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Aeroelastic coupling analysis of the flexible blade of a wind turbine

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ABSTRACT

This paper presents an aeroelastic coupling analysis of the flexible blade of a large scale HAWT (horizontal axis wind turbine). To model the flexibility of the blade more accurately, 'SE' (super-element) is introduced to the blade dynamics model. The flexible blade is discretized into a MBS (multi-body system) using a limited number of SEs. The blade bending vibration and torsional deflection are both considered when calculating the aerodynamic loads; thus, the BEM (blade element momentum) theory used in this study is modified. In addition, the B–L (Beddoes–Leishman) dynamic stall model is integrated into the BEM-modified model to investigate the airfoil dynamic stall characteristics. The nonlinear governing equations of the constrained blade MBS are derived based on the theory of MBS dynamics coupling with the blade aerodynamics model. The time domain aeroelastic responses of the United States NREL (National Renewable Energy Laboratory) offshore 5-MW wind turbine blade are obtained. The simulation results indicate that blade vibration and deformation have significant effects on the aerodynamic loads, and the dynamic stall can cause more violent fluctuation for the blade aerodynamic loads compared with the steady aerodynamic model, which can considerably affect the blade fatigue load spectrum analysis and the fatigue life design.

1. Introduction

Under the excitations of mechanical loads, such as aerodynamic loads and gravity, random vibration of wind turbine blades would occur. With the increasing unit capacity of wind turbines, blades are becoming longer (e.g., the NREL (National Renewable Energy Laboratory) 5-MW wind turbine blade has very large aspect ratio) [1]. Furthermore, blades are usually made of composite materials with low Young's modulus and stiffness; therefore, blade magnitude of deformation is beyond the scope of assumption for small blade deflection [2]. In this case, the blade operates in unsteady conditions because of the blade vibration. The unsteady conditions can cause the following effects: the feedback of blade vibration and the relatively large deflection on the aerodynamic loads cannot be ignored, and the feedback needs to be quantifiably analyzed. The blades generally work in a high angle of attack or even in severe stall conditions when the vibration and deformation increase. The unsteady characteristics of the blade airfoil dynamic stall need to be simulated accurately, which is the basis of the blade dynamic aerodynamic load calculation [3]. Aeroelastic coupling analysis based on the unsteady aerodynamic model of a flexible blade is essential for the blade aerodynamics and structural design as well as the fatigue life design.

When operating in a random wind condition, the angle of attack of a blade airfoil is time varying. If the blade torsional deformation and vibration increase, a hysteresis phenomenon and dynamic stall will occur [4]. In this case the aerodynamic coefficients will considerably deviate from their static values. For example, the error between the predicted data and the measured data is approximately 15%–20% for a NREL Combined Experiment turbine [5], which means that the energy output reduces by up to 20%. The hysteresis of aerodynamic loads will in turn cause more violent vibration, resulting in the decline of blade fatigue life. Research conducted by Shipley [6] showed that a dynamic stall could cause more violent fluctuation for aerodynamic loads. Due to the complication of airflow flow, there have not been any completely accurate theoretical models to simulate the airfoil unsteady aerodynamic response. The semi-empirical models based on the experimental summary are often used [7–9], including the incompressible Theodorsen thin wing model [10], the Onera Edlin model and the B–L (Beddoes–Leishman) model, etc. [11,12]. Although the development of CFD (computational fluid dynamics) makes it possible to calculate the airfoil aerodynamic response under operating conditions, its practical application in the blade

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aeroelastic coupling analysis of wind turbines does not seem possible in the near future because of its extensive cost of calculation and complicated solving process [13]. At present, applying semi-empirical models to calculate the unsteady aerodynamic loads are still the dominant method, among which the B–L model receives much attention and recognition [14]. Liu et al. [3,4,7] and Dai et al. [13] adopted the B–L model to analyze the dynamic aerodynamic loads of blades and investigated the unsteady characteristics.

Wind turbine blades have complicated time-varying MBS (multi-body system) coupling nonlinear airflow flow and blade elastic deformation. In addition, the interactive effects between blade vibration and aerodynamic loads involve the simultaneous solution for the blade dynamics equations, which are a set of time-varying DAEs (differential and algebraic equations). Hence the blade mechanics model needs to be analyzed with fewer DOFs (degrees of freedom). To discretize the components, which undergo spatial motion and elastic deformation, Molenaar [15], Zhao [16] and Holierhoek [17] introduced a 'super-element;' thus, it is suitable for the mechanical modeling of MBS with flexible components [18]. Li et al. [19] discretized flexible components such as wind turbine blades and towers into a series of rigid bodies connected with joints, springs and dampers by applying the super-element mentioned above. They then established the aeroelastic coupling equations of the rigid-flexible MBS of wind turbines using the theory of MBS dynamics, the Roberson-Wittenburg modeling methodology, and the BEM (blade element momentum) theory. Eventually, the time domain aeroelastic coupling response was obtained for a wind turbine via numerical simulation.

Taking account the aeroelastic coupling, the present studies introduce the airfoil vibrational velocity and the torsional deflection of a flexible blade in the calculation of the inflow angle and the angle of attack. Thus, the BEM model is correspondingly modified. To investigate the unsteady aerodynamic characteristics, the BEM-modified model incorporates with the B–L dynamic stall model. Based on the blade MBS model and the aerodynamics model, an analysis on the time domain aeroelastic coupling responses of the blade is completed. The effects of blade torsional deflection and bending vibration on the aerodynamic loads are quantifiably analyzed. The comparison and analysis on the simulation results clearly indicate the significance and necessity of considering the blade flexibility and the unsteady aerodynamic characteristics in the blade aerodynamic load calculation during the blade design stage.

2. BEM modified model and B–L model

Wind speed changes with time and altitude during blade operation. The airstream flows along the spanwise and chordwise directions and flow separation and vortex shedding may occur. If the blade motion combines with the blade bending vibrations (i.e., in-plane vibration and out-of-plane vibration) and the torsional vibration, a blade unsteady aerodynamic effect will occur. The unsteady aerodynamic loads can be numerically calculated via the BEM modified model integrating the B–L dynamic stall model.

2.1. BEM modified theory (used in steady analysis)

Usually, blade profiles consist of a series of airfoils with different aerodynamic characteristics along the span. Conventionally, the BEM modified theory is applied to compute the steady aerodynamic loads. This theory combines the blade element theory and the momentum theory. It is widely used in aerodynamic analysis of wind turbines due to its relatively simple calculation process and reliable calculation result.

The blade is discretized into a series of rigid bodies along the span, and it is assumed that the profile of each rigid body consists of the same airfoil. According to the blade element theory, when the spanwise length of the blade element is small enough, the spanwise flow of the airstream can be neglected, and aerodynamic loads (lift and drag) are uniformly distributed along the span; they act on the quarter chord point or the AC (aerodynamic center). When the angle of attack is obtained, the airfoil steady lift $C_L(\alpha)$, drag $C_D(\alpha)$ and moment coefficients $C_M(\alpha)$ can be computed by interpolating the steady aerodynamic data. Then, the lift L_i, drag D_i and moment M_i loads per unit length on each blade rigid body can be calculated according to the blade element theory. Thus, the lift F_L, drag F_D and moment M_{aero} exerted on the AC of the rigid body B_i can be obtained as

$$F_L = L_i \times l_i, \quad F_D = D_i \times l_i, \quad M_{\text{aero}} = M_i \times l_i \tag{1}$$

where l_i is the spanwise length of rigid body B_i.

When the infinitesimal span dr, an infinitesimal span of the spanwise length of a rigid body, rotates in a circle about the rotor axis, the thrust dT and the torque dQ on this annular element are obtained by the equations below:

$$dT = 0.5B\rho cW^2(C_L(\alpha)\cos\phi + C_D(\alpha)\sin\phi)dr \tag{2}$$

$$dQ = 0.5B\rho cW^2(C_L(\alpha)\sin\phi - C_D(\alpha)\cos\phi)rdr \tag{3}$$

where B is the number of blades, c is the sectional chord length, ρ is the density, W is the sectional relative velocity of airflow, r is the radial distance from the rotational axis to the infinitesimal span dr, and ϕ is the inflow angle.

The momentum theory further introduces the 3-D airstream flow, the tangential induction factor a' and the axial induction factor a. Furthermore, the tip loss and hub loss models by Prandtl are introduced to correct the aerodynamic load calculation when considering the airstream vortex characteristics on the blade tip and hub. Thus, the thrust dT and the torque dQ on this annular element are given as:

$$dT = 4\pi r\rho U_\infty^2(1-a)aFdr \tag{4}$$

$$dQ = 4\pi r^3\rho U_\infty \Omega(1-a)a'Fdr \tag{5}$$

where F denotes the combined factor which includes the blade tip loss and hub loss, whose value can be found in Ref. [20]. The aerodynamic parameters involved in this BEM theory are shown in Fig. 1.

In this article, the effects of blade torsional deformation and bending vibration on the aerodynamic forces embody in the effects of out-of-plane and in-plane velocities on the inflow angle ϕ and the angle of attack α, yielding:

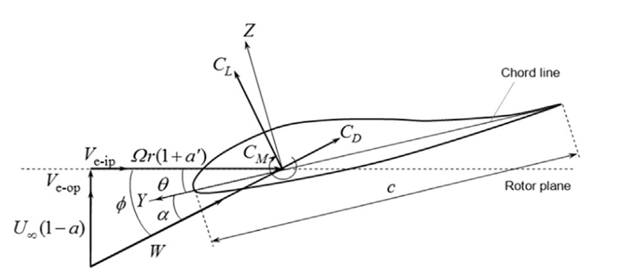

Fig. 1. Aerodynamic parameters of airfoil cross section and body-fixed coordinate system of the aerodynamic center of rigid body B_i.