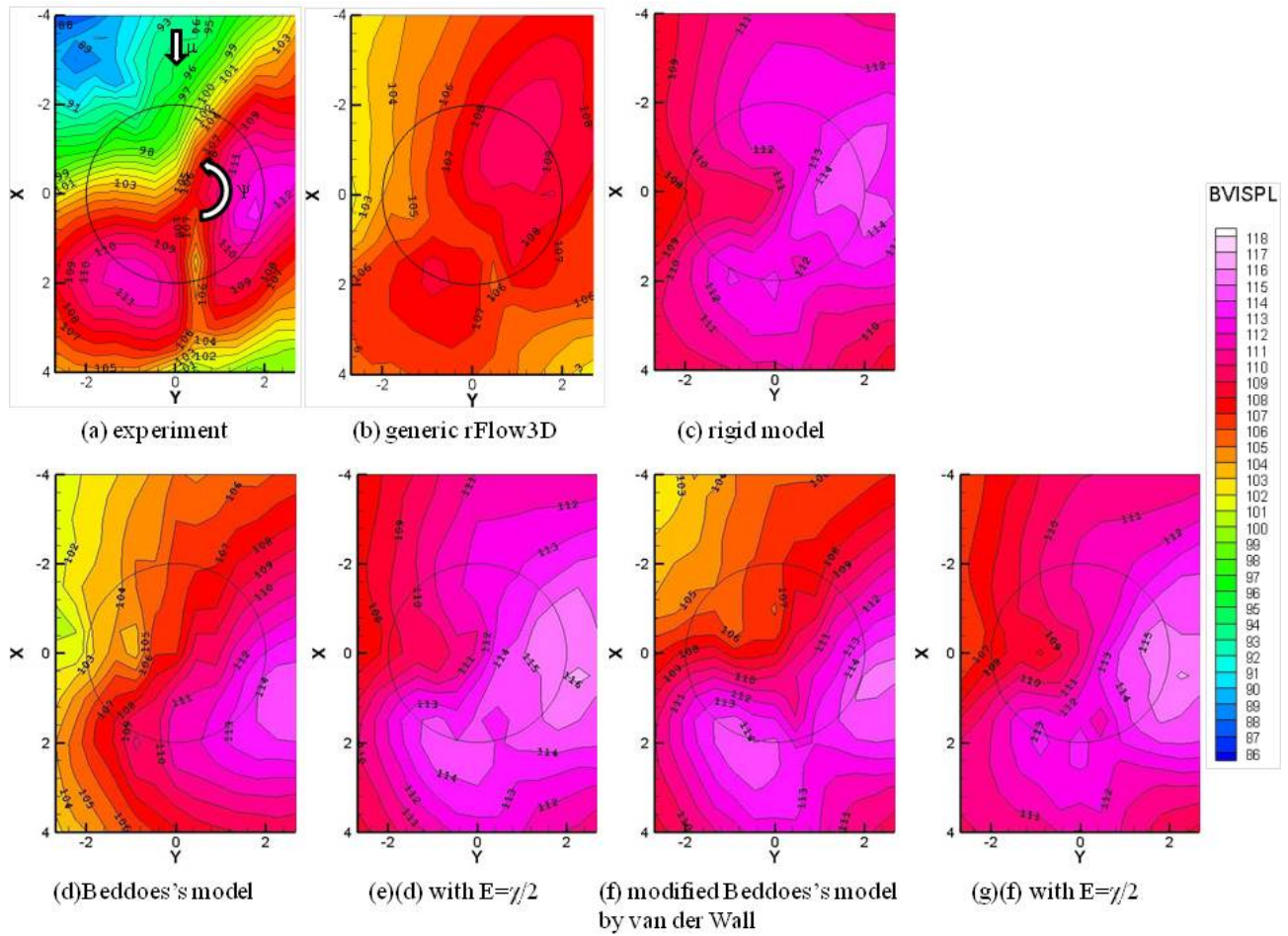


Fig. 13 Comparison of BVI noise distributions

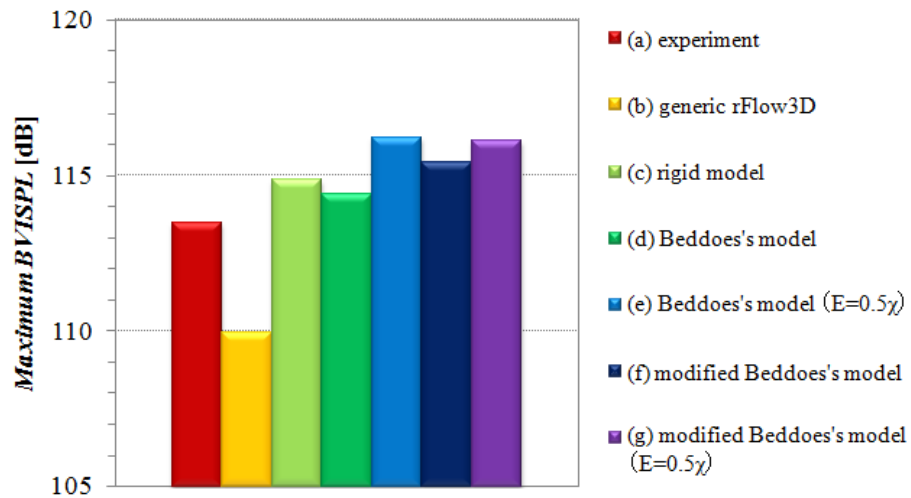


Fig. 14 Comparison of maximum BVI noise

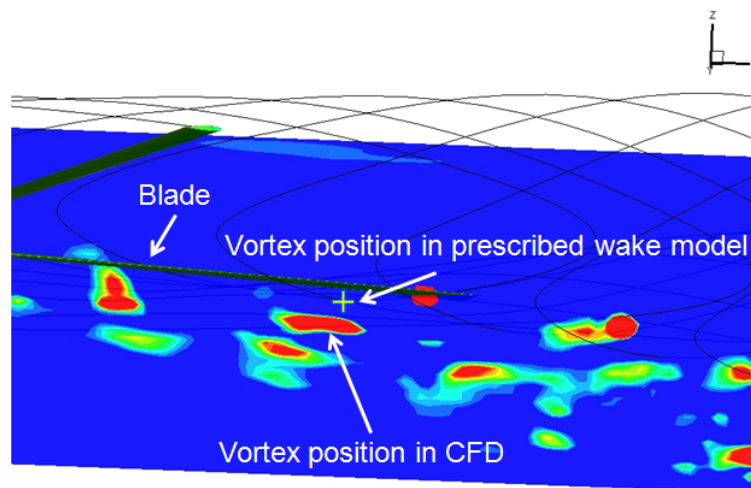


Fig. 15 Comparison of vortex positions ($\Psi=30\text{deg}$)

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