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Simulation of aeroelastic behavior in a composite wind turbine blade

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ABSTRACT

Aeroelastic analysis of a full scale composite wind turbine blade is investigated using its 3D model. Aerodynamic loading is determined using modified Blade Element Momentum theory and Computational Fluid Dynamics method is employed for verification. 3D finite element model of the blade is built and then Fluid–Structure Interaction iterative approach is constructed to investigate the aeroelastic behavior. Influence of deformation on power performance is determined implying on a reduction in output power. Susceptibility of dynamic instability is investigated and it is found out at high wind speed that the blade may experience instability.

1. Introduction

Renewable energy studies have been growing rapidly due to rising energy demand, finite fossil fuels and environmental concerns. Wind energy is one of the fastest growing forms of clean energy resources and this growth is set to continue so that, e.g. over the past 5 years, US wind energy capacity increases from 25,000 MW to over 61,000 MW (American Wind Energy Association, na). The emerging demand for electricity generation by capturing wind energy stimulates industrial sectors to design and manufacture horizontal axis wind turbines (HAWT) with larger blades. Thus, both aerodynamic performance and structural efficiency of the blade play important roles in economical power generation. Satisfying complex design constraints consisting of lower weight, high strength and proper resistance to the fatigue phenomenon, blades of HAWTs are made of composites. Moreover, employment of composite materials facilitates manufacturing complicated geometrical shape of wind turbine blade dictated by aerodynamical concerns. Previously, design problem of wind turbine blades usually falls into either static or fatigue categories. Recently, aeroelasticity analysis of a wind turbine blade is necessarily taken into account during the design procedure due to their flexible and large structures. Neglecting aeroelasticity investigations on a wind turbine blade may not only lead to the overestimated output power of wind turbine, but also will ignore the possibility of dynamic aeroelastic instability known as flutter. This instability is a self-excited phenomenon growing exponentially (Bir and Jonkman, 2007). Classical flutter is known as an aeroelastic instability which occurs when the flow around the blade work as negative damper. The flutter speed for small wind turbine has been determined to be about five times the operating speed (Lobitz and Veers, 1998) and for larger one this critical wind speed is approximated two times the operating speed (Lobitz, 2004). Hansen (2007) studied the probability of aeroelastic instability for stall-controlled wind turbines and pitch regulated wind turbines. Risk of flutter is experienced if four criteria are satisfied including attached flow, high tip speeds, low stiffness and aft center of gravity.

Performing a review on literature, it can be seen that limited studies have been done on the aeroelasticity analysis of a full scale wind turbine blade. Due to difficulties in the modeling and analysis of a full scale wind turbine blade, majority of aeroelastic analyses have been done on either two dimensional cross sections of blades or blades with simple geometries (MacPhee and Beyene, 2011; Nguyen-Thanh et al., 2011; Thai et al., 2012; Valizadeh et al., 2013; Krawczyk et al., 2013; Sarkar et al., 2009; Sarkic et al., 2015; Miyata, 2002; de Miranda et al., 2013). MacPhee and Beyene (2011) presented a morphing airfoil concept which passively controls airfoil pitch through elastic deformation instead of power control system to decrease cost and increase power production. In their study 2D fluid–structure interaction is used to determine aeroelastic behavior of a 2D airfoil. Limitations of analytical methods lead researcher to use numerical approach such as finite element method (FEM) in different problems. Many studies have been accomplished to closely link finite element analysis and computer aided design (CAD) that results in accurate analysis of

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the problems (Nguyen-Thanh et al., 2011). Recently, NURBS-based isogeometric analysis has been carried out in vibration, flutter (Thai et al., 2012) and composite problems (Valizadeh et al., 2013). Krawczyk et al. (2013) investigated a computational fluid dynamics (CFD)-FEM of a morphing airfoil including different wind velocity regimes and Young's modulus of a blade material. Fluid–structure interaction (FSI) approach is extensively not only used in aeroelastic analysis of other structures like bridge (Sarkar et al., 2009; Sarkic et al., 2015; Miyata, 2002; de Miranda et al., 2013), airplane and building but also is executable in fracturing structures (Rabczuk et al., 2000).

Carrión et al. (In press) performed aeroelastic analysis of MEXICO and NREL wind turbines using CFD-CSD method. In this research, flampwise and edgewise time domain vibrations and frequencies of vibrations in different wind speed are determined. Bergami and Gaunaa (2010) investigated divergence and flutter instability of a 2D airfoil section equipped with a trailing edge flap which can be used in a wind turbine blade and dependency of stability limits on the flap was reported. Liu et al. (2013) studied the aeroelastic stability of laminated cross section of wind turbine blades. The structural equation of motion with bending–bending–twist coupling is derived. In this study, occurrence of instability is determined by means of time-marching and eigenvalue analysis. Baxevanou (2008) predicted flutter limits for an airfoil of wind turbine blade in the time domain approach. Aeroelastic analysis has been done implicitly and explicitly by integrating between three degrees of freedom equations of motion and CFD analysis. Lee et al. (2012) studied static aeroelasticity of a fiber-reinforced plastic (FRP) wind turbine blade and suggested three methods to compensate reduction in power performance which are the pre-twist angle, pitch control system and fiber orientation. Lee et al. (2013) studied the application of bend–twist coupled on performance of wind turbine. In their research, the influence of different parameters such as solidity, diameter of the turbine and number of composite plies on annual energy and thrust loading is determined, using FSI method. Chattot (2007) simulated aeroelastic behavior of a wind turbine using vortex method as aerodynamic analysis and flexibility of the blade has been determined for predicting forces and bending moments along the blade. Rafiee and Fakoor (2013) have simulated static aeroelasticity on a wind turbine blade by coupling CFD and finite element analysis. They have reported that stress components vary significantly in the event of power production at the rated wind speed which should be considered in fatigue analysis.

In this study, aeroelastic analysis of a composite wind turbine blade is presented using full 3D modeling. Aerodynamic analysis of the blade is carried out using modified blade element momentum (BEM) theory in order to decrease the runtime. Drag force is considered to obtain more accurate results. Verification of the blade element momentum theory is done using CFD simulation. Then, finite element model of the composite blade is constructed in ANSYS commercial software. The blade element momentum theory for analyzing aerodynamic loading on the blade is coupled with structural solver of ANSYS analyzing both static and dynamic aeroelastic behaviors of the blade.

2. Aerodynamic analysis

In addition to experimental aerodynamic of wind turbine blades (Hand et al., 2001), theoretical aerodynamic analysis can be categorized in four groups: Blade Element Momentum (BEM), vortex method (Badreddinne et al., 2005), dynamic stall model (Larsen et al., 2007) and CFD (Hsu et al., 2014; Bazilevs et al., 2011; Sayed et al., 2012). Blade Element Momentum (BEM) theory is developed by equating aerodynamic loads applying on the turbine blades to change of streamwise momentum across the wind turbine. This model is not capable to predict aerodynamic behavior of the wind turbine at high tip speed ratio and high solidity rotors. But very efficient, acceptable results and low computational cost have made it as a popular model in aerodynamic analysis of a wind turbine (Borg et al., 2014). In vortex method (Badreddinne et al., 2005; Borg et al., 2014) potential flow is assumed and each section of the blade is replaced by a number of vortex filaments. Vortex model is more accurate because circulation that is shed from the blade influences the induced velocity of the blade, but it requires high computational time (Borg et al., 2014). Dynamic stall is a nonlinear aerodynamic phenomenon and observed when wind turbine is subjected to time varying wind that fluctuated blade. Stall delay and hysteresis loop are their aerodynamic characteristics. The mechanism of dynamic stall is complicated and it has not been completely understood. Several empirical and semi-empirical dynamic stall models are available for the wind rotor aerodynamic analysis such as Beddoes–Leishman model, ONERA model and Boeing–Vertol model (Larsen et al., 2007; Wang, 2012). CFD is a developing method in aerodynamic analysis of wind turbine. This method is based on Navier–Stokes equations, has potential to provide realistic simulation of the turbine flow field and can be used to solve the complex flow over the wind turbine. The turbulence models like DNS, RANS or LES may be used in flow simulation around wind turbine. In spite of accurate results from CFD, this method has very high computational cost (Hsu et al., 2014; Bazilevs et al., 2011; Sayed et al., 2012). Lanzafame et al. (2013) investigated aerodynamic analysis of a wind turbine using CFD and BEM. According to the experimental data, accuracy of both methods is obtained while lower run time is required for BEM method. Yang et al. (2014) presented application of BEM theory without corrections on a wind turbine. But, airfoil data including lift and drag coefficients are determined from 3D CFD analysis of the wind turbine which are loaded in the BEM code. Good agreement was obtained when compared with the experimental data. Because of low computational cost and accurate results, BEM is employed in most aerodynamic and aeroelastic analysis of wind turbine blade. BEM method presented by Glauert (1948) enables us to calculate the steady loads and power.

In order to determine aerodynamic forces along the blade length BEM theory is programmed in MATLAB software. For the verification of BEM method, its results are compared with those obtained by CFD. To verify BEM results, CFD method is employed and because of huge required computations, it is limited to four wind speeds. Moreover, the obtained results from BEM are compared with available at-site measurement for validation purpose. The detailed procedure of BEM theory employed in this research is explained in proceeding section.

2.1. Aerodynamic modeling

In this study, the V47–660 kW wind turbine blade is selected as a case study and required information of this turbine is presented in Table 1.

From aerodynamic point of view, V47–660 kW wind turbine blade includes five different airfoils which are FFA-W3, MIX, NACA 63–600, NACA 63–450 and NACA 63–150. These five types of airfoil are presented in Fig. 1.

Because of aerodynamical and structural considerations, the blade is twisted and tapered from its root to tip. The cross sections of different airfoils along the blade length accompanied with chord and twist distributions are shown in Fig. 2.