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The influence of wind shear on vibration of geometrically nonlinear wind turbine blade under fluid–structure interaction

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ABSTRACT

For the large-scale offshore wind turbine blades, the governing equations in fluid domain and the motion equations in structural domain with geometric nonlinearity were developed based on ALE description, and the corresponding discrete equations were obtained. Blade entity model was built up using Pro/E, and the blade vibration characteristics under fluid–structure interaction (FSI) were simulated using ANSYS. Numerical results show that wind shear effect greatly increases the peak values of response curves for displacement and stress, makes the effect of bi-directional fluid–structure interaction (BFSI) more obvious, and also accelerates the attenuation of vibration curves. The displacement of blade airfoil increases nonlinearly along the span direction, and reaches the maximum at the blade tip. The maximum Mises stress appears in the middle of the blade, and reduces gradually towards each end of the blade. Furthermore, the contribution of wind shear effect (WSE) to displacement and Mises stress is much greater than that of FSI.

1. Introduction

The slender flexible blade, regarded as the core part of the wind turbine, is subjected to complicated and changeable forces which lead to a variety of mechanical vibrations. The aerodynamic force and the elastic force as well as the wind shear effect will accelerate the blade damage due to induced vibrations in the actual running process of offshore wind turbines (Joselin Herbert et al., 2007; Gordon Leishman, 2002; Shen et al., 2011). Therefore, it has become a very important research topic to explore the influence of wind shear on the vibration characteristics of wind turbine blade under fluid–structure interaction (FSI).

In order to reveal the vibration mechanism and the response characteristics of the blade structure under the real wind loading, researchers have conducted work using different methods with the consideration of either FSI effect or wind shear effect (WSE). In the aspect of FSI, Sternel et al. (2008) employed an implicit partitioned arbitrary Lagrangian–Eulerian approach for FSI computations and investigated enhancements of the coupled solution procedure using a nonlinear multi-grid technique, an adaptive under-relaxation method, and a proper grid movement technique. Kamakoti and Shyy (2004) reviewed the recent advancements in the field of fluid–structure interaction, and the flutter predictions performed on an AGARD 445.6 wing at different Mach numbers were selected to highlight the state-of-the-art computational and modeling issues. Glück et al. (2003) applied a partitioned coupling approach for time-dependent fluid–structure interactions to thin shells and membranous structures with large displacements, and investigated the dynamic responses of flexible L-shaped plate and membranous roof of glass–fiber synthetics with a complex shape. For the WSE, Dai et al. (2011) proposed a set of methods to calculate aerodynamic loads of large scale wind turbines by combining blade element momentum modified theory with a dynamic stall model, and concluded that the aerodynamic loads were influenced to different degrees by many factors such as tower shadow, wind shear, dynamic stall, tower and blade vibrations. Nilay and Oguz (2013) investigated the influences of three different wind shears (uniform in-flow, stable vertical wind shear and transient extreme wind shear) on wake structure and performance characteristics of a horizontal axis wind turbine rotor. They identified that the existence of the wind shear in the free stream can create substantial asymmetries and non-periodicities in the structure of the wake behind the turbine rotor. Han et al. (2011) considered wind shear effect and carried out the numerical simulation analysis for 3D steady flow field around wind turbine blades at different wind speeds. They found that the wind speed nonuniformity caused by vertical height could not be ignored when the wheel diameter was large.

It should be mentioned that the research on the effects of wind shear and FSI on the dynamic characteristics of offshore wind turbine blades is still in an early stage. Some references only

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considered either wind shear effect or FSI effect separately, which does not accurately reflect the real working conditions of the blade. In view of this, the vibration characteristics analysis was carried out under unidirectional fluid–structure interaction (UFSI), bi-directional fluid–structure interaction (BFSI) and the combined effect of wind shear and BFSI for 1.5 MW offshore wind turbine blades. The influence of WSE on wind turbine blade vibration is revealed, providing theoretical basis and technical guidance for operation safety and reliability design of wind turbine blades.

2. Theoretical model

2.1. Physical model

In order to effectively avoid the deficiency of the wind tunnel test based on scaling experiments, and to really reflect the interaction between flow field around the wind turbine and the blade structure, the blade physical model with the same proportion as under FSI is established in this study. After considering the impact of the upstream wind turbine on the downstream one, the length of inflow area in fluid computational domain is determined to be equal to that of the blade, and the length of wake region is triple that of the blade, as shown in Fig. 1.

2.2. Governing equations of fluid domain and structural domain

The specific solution to the physical phenomena is based on basic equations of fluid mechanics in the process of numerical simulation by CFD. In order to solve the coordinate disunity problem of moving interfaces between fluid domain and structural domain under FSI, ϕ is denoted as the general variable which stands for the velocity components u^*, v^*, w^* in three-dimensional coordinates, so the governing equations of fluid domain described by the ALE method can be written as (Zhang et al., 2011)

$$\frac{\partial(\rho\phi)}{\partial t}+\mathrm{div}(\rho u_i^*\phi)=\mathrm{div}(\Gamma\,\mathrm{grad}\phi)+S \qquad (1)$$

where ρ, Γ, S are respectively the air density, the generalized diffusion coefficient and the generalized source term; for the continuity equation, $\phi=1$; for the momentum equation, $\phi=u_j^*$, u_i^* and u^*_j are speed components in each direction; for the two-equation $k-\varepsilon$ turbulence model, $\phi=\{k,\varepsilon\}$; the indicators i and j take the values of either 1, 2 or 3, and Γ, S are ascertained according to ϕ.

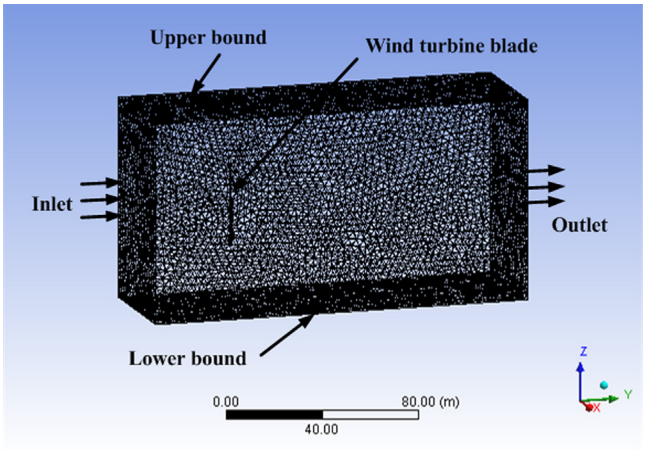

Fig. 1. Schematic diagram of fluid–structure interaction and fluid domain meshing.

Geometrically nonlinear equations of motion under FSI for the blade can be expressed as (Bai, 1996)

$$\sigma_{ij,j}+\boldsymbol{f}_i=\bar{\rho}\frac{\partial^2\boldsymbol{U}_i}{\partial t^2}\quad (i,j,k=1,2,3) \qquad (2)$$

where $\sigma_{i\,j}$, $\boldsymbol{U}_i$, $\bar{\rho}$ are respectively the stress tensor, the displacement vector and the material density of the blade; $\boldsymbol{f}_i$ is a vector related to the wind pressure distribution. The constitutive equation and the geometric equation for the geometrically nonlinear elastomer can be written as

$$\sigma_{ij}=2G\varepsilon_{ij}+\lambda\delta_{ij}\varepsilon_{kk} \qquad (3)$$

$$\varepsilon_{i,j}=\frac{1}{2}(\boldsymbol{U}_{i,j}+\boldsymbol{U}_{j,i}+\boldsymbol{U}_{k,i}\boldsymbol{U}_{k,j})\quad (i,j,k=1,2,3) \qquad (4)$$

where G and λ are respectively shear modulus and Lame coefficient; δ_{ij} is the unit tensor.

2.3. Discrete equations of fluid domain and structural domain

The finite volume is employed to discretize the governing equations of fluid. According to the computational grid, the integral operation is applied to the control volume P. The time interval Δt and Guass divergence theorem are introduced, and then the general form of the discrete equations is expressed as (Zhang et al., 2011)

$$a_p\phi_p=\sum a_{nb}\phi_{nb}+b \qquad (5)$$

where nb is an adjacent node, $nb=\{w,e,s,n,b,t\}$; a is a coefficient; b is from the source item.

In the cases of FSI and WSE, Eq. (5) is solved by iteration computation to obtain a velocity field which satisfies the continuity equation. Therefore, the wind pressure distribution on the blade surface can be figured out. In general, the discrete motion differential equation in structural domain can be described as

$$[M][\ddot{x}]_{t+\Delta t}+[C][\dot{x}]_{t+\Delta t}+[\bar{P}]_{t+\Delta t}=[P]_{t+\Delta t} \qquad (6)$$

where $[M]$ and $[C]$ are respectively the mass matrix and the damping matrix; $[\dot{x}]_{t+\Delta t}$ and $[\ddot{x}]_{t+\Delta t}$ are respectively the speed and the acceleration of the blade at time $t+\Delta t$, $[x]=[u,v,w]^r$; $[P]_{t+\Delta t}$ is the wind pressure distribution obtained from data transfer calculation based on a dynamic mesh technique at $t+\Delta t$; $[\bar{P}]_{t+\Delta t}$ is the nonlinear term, which can be defined as

$$[\bar{P}]_{t+\Delta t}=[\bar{P}]_t+[K_T]_t([x]_{t+\Delta t}-[x]_t) \qquad (7)$$

where $[K_T]_t$ is the tangential stiffness matrix computed using nodal displacement at t.

For the discrete motion differential Eq. (6), the displacement, the velocity and the acceleration of the blade at $t+\Delta t$ are calculated using the Newmark method (Zhang and Li, 2006) and iterative algorithm.

2.4. Structural damping calculation

In this study, we consider only the effect of structural damping on blade structure. The strength of structural damping is usually denoted by the energy dissipation rate of vibration. The Rayleigh damping model, which is widely used in practical engineering, is an orthogonal damping model, and the mathematical expression can be written as

$$[C]=\alpha[M]+\beta[K] \qquad (8)$$

where α and β are the factors proportional to mass and rigidity, respectively.