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Wake impacts on aerodynamic and aeroelastic behaviors of a horizontal axis wind turbine blade for sheared and turbulent flow conditions

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ABSTRACT

The magnitude and temporal variations of wind speed considerably influence aerodynamic and structural responses of MW-sized horizontal axis wind turbines. Thus, this paper investigates the variations in airloads and blade behavior of a wind turbine blade resulting from operations in sheared and turbulent flow conditions. First, in order to validate the present methods, comparisons of aerodynamic results were made among the blade element momentum method, free-wake method, and numerical results from the previous studies. Then, the validated methods were applied to a national renewable energy laboratory 5 MW reference wind turbine model for fluid–structure interaction analyses. From the numerical simulations, it can be clearly seen that unfavorable airloads and blade deformations occur due to the sheared and turbulent flow conditions. In addition, it is clear that wake impacts are not as substantial at those of high wind speeds; however, the effects obviously affect the aerodynamic and structural behaviors of the blade at lower wind speeds. Therefore, it is concluded that the numerical results markedly indicate the demand for accurate assessment of wake dynamics for accurate estimations of the aerodynamic and structural responses for sheared and turbulent flow environments.

1. Introduction

The state-of-the-art in horizontal axis wind turbine aerodynamics for a uniform inflow condition can be accurately modeled and is considerably well understood (Rozenn et al., 2010). In general, the aerodynamic characteristics of modern commercial wind turbines are predominantly determined by the mean wind inflow speed. However, wind turbines actually operate with non-uniform flow and turbulent flow conditions on the rotor disk. The increase of wind speed with height is known as wind shear; interest in this condition has been motivated by the increasing size of wind turbine rotor diameters and hub-height. Also, turbulent flow, which is inclined to produce variations of wind speed magnitude with time,

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can strongly affect the aerodynamic characteristics (Madsen et al., 2012; Ananth et al., 2013). Thus, a numerical model that can consider not only uniform flow but also non-uniform flow conditions is required.

The blade element momentum (BEM) method is one of the most widely used numerical methods for understanding wind turbine aerodynamics because the formulation is relatively simple, fast, and inexpensive (Tong, 2010). Skjoldan and Hansen (2012) used the BHawC aeroelastic code based on the BEM method to compute fatigue loads in a wind shear condition. Madsen et al. (2012) also used BEM for sheared inflow conditions to predict performance; the aerodynamic responses were compared with advanced model results. However, this BEM method may possibly be inaccurate for computing asymmetric inflow distributions because there are substantial uncertainties in the detailed description and assumptions for the non-uniform inflow condition. Although almost all wind research institutes have used simulation codes based on the BEM model e.g., FLEX5 (Øye, 1996), BLADED (Bossanyi, 2003), HAWC2 (Larsen et al., 2005; Larsen and Hansen, 2007), FAST (Jonkman and Buhl, 2005) and General Aerodynamic and Structural prediction Tool (GAST), the numerical results of these methods disagree with one another for non-uniform inflow conditions (Madsen et al., 2012). In order to overcome the limitations of the BEM method for non-uniform inflow, advanced aerodynamic methods, such as the vortex theory or Navier–Stokes computational fluid dynamics (CFD), are required. However, previous studies involving CFD computations have until recently been few in number due to concerns for the enormous requirements of the aerodynamic grids (Madsen et al., 2012). For these reasons, to save computational time and cost, lifting line, lifting surface, and panel methods have been used, instead of BEM and full three-dimensional CFD computations. Garrel (2003) developed an aerodynamic wind turbine simulation module (AWSM) code based on Prandtl's lifting line theory at the Energy Research Centre of the Netherlands (ECN); Grasso (2010) conducted aerodynamic calculations for wind shear conditions to extend the versatility of AWSM. Shen et al. (2011) employed the lifting surface approach with the free-wake method to predict aerodynamic loads in sheared inflows. Sezer-Uzor and Uzor (2013) used an unsteady vortex-panel method potential flow solver based on free-wake methodology to investigate the effect of steady and transient free-stream wind shear on the wake structure and aerodynamic performance of a wind turbine.

The types of incoming flow and the wake effects may cause variations of the flapwise and edgewise blade deflections at a particular azimuthal position because such effects influence the aerodynamic loads. Large blade deformations have resulted in one or more blade accidents due to blade-tower collisions (Kallesøe, 2007a,b), and so an understanding of the interactions between wind magnitude, pitch action, and blade behavior has become even more crucial to the design and analysis of newly developed MW-sized wind turbines (Kallesøe, 2007a,b). In this study, we investigate the effects of inflow types and wake dynamics on the aerodynamic and structural behaviors of the turbine blade. The aerodynamic results of a National Renewable Energy Laboratory (NREL) 5 MW reference wind turbine (RWT) blade for uniform inflow conditions and structural dynamic responses were first compared with numerical results from a previous study (Madsen et al., 2012) so as to validate the present methods. Finally, to investigate the importance of the wake effects of large-scaled wind turbines, the aerodynamic and structural behaviors of a given blade in sheared and turbulent flow conditions were predicted using the BEM method and free-wake method.

2. Modeling

2.1. Wind turbine aerodynamic model

2.1.1. Blade element momentum theory

Momentum theory concerns itself with the global balance of momentum on a rotating annular stream tube passing through a wind turbine; blade element theory (BET) is an analysis of the aerodynamic loads on a blade section. The formulations of these theories are combined into the blade element momentum (BEM) method. The fundamental concept of the BEM method is to balance the linear and angular momentum changes of the air masses flowing through the rotor plane with the axial load on the blades (Hansen, 2007). This balance is accomplished by considering the flow through annular strips of width and the aerodynamic forces on blade elements of the same width. The induced velocity can be calculated using the following equation:

$$v_{id} = aV_{wind} = \frac{\sigma C_n}{4\sin^2\phi + \sigma C_n} V_{wind}, \tag{1}$$

where a is the axial induction factor, V_{wind} is the wind speed, and ϕ is the flow angle between the rotor plane and the relative velocity. The effective angle of attack can be computed using the following equation:

$$\alpha_{effective} = \phi - \theta_{twist} = \left(\frac{V_{wind} - v_{id}}{\Omega r}\right) - \theta_{twist}, \tag{2}$$

where Ω is the rotation speed, r is the radial position of the blade, and θ_{twist} stands for the structural twist angle. The lift, drag, and moment coefficients, which are applied to the blade, can be predicted through the look-up table method.