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Fluid structure interaction modelling of horizontal-axis wind turbine blades based on CFD and FEA

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ABSTRACT

The increasing size and flexibility of large wind turbine blades introduces considerable aeroelastic effects, which are caused by FSI (fluid structure interaction). These effects might result in aeroelastic instability problems, such as edgewise instability and flutter, which can be devastating to the blades and the wind turbine. Therefore, accurate FSI modelling of wind turbine blades is crucial in the development of large wind turbines. In this study, an FSI model for wind turbine blades at full scale is established. The aerodynamic loads are calculated using a CFD (computational fluid dynamics) model implemented in ANSYS FLUENT, and the blade structural responses are determined using a FEA (finite element analysis) model implemented in ANSYS Static Structural module. The interface of CFD and FEA is based on a one-way coupling, in which aerodynamic loads calculated from CFD modelling are mapped to FEA modelling as load boundary conditions. Validated by a series of benchmark computational tests, the one-way FSI model was applied to the modelling of WindPACT 1.5 MW wind turbine blade, a representative large-scale horizontal-axis wind turbine blade. Five operational conditions are assessed, with the worst case found to be near the rated wind speed. Maximum tensile/compressive stresses and tip deflections in each case are found to be within material and structural limits, according to relevant design standards.

1. Introduction

The size of large wind turbines has increased dramatically over the past three decades, from a rated power of 75 kW with rotors of 17 m diameter for earlier designs up to commercial 5 MW turbines with rotors of 125 m (Premalatha et al., 2014). However, as a result of growth in size and flexibility of large wind turbine blades, the blades are becoming more susceptible to aeroelastic issues caused by FSI (fluid-structure interaction). Specifically, during the operation of wind turbines, the aerodynamic loads on the blade may cause blade deflection. This deflection can in turn lead to additional variation in the flow field, resulting in further load alteration. The interaction of fluid and structure may lead to aeroelastic instability problems, such as edgewise instability and flutter, which can have a devastating impact on the blade itself and the wind turbine as a system. Therefore, accurate FSI modelling of wind turbine blades is crucial in the development of large wind turbines (Wang, 2015).

FSI modelling requires both aerodynamic and structural components to establish both aerodynamic loads and the corresponding structural responses. Currently, there are a variety of methods for establishing these model components, and approaches for coupling them, in order to investigate FSI behaviour of wind turbine blades.

For the aerodynamic component of FSI modelling, the BEM (blade element momentum) model (Glauert, 1935) has been extensively applied due to its efficiency and reasonable accuracy. The high efficiency of the BEM model also makes it suitable for design optimisation, which generally involves a large number of design iterations. Based on the BEM model and different optimisation strategies, a series of case studies has been performed to optimise the aerodynamic performance for both fixed-speed (Wang et al., 2012; Liu et al., 2013) and variable-speed wind turbine blades (Wang et al., 2012; Zhao et al., 2012). However, the BEM model is incapable of providing detailed information on the flow field, such as flow visualisation and wake development. This information is important for wind turbine designers to have a better understanding of the flow field around the blade and to further optimise the design. Obtaining detailed information on the flow field requires CFD (computational fluid dynamics) modelling (Tu et al., 2012), which has been receiving greater attention in recent years due to the rapid advancement of computer technology. Compared to BEM model, the CFD model is more computationally expensive, but it is capable of accurately modelling complex 3D (three-dimensional) flow fields and representing realistic fluid dynamics more accurately (Plaza et al., 2015; Orlandi et al., 2015; Makridis

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and Chick, 2013). Due to its high level of accuracy and flexibility, the CFD model is chosen as the aerodynamic component of FSI modelling in this study.

For the structural component of FSI modelling, beam models and FEA (finite element analysis) models are the two most common approaches referred in the literature (Hansen et al., 2006; Zhang and Huang, 2011). Beam models are 1D (one-dimensional) representations of 3D structures which discretise properties such as stiffness and mass into points along the 1D beam. They are computationally efficient and generally give reasonable results. Based on a nonlinear beam model Wang et al. (2014) developed a nonlinear aeroelastic model for wind turbine blades, taking account of both large blade deflections and geometric nonlinearities. The beam model is characterised by cross-sectional properties, such as mass per unit length and cross-sectional stiffness, which can be obtained by using specialised cross-sectional analysis models (Wang et al., 2014). However, a beam model is incapable of providing some important information for the blade design, such as detailed stress distributions within the blade structure. In an FEA model, wind turbine composite blades are generally constructed using 3D composite shell elements, which are capable of describing composite layer characteristics throughout the shell thickness. FEA model has the advantages of being high-fidelity and capable of examining the detailed stress distributions within each layer of composite blade structure (Wang et al., 2016). For this reason, FEA model is selected as the structural component of FSI modelling in this paper.

The coupling methods for FSI modelling can be roughly categorised into two groups, i.e. two-way coupling and one-way coupling. In a two-way coupling approach, typically the aerodynamic model is solved to acquire load data separately. These loads are then mapped to the structural model as boundary conditions and used to generate the model deflection. This deflection is then mapped back to the aerodynamic model and the process is repeated until result convergence is achieved. However, whilst full coupling produces the most accurate results through effective model synchronisation, it is computationally expensive due to the frequent transfer of information between models during each time step. In a one-way coupling model, the aerodynamic loads are mapped to the structural model to assess model deflection in the same way as two-way coupling. However, these deflections are not mapped back to the aerodynamic model. Compared to the two-way coupling, the one-way coupling saves much computational resources, making it preferable for initial modelling purposes. Considering the computational efficiency, the one-way coupling is selected as the coupling method of FSI modelling in this study.

Presently, the majority of commercial aeroelastic codes (such as FAST (Jonkman and Buhl, 2005), GH-Bladed (Bossanyi, 2009) and HAWC2 (Larsen, 2009)) utilise variations of low-order aerodynamic models (e.g. BEM model) to model aerodynamic loading (Hansen et al., 2006; Zhang and Huang, 2011). However, in order to establish complex 3D flow accuracy, higher resolution methods are required.

Studies have been carried out to couple higher resolution methods (such as FEA and CFD) for FSI modelling, and a comprehensive review of aeroelastic modelling of wind turbine blades can be found in Ref. Wang et al. (2016). It should be noted that a wind turbine blade generally has complex structures including several layers of composite materials with shear webs. Due to the difficulties in modelling and analysing a full-scale wind turbine composite blade, majority of FSI modelling have been done on either 2D cross sections of blades or 3D blades with simplified structures. MacPhee and Beyene (2013) developed a 2D FSI model to simulate the aeroelastic response of a symmetric NACA 0012 blade subjected to variable loading. Krawczyk et al. (2013) developed a similar 2D FSI model based on CFD and FEA and applied it to aeroelastic analysis of a NACA 4412 blade. Bagheri and Nejat (2015) developed a 3D FSI model and applied it to aeroelastic analysis of NREL Phase VI rotor. The torque and pressure coefficient at different blade sections over wind speed of 7–15 m/s were investigated based on the 3D FSI model. However, the composite blade was simplified by a solid blade (stiffer than the real one) subtracting an inner-subpart cross section. In order to develop a reliable aeroleastic model of wind turbine composite blades, it is crucial to model the composite blades at full scale and consider the detailed composite layups.

This paper presents a one-way coupled FSI model for wind turbine composite blades at full scale, taking account of detailed composite layups of the blade. The aerodynamic loads are calculated using CFD and blade structural responses are determined using FEA. The coupling strategy is based on the one-way coupling strategy, in which aerodynamic loads calculated from CFD modelling are mapped to FEA modelling as load boundary conditions. The established FSI model is validated by a series of benchmark tests as compared with data reported in the literature, and applied to the FSI simulation of WindPACT 1.5 MW horizontal-axis wind turbine (Malcolm and Hansen, 2002), which is a representative of megawatt-class horizontal-axis wind turbines. In addition to horizontal axis wind turbines, the established FSI model can be also applied to other similar applications, such as vertical axis wind turbines (Kolios et al., 2013) and tidal devices (Pintar and Kolios, 2013), due to its high flexibility.

This paper is structured as follows. Section 2 presents the methodology comprising four components, i.e. wind turbine model, CFD modelling, FEA modelling and one-way FSI coupling. Results and discussions are presented in Section 3, followed by a conclusion in Section 4.

2. Methods

2.1. Wind turbine model

The wind turbine model used in this study is the WindPACT 1.5 MW wind turbine (Malcolm and Hansen, 2002; Griffin, 2001; Malcolm and Hansen, 2003; Resor and Bushnell, 2011), which is a reference wind turbine designed by NREL (National Renewable Energy Laboratory) in the WindPACT (Wind Partnership for Advanced Component Technologies) project between years 2000 and 2002. This wind turbine is a conventional three-bladed upwind horizontal-axis wind turbine, utilising variable-speed variable-pitch control. The details of the WindPACT 1.5 MW wind turbine can be found in Malcolm and Hansen (2002), Griffin (2001), Malcolm and Hansen (2003), Resor and Bushnell (2011), and its main parameters are summarised in Table 1. The blade includes two shear webs and three types of airfoils, i.e. S818, S825 and S826. The modelled 3D geometry of the blade is presented in Fig. 1.

Table 1
Main parameters of WindPACT 1.5 MW wind turbine.

Parameters	Values	Units
Rated Power P_{rated}	1.5	MW
Number of blades N_B	3	–
Rotor radius R	35	m
Rated wind speed V_{rated}	11.5	m/s
Rate rotor speed Ω_{rated}	20.5	rpm