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Performance Prediction of a 5MW Wind Turbine Blade Considering Aeroelastic Effect

Dong-Hyun Kim and Yoo-Han Kim

***Abstract*—**In this study, aeroelastic response and performance analyses have been conducted for a 5MW-Class composite wind turbine blade model. Advanced coupled numerical method based on computational fluid dynamics (CFD) and computational flexible multi-body dynamics (CFMBD) has been developed in order to investigate aeroelastic responses and performance characteristics of the rotating composite blade. Reynolds-Averaged Navier-Stokes (RANS) equations with *k-ω SST* turbulence model were solved for unsteady flow problems on the rotating turbine blade model. Also, structural analyses considering rotating effect have been conducted using the general nonlinear finite element method. A fully implicit time marching scheme based on the Newmark direct integration method is applied to solve the coupled aeroelastic governing equations of the 3D turbine blade for fluid-structure interaction (FSI) problems. Detailed dynamic responses and instantaneous velocity contour on the blade surfaces which considering flow-separation effects were presented to show the multi-physical phenomenon of the huge rotating wind- turbine blade model.

***Keywords*—**Computational Fluid Dynamics (CFD), Computational Multi-Body Dynamics (CMBD), Reynolds-average Navier-Stokes (RANS), Fluid Structure Interaction (FSI), Finite Element Method (FEM)

I. Introduction

THE current technical trend in the development of wind turbine system shows a vast increase in turbine dimensions. Generated power captured by wind turbines is directly proportional to the square of the rotor diameter and the cost-effective efficiency of the designed wind-turbine can be more and more increased as its size increases. In addition, the trend for current wind turbine development is to go offshore, where wind turbines have a higher energy potential because of the higher wind speed levels of the ocean. Due to the combination of high wind speeds and its large size problems, tremendous wind loads are imposed on the rotating turbine blade structures. Therefore, the development of accurate aeroelastic performance analysis system for large wind turbine blade is very important in the design process so that design engineers can estimate accurate performance and investigate the operational instability problems of the blade model. Also, there are some previous researches about flutter analyses of wind turbine blade models [1]-[5].

Generally, wind turbine systems consist of rotor blade, hub, generator, and gear box etc., and the wind turbine system are defined as HAWT (Horizontal Axis Wind Turbine) and VAWT (Vertical Axis Wind Turbine). Recently, MW-class huge wind-turbines are conventionally designed as HAWT type with three-blades constructed by advanced composite materials.

In the case of aeroelastic problems, the structural deformation and the oscillatory motion of the blade necessitates the use of unsteady aerodynamic loads. In this study, to obtain numerical results for blade aerodynamic loads with sufficient quality, Reynolds-averaged Navier-Stokes (RANS) equations are applied with an appropriate fine grid mesh in the computational domain. Multi-body dynamic analyses of rotating wind-turbine blade have been conducted using the general nonlinear finite element method. Advanced coupled aeroelastic analysis system based on computational fluid dynamics (CFD) and computational multi-body dynamics (CMBD) has been developed in order to investigate detailed aeroelastic responses and flutter stability of general wind-turbine blade configurations. Especially, effects of rotation and flow separation with respect to the rotating and vibrating blade are considered in numerical analyses. Fluid domains are modeled using the unstructured grid system with dynamic moving and local deforming techniques. Unsteady, Reynolds-averaged Navier-Stokes equations with k-ω SST turbulence model are solved for unsteady flow problems with blade rotation and deformation effects. A fully implicit time marching scheme based on the Newmark time-integration method is typically used for computing the coupled aeroelastic governing equations of the rotating blade fluid-structure interaction problems. Fluid-structure coupling algorithms and main integration code including required various sub-modules have been successfully developed in this study. Practical fluid-structure interaction (FSI) program (FSIPRO3D) originally developed by the first author is modified and applied to general fluid-structure interaction problems of the wind-turbine blades. The present FSI analysis system was successfully verified for the wind-tunnel experimental data of the AGARD 445.6 wing model [6]. In order to conduct accurate aeroelastic response analysis, 2-way coupling engineering feedback mechanism (Fig. 1) is fully considered herein. The practical results for aeroelastic performance analyses of the 5 MW-class wind turbine blade are presented in this paper. The results for aerodynamic, vibration and aeroelastic analyses are also presented in detail. Before conducting the aeroelastic analyses of a MW-class wind turbine, NREL Phase VI wind turbine blade is considered to verify the CFD-based aerodynamic analyses considering rotating effects [7].

D. H. Kim is with Gyeongsang National University (GNU), Jinju City, Gyungnam, Republic of Korea (phone: 82+55-755-2083; fax: 82+55-755-2083; e-mail: dhk@gnu.ac.kr).
Y. H. Kim is with Gyeongsang National University (GNU), Jinju City, Gyungnam, Republic of Korea (e-mail: kyh@gnu.ac.kr).

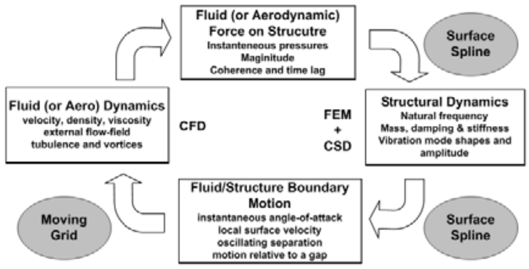


Fig. 1 Aeroelastic engineering feedback mechanism between fluid and structure domains

II. Computational Backgrounds

A. Unsteady Aerodynamic Model

Unsteady compressible RANS equations can be given as tensor form by

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial t}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i \tilde{u}) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}[\tau_{ij} + R_{ij}] \tag{2}$$

where the viscous stress tensor and deformation tensor are defined as

$$\tau_{ij} = 2\mu[S_{ij} - \frac{1}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}]$$

$$S_{ij} = \frac{1}{2}[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}]$$

Also,

$$\tilde{u} = u_j - u_{g,j}$$

where $u_{g,j}$ is the grid velocity. And turbulence Reynolds stress tensor R_{ij} must be modeled in order to close (2). This tensor may be approximated by Following Boussinesq hypothesis:

$$R_{ij} \cong \mu_T[S_{ij} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}] - \frac{2}{3}(\rho k)\delta_{ij} \tag{3}$$

In this study, the equations (1)~(3) are solved by using the finite-volume method. Also, aeroelastic coupling program written by C language is originally developed based on the user defined function concept and the structural equations are effectively solved in the modal domain. In this study, the implicit coupled solver and the two-equation *k-ω SST* turbulence model are used. For the discretization of RANS equations, second-order upwind scheme is applied.

B. Aeroelastic Governing Equations

The governing aeroelastic equations of motion of a flexible blade can be obtained by using the Rayleigh-Ritz method. In this method, the resulting aeroelastic displacement at any time can be expressed as a function of a finite set of selected modes. The general motion of the blade can be described by the separation of time and space variables as follows:

$$\begin{aligned} \{u(t)\} &= [\Psi_x(x, y, z, \omega)]\{q(t)\} \\ \{v(t)\} &= [\Psi_y(x, y, z, \omega)]\{q(t)\} \\ \{w(t)\} &= [\Psi_z(x, y, z, \omega)]\{q(t)\} \end{aligned} \tag{4}$$

where {u}, {v} and {w} are the structural deflections and $[\psi_x]$, $[\psi_y]$ and $[\psi_z]$ are the matrices of x-, y-, z-direction displacements of the natural vibration modes and those are the function of rotation speed. The aeroelastic equations of motion for an elastic wing are formulated in terms of generalized displacement response vector {q(t)} which is a solution of the following equation:

$$[M_g(\omega)]\{\ddot{q}(t)\} + [C_g(\omega)]\{\dot{q}(t)\} + [K_g(\omega)]\{q(t)\} = \{F_g(t, q, \dot{q}, \omega)\} \tag{5}$$

where t is the physical time, $[M_g]$ is the generalized mass matrix, $[C_g]$ is the generalized damping matrix, $[K_g]$ is the generalized stiffness matrix, and $\{F_g\}$ is the vector of generalized aerodynamic forces computed by integrating the pressure distributions on the wing surface as

$$F_{g_i} = \frac{1}{2}\rho U^2 c_r^{\,2} \iint_S -Cp(x, y, z, \omega, t)(n_x\psi_{xi} + n_y\psi_{yi} + n_z\psi_{zi})\frac{dS}{c_r^{\,2}} \tag{6}$$

where ρ is the free stream air density, U is the free stream velocity, c_r is the reference chord length, S is the wing area, C_p is the instantaneous unsteady pressure coefficient on the arbitrary blade surface, n_x, n_y and n_z mean the surface normal vectors for x, y and z direction, respectively and ψ_i are the i-th natural mode shape vectors interpolated on the aerodynamic surface mesh. The generalized aerodynamic forces of (6) are integrated numerically on the blade surfaces.

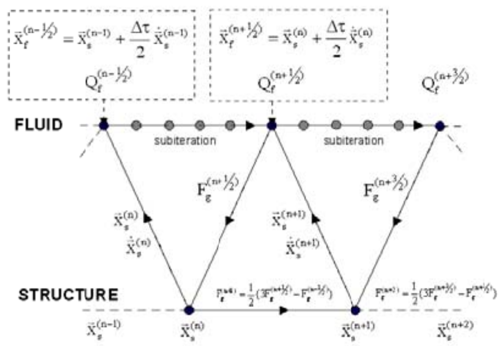


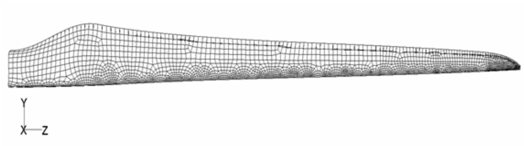
Fig. 2 Fluid-Structure coupled computational process using the second-order time-accurate staggered method

In this study, the coupled time-marching method is used to effectively investigate characteristics of nonlinear aeroelastic responses of rotating blade systems in detail. The time marching process of the structure-fluid coupling is performed by similarly adopting the second-order staggered algorithm. The computational process for the present coupling process applied in this study is shown in Fig. 2. More detailed theoretical description and applications for the present computational method can be found in Refs.6-8.

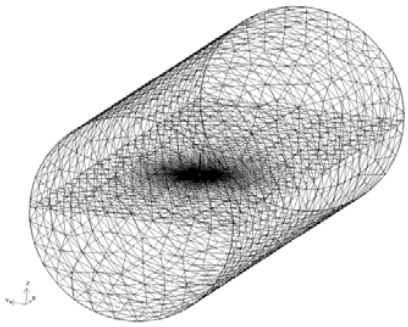
$$\{q(t)\}^T = [q(t)_1, q(t)_2, q(t)_3 \cdots, q(t)_m]$$
$$[M_g(\omega)] = [\phi(\omega)]^T [M][\phi(\omega)]$$
$$[C_g(\omega)] = [\phi(\omega)]^T [C][\phi(\omega)]$$
$$[K_g(\omega)] = [\phi(\omega)]^T [K(\omega)][\phi(\omega)]$$
$$\{Q(t, q, \dot{q}, \omega)\} = [\phi(\omega)]^T \{F(t, u, \dot{u}, \omega)\}$$

III. Result and Discussion

In this study, the performance analyses of a 5MW class wind-turbine composite blade model have been performed using an advanced computational approach with FSIPRO3D. The total diameter of rotor is about 128 m and the length of blade is 62 m. The blade is composed of upper skin, lower skin, spar cab, shears web and bonding parts.



(a) Computational surface grid



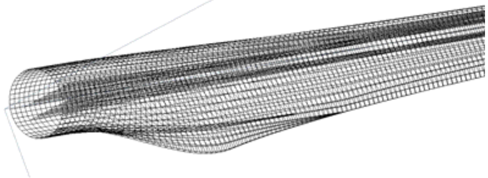
(b) Computational domain grid

Fig. 3 CFD grid of the present 5MW turbine blade

The generated fluid domain grid of the MW-class blade is presented in Fig. 3. The fluid conditions at sea level altitude with 13 m/s and 16 m/s are considered. The rotating speed of blade is 12 rpm. Multiple Rotating Frames (MRF) method is effectively applied to consider rotating motion of the blade and the RANS model with two-equation k-ω SST turbulence model is applied to solve the fluid domain.

For aeroelastic simulations, structural finite element model for a 5MW-class wind turbine rotor was constructed based on quadrilateral composite plate elements. The wind-turbine structural model is majorly composed of laminated spar and sandwich skin panels as presented in Fig. 4. Material properties of laminated composite blade are presented in Table I. The rotating speed was applied to the structure and the root section is clamped to impose structural boundary condition.

(a) Whole blade



(b) Closed view

Fig. 4 Finite element structure of blade

TABLE I.
MATERIAL PROPERTIES FOR COMPOSITE BLADE.

UD				
E11(GPa)	E22(GPa)	G12(GPa)	ν12	ρ(kg/m^3)
43.1	13.2	3.62	0.241	1,939
S1T(MPa)	S2T(MPa)	S1C(MPa)	S2C(MPa)	SS(MPa)
916	41	759	124	38

Balsa Wood		
E(GPa)	ν	ρ(kg/m^3)
3.72	0.1	151

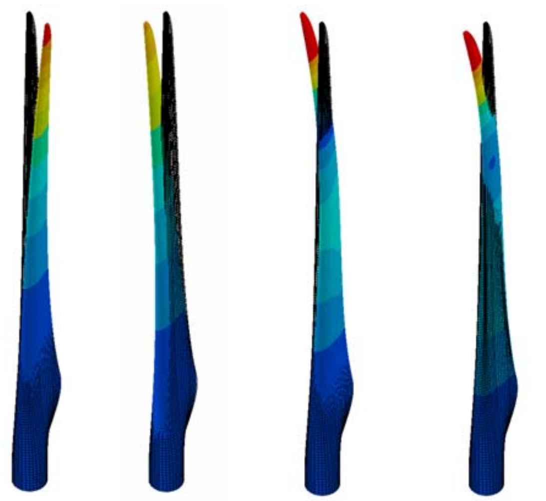


Fig. 5 Natural vibration mode shapes and frequencies

Calculated natural frequencies are presented in Table II and natural vibration mode shapes are presented in Fig. 5. The results typically show that the 1st eigenmode is the fundamental flapwise bending mode. The 2nd eigenmode is 1st edgewise bending mode. The 3rd mode looks like the 2nd flapwise bending mode. The 4th mode corresponds to 2nd edgewise bending mode.

TABLE II
NATURAL FREQUENCIES OF 5MW-CLASS WIND-TURBINE BLADE.

RPM	1st mode	2nd mode	3rd mode	4th mode
8	0.74	1.14	2.22	3.85
13	0.76	1.15	2.25	3.87

Fig. 6 shows the comparison results of the shaft power between the rigid and the flexible blade models for the wind speed of 13 m/s and 16 m/s. It is importantly shown that estimated power of the blades can be significantly different due to the effect of aeroelastic deformation. This means that the designed data for blade control logic also need to be modified considering aeroelastic deformation effects for huge wind-turbine blade models. It can be expected that the much larger blade can show the much different effect.

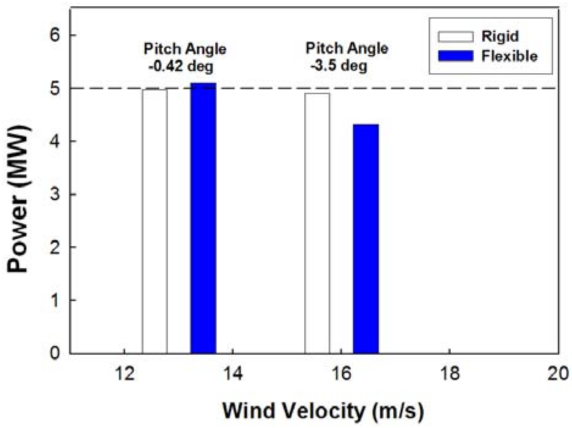
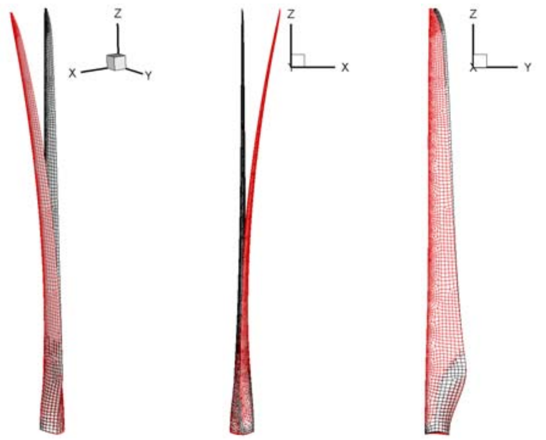


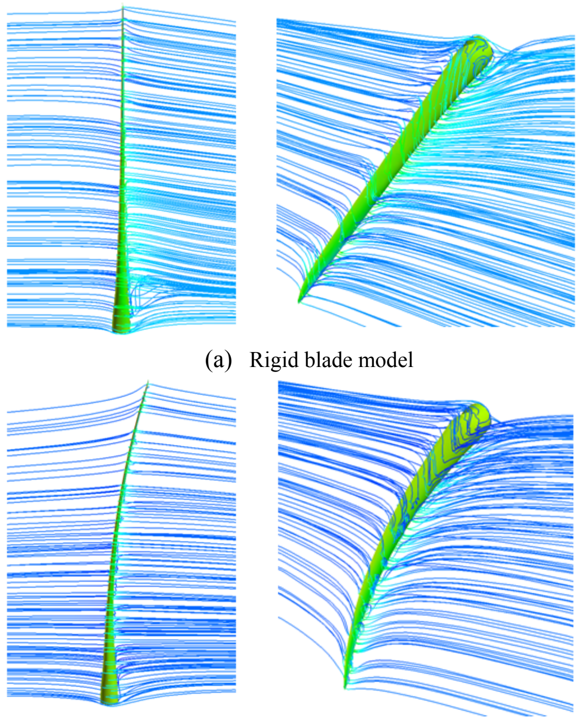
Fig. 6 Comparison of aerodynamic power between the rigid and the aeroelastic blade models



Isoperimetric view X-Z plane view Y-Z plane view

Fig. 7 Instantaneous aeroelastic deformation shapes

Fig. 7 shows the instantaneous aeroelastic deformed shape of rotating wind-turbine blade. It is shown that the total aeroelastic deformation is composed of the flapwise and edgewise bending deflections. Normally the bending deflection of the wind-turbine blade shows dominant due to large thrust forces during regulated operations. Fig. 8 shows the comparison of instantaneous pressure contours with stream lines between rigid and elastic model. As can be expected, the instantaneous flow patterns show different characteristic due to aeroelastic deformation. This is the reason why the generated power for the rigid and the flexible blade model can be different for the same flow condition.



(a) Rigid blade model

(b) Aeroelastic blade model

Fig. 8 Comparison of instantaneous pressure contours with stream lines of the 5 MW class wind-turbine blade.

IV. CONCLUDING REMARKS

In this study, generated power predictions for aeroelastic blade have been successfully conducted considering flow separation effect. Advanced computational analysis system based on coupled computational fluid dynamics (CFD) and computational flexible multi-body dynamics (CFMBD) technique has been developed and applied to numerical simulations. Detailed aeroelastic responses are computed in the time-domain in order to investigate the aeroelastic characteristics of the 3D wind-turbine blade model. It is importantly shown that the estimated power of the blades can be significantly different due to the effect of aeroelastic deformation. Also, developed general CFD-CFMBD coupled fluid-structure interaction analysis program (FSIPRO3D) show the strong application potential for accurate aeroelastic analysis of the huge wind-turbine blade system.

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REFERENCES

[1] S. Streiner, E. Kramer, A. Eulitz, and P. Armbruster, “Aeroelastic Analysis of Wind Turbines Applying 3D CFD Computational Results”, Journal of Physics, 2007,Conference series 75.
[2] A. Ahlstrom, “Aeroelastic Simulation of Wind Turbine Dynamics”, Doctoral Thesis from Royal Institute of Technology Department of Mechanics, Sweden, 2005.
[3] A. Ahlstrom, “Aeroelastic FE Modeling of Wind Turbine Dynamics”, Doctoral Thesis from Royal Institute of Technology Department of Mechanics, Sweden, 2005.
[4] J. M. Jonkman, and P. D. Sclavounos, “Development of Fully Coupled Aeroelastic and Hydrodynamic Models for Offshore Wind Turbines”, ASME Wind Energy Symposium, 2006.
[5] I. Dobrev, and F. Massouh, “Fluid-structure interaction in the case of a wind turbine rotor”, 18th Congrès Français de Mécanique, 2007.
[6] Y. H. Kim, D. H. Kim, Y. S. Kim, and S. H. Kim, “Comparison Study of Viscous Flutter Boundary for the AGARD 445.6 Wind Using Different Turbulent Boundary Layer Models”, The Korean Society of Mechanical Engineers 2009.
[7] D. H. Kim, Y. S. Kim, D. H. Kim, Y. H. Kim, and S. H. Kim, “Coupled Aeroelastic Analysis of a 3D Wind Turbine Blade Considering Rotating Flow Separation Effects:, 9th World Wind Energy Conference, 2009.