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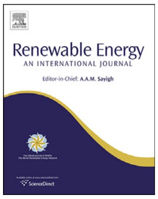

Large-eddy simulation and wind-tunnel measurement of aerodynamics and aeroacoustics of a horizontal-axis wind turbine

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ABSTRACT

Large-eddy simulation of the whole three-dimensional vortex dynamics and noise radiation around a horizontal-axis wind turbine has been studied and analyzed together with wind-tunnel experimental measurement. A computational framework that takes into account of the true shape of the wind turbine blade geometry for calculating the aerodynamics and aeroacoustics is developed and validated against the experimental data. The LES results generally agree well with the experimental data in terms of both the aerodynamics and aeroacoustics statistics. The formation and development of the complex three-dimensional wake vortexes are captured and analyzed, and the aerodynamic noise is further studied based on the flow field using the FW–H method. It is found that noise generation and acoustic radiation are closely associated with the generation and evolution of these vortex structures. The blade tip region is the main resource area of the aero-noise and the acoustic radiation intensity of the rotor decreases rapidly downstream.

1. Introduction

The aerodynamic research and wake flow analysis for wind turbines have contributed a lot to the success of modern wind energy utilization [1–3], and technologies for wind energy conversion have significantly advanced during the past few decades. The Horizontal-Axis Wind Turbine (HAWT) is the least expensive and clean way to make use of the wind power. As the interaction between the wind and the blade influences the efficiency, the design and development of more efficient and reliable wind turbines rely heavily on accurate prediction of aerodynamic behaviors and can benefit significantly from a good knowledge of parameters related to the wake [4,5]. However, some environmental and social problems still remain unsolved, and the wind turbine noise becomes the most serious issue among them [6]. The wind turbine noise, especially the aerodynamic noise is even hindering the global use of the wind turbine. It is thus very important to understand the noise source mechanisms, depending on the rotor aerodynamic characteristics and the operating conditions for a wide range of the rotor's frequency spectrum [7,8].

Methods of different levels of complexity to investigate the aerodynamic and aeroacoustic behaviors of a wind turbine rotor have been developed. These methods include the Blade Element Momentum (BEM) theory, the wind tunnel experiment, the field experiment and the computational fluid dynamics (CFD) [1]. The BEM theory that proposed by Glauert is the most classical approach for the aerodynamic design of wind turbine [9]. However, it requires adding a number of amendments to the project [10]. The BEM theory occupies fewer resources in the calculation and it would be relatively more rapid, but it cannot get the details of the blade surface pressure distribution, and cannot provide accurate aerodynamic load data for the structural analysis of wind turbine blades. On the contrary, CFD simulation is a cheap and efficient way to provide valuable quantitative insight into the aerodynamic and aeroacoustic behaviors of flow around wind turbine. It has helped the industry become more efficient and productive and has enabled new designs and levels of efficiency not possible before [11,12].

CFD modeling and experiment have both advantages and disadvantages. They can be complementary to each other and one can expect more effective understanding of the phenomenon. The CFD

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method is useful to utilize as an efficient tool for the wind turbine and can complement experimental data that is difficult to measure. It is also possible to obtain useful CFD results based on verification and validation by the experimental results. Moreover, the verified model can be used to deliver correct results for any arbitrary condition without considering the limitations of experimental equipment, measurement errors and problems with measurement systems.

For CFD simulations, the Reynolds-averaged Navier–Stokes simulation (RANS), the large-eddy simulation (LES), and the direct numerical simulation (DNS) are three commonly used approaches with different accuracies. The RANS approach, especially the k-ε turbulence model, is traditionally used with the advantages of robustness, economy, and reasonable accuracy for a wide range of turbulent flows. DNS solves the Navier–Stokes equations without any closure model, but is not feasible for practical engineering problems involving high Reynolds number flows because of high demand of computational resources. LES is developed as an intermediate approach between DNS and RANS. The general idea is that the large, non-universal scales of the flow are computed explicitly, while the small scales are modeled [13]. LES has been proven to be a successful approach to simulate unsteady flows around airfoils [14], but only recently have there been some efforts to apply LES to simulate wind turbine wakes [15–17]. It is more accurate than RANS and requires substantially finer meshes than those typically use the k-ε turbulence model. So time-accurate LES solver can capture the noise-generating region well and hence becomes a very promising method for predicting noise.

Although there have been some aerodynamic studies of wind turbine by means of LES or experimental measurement independently, it is still difficult to fully calculate both the noise source and its propagation to the far-field, and as yet no detailed and open experimental data for wind turbine noise is available for model validation. In the present work, both the aerodynamic and aeroacoustic characteristic of a horizontal-axis wind turbine is studied with the LES and wind tunnel experiment. The main objective is to develop a LES framework for simulations of aerodynamics and aeroacoustics around a horizontal-axis wind turbine and improve the fundamental understanding of turbulence–noise interaction. The wind turbine used in the simulation is exactly the same as the real model measured in the Key Laboratory of Renewable Energy in Inner Mongolia University of Technology for LES validations.

2. Wind tunnel experiment

2.1. PIV measurement

Particle image velocimetry (PIV) is an advanced non-contact flow measurement technology that became applicable in the late 1990s [18]. It has been applied to explore research of wind turbine wakes [19]. In the present work, PIV measurement of a fixed area in the near wake of a horizontal-axis wind turbine has been done in the Key Laboratory of Renewable Energy in Inner Mongolia University of Technology.

The experiment is conducted in the open section of the wind tunnel using the phase-locked periodic sampling method. The B1/K2 wind tunnel used in the experiment is shown in Fig. 1, together with the wind turbine and the CCD camera. The diameter of the open test section of the wind tunnel is 2.04 m and the maximum steady wind speed is 20 m/s. The wind turbine model is a NACA4415 horizontal-axis wind turbine with three blades. Its blade has a diameter of D = 1.4 m and the rated wind speed is 8 m/s. The rated tip-speed ratio λ is 5 and the rated power is 100 W in this case. The tail is removed in order to achieve stable experimental conditions. The wind turbine is fixed to the system to ensure that the wind blade rotational plane is vertical to the inlet flow direction.

Fig. 1. B1/K2 wind tunnel and the wind turbine.

Fig. 2 shows the planes illuminated by the laser light sheet. They are vertical to the wind turbine rotation axis. In the PIV results, the coordinates of the blade tip is (224.1 mm, 57.4 mm). The size of the PIV picture is 257.34 mm × 190.38 mm and the resolution is 1200 × 1600 pixels [20]. PIV measurement accuracy depends on the accuracy of the measurement of the particle displacement and the control accuracy of the time interval of two images. In the monitoring of wind speed during the present experimental process, the velocity uncertainty is about 5%.

2.2. Acoustic radiation measurement

The acoustic radiation test is conducted in the same section of the wind tunnel with the same wind turbine. Acoustic analysis requires detailed records of sound information. The microphone

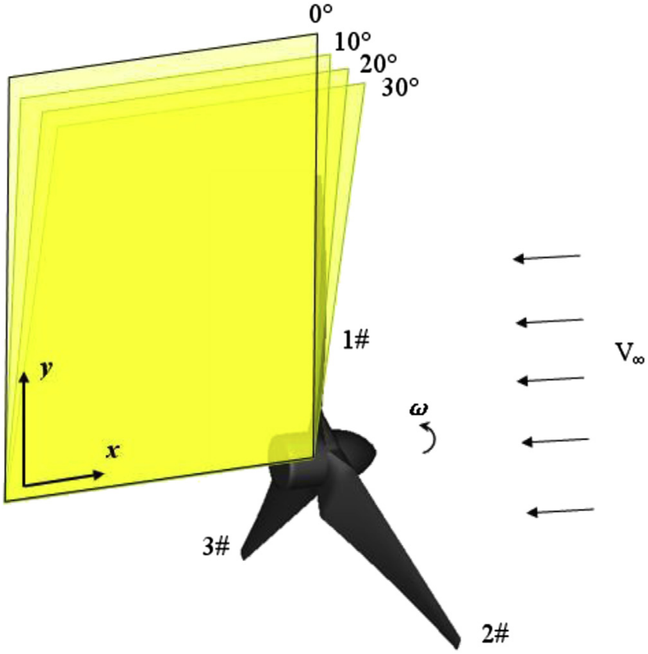

Fig. 2. PIV testing sketch.