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Turbulence effects on the wake characteristics and aerodynamic performance of a straight-bladed vertical axis wind turbine by wind tunnel tests and large eddy simulations

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ABSTRACT

The wake characteristics of wind turbines are of crucial importance for the optimum placement of multiple turbines. In this study, the wake development of a straight-bladed VAWT (vertical axis wind turbine) was investigated and compared in low-turbulence smooth and grid-turbulence flows. The wake fields in both flow regimes were measured with WTTs (wind tunnel tests). To further examine the flow physics, LES (large eddy simulation) was performed with a structured mesh. An algebraic wall-modeled LES capable of overcoming the Reynolds number scaling problem was used. The LES models accurately captured the velocities in both flow regimes from the WTTs. It was shown in the WTTs that the grid turbulence benefited both self-starting and wake recovery. The LES results also suggested delayed dynamic stall and greater power production in the turbulent flows. Moreover, it was revealed by the WTTs and LES that the wake exhibited great asymmetry in the horizontal direction, whereas it was approximately symmetrical against the blade mid-span plane. Further, vortex-ring structures consisting of counter-rotating vortices in the wake were discovered in both flow regimes. This kind of flow pattern was assumed to contribute to fast wake recovery.

1. Introduction

Wind energy is clean and renewable and has gained an increasing market share in recent decades [1]. HAWTs (Horizontal axis wind turbines) are the most common options to harness wind energy. Nevertheless, HAWTs are ineffective and lose significant power in turbulent conditions [2,3]. In fact, wind within the ABL (atmospheric boundary layer) is by nature turbulent to a varying extent, and the velocity field constantly changes in both time and space [4]. Moreover, for a significant proportion of time, wind is characterized by high levels of turbulence [5]. VAWTs (Vertical axis wind turbines) display better performance than HAWTs in harsh flow conditions [6,7]. Researchers have claimed that VAWTs may be more applicable to complex urban terrains with high levels of turbulence [8–10]. However, concrete evidence to support the statement is still lacking because most studies have been performed in low-turbulence smooth flows. In this study, the effects of grid turbulence on the wake and aerodynamic performance of a Darrieus-type straight-bladed VAWT are investigated.

The combination of dynamic stall caused by constantly changing AOAs (angles of attack, α) and harsh turbulent conditions in the downstream half-revolution contributes to the complex aerodynamics of VAWTs. Aerodynamic studies of straight-bladed VAWTs can be classified into two basic areas: blade aerodynamics [11–15] and wake aerodynamics [16–19]. Analysis of blade aerodynamics aims at improvement of the power performance of an individual turbine. In comparison, investigations of wake aerodynamics seek to raise the power output of multiple turbines. McLaren conducted a series of full-scale WTTs (wind tunnel tests) to measure the unsteady loading on the blades of a straight-bladed VAWT [20]. 2-D (Two-dimensional) CFD (computational fluid dynamics) simulations with the SST (shear stress transport) k–ω turbulence model [21] were constructed to predict the aerodynamic forces. It was noticed that the 2-D CFD model always overestimates the thrust and radial forces by a factor of approximately 1.4. This overestimation problem is intrinsic to 2-D CFD models due to their inability to cope with the vortices of blade tips. Elkhoury and colleagues carried out experimental and numerical

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analyses of the aerodynamics of a straight-bladed VAWT with variable pitch [22]. LES (Large eddy simulation) was performed with the dynamic Smagorinsky-Lilly SGS (subgrid scale) model [23] to examine the flow structures in detail. The 3-D (three-dimensional) LES model has demonstrated its ability to accurately predict the power performance of the VAWT.

Studies of the wake aerodynamics of straight-bladed VAWTs are more limited than those of the blade aerodynamics. Simão Ferreira carried out a comprehensive investigation of the near wake of a straight-bladed VAWT by means of PIV (particle image velocimetry) tests and CFD simulations [16]. The development of wake flow physics in the near wake of the VAWT and the dynamic stall behavior were both examined with PIV tests. Comparisons of the results from different turbulence models have revealed that the URANS (unsteady Reynolds-averaged Navier-Stokes) models fail to accurately predict large eddies and their effects. Tescione and colleagues conducted near wake measurements by stereoscopic PIV tests in an open-jet wind tunnel [17]. The velocity and vorticity fields were measured at the symmetry plane up to two turbine diameters (2D) downstream. The stream-wise and cross-stream velocity profiles at seven downstream distances were presented. Wake asymmetry, in which the wake expands more toward the windward than toward the leeward, was clearly observed. Lam and Peng carried out a numerical investigation of the near- and far-wake characteristics of a straight-bladed VAWT using both 2-D and 3-D CFD models [19]. The wake asymmetry of VAWTs is confirmed, and the asymmetry further escalates with the downstream distance. 3-D CFD models are recommended for faithful predictions of wake aerodynamics due to the inability of 2-D models to respect the strong vortex shedding at the blade tips and the span-wise flow movements.

Cautious review of the literature reveals that current studies of VAWTs focus predominantly on the blade aerodynamics in low-turbulence smooth flows. Few studies have been performed on the effects of turbulence on the aerodynamic performance. Moreover, the wake characteristics are of crucial importance for the optimum placement of multiple VAWTs in a wind farm. Nevertheless, research efforts on the wake aerodynamics of VAWTs in the literature are rather limited. In this study, the wake flow fields of a five-straight-bladed VAWT were measured and analyzed in low-turbulence smooth and grid-turbulence flows. Homogeneous turbulence was produced by installing a wooden grid with equally spaced meshes at the wind entrance. To provide a comprehensive understanding of the wake flow structures, LES models were constructed with a structured mesh. The LES results agreed well with the WTT data. The aerodynamic and power performance was studied with the LES models. Furthermore, the vortical structures that evolved in the wake were analyzed. Finally, comparisons and discussions of the blade aerodynamics and the wake characteristics in the two flow regimes were made, respectively.

2. Wind tunnel tests

2.1. Experimental methods

2.1.1. Wind turbine and wind tunnel

Fig. 1 presents the straight-bladed VAWT in the wind tunnel located in City University of Hong Kong, Hong Kong. The diameter, D, of the VAWT is 0.3 m; the blade depth, H_b, is 0.3 m; and the number of blades, N, is five. The blades extend straight from a cambered airfoil. A cambered airfoil performs better than a symmetrical airfoil in deflecting the oncoming air flows onto the upper and lower surfaces and thereby generates larger lift forces. A lift-driven straight-bladed VAWT with cambered blades shows better self-starting performance than one with symmetrical blades. The

Fig. 1. Five-straight-bladed VAWT in the wind tunnel.

chord length, c, is 0.045 m. Hence, the solidity ratio, $\sigma = Nc/(\pi D)$, is 0.24, which corresponds to a high-solidity VAWT. The pitching position of the blades is at the blade mid-chord. The height, h, of the VAWT from the ground to the blade mid-span is 1.0 m. The VAWT rotates counterclockwise as viewed from the top. The wind tunnel has a uniform cross-section of 2.0 m × 2.5 m (height by width), and its length is 10.0 m. The blockage ratio of the turbine is 1.8%, and thus no correction of the measured results is required [26,27].

2.1.2. Experimental setup

A schematic of the experimental setup for wake measurements is presented in Fig. 2. The VAWT stood 6.0 m downstream of the wind entrance ($L' = 6.0$ m) and 4.0 m upstream of the wind exit ($l = 4.0$ m). The tower of the VAWT was located at the middle width of the tunnel cross-section. A four-hole cobra probe capable of providing three-component velocities was mounted onto a TDTS (three-dimensional traversing system) for automatic transportation. The laser displacement sensor to measure the rotational speed of the VAWT was positioned at the tower foundation. A wooden grid was installed for the generation of homogeneous turbulence (see Fig. 1). By adjusting ΔL, different turbulence levels can be obtained. In this study, the grid was installed with $\Delta L = 0$ m, and the mesh size of the wooden grid was 0.48 m × 0.48 m. The wooden grid was removed from the setup for the measurements in smooth flows. The center of the tower base was set as the origin of the Cartesian coordinate system in the wind tunnel, with x pointing downstream, y pointing into the figure, and z pointing upward.

2.1.3. Measurement campaign

The wake velocities were measured at four downstream distances: $x = 2D$, 4D, 6D, and 8D. The measurements were implemented at the level of the blade mid-span, i.e., $z = 1.0$ m, which corresponds to the symmetry plane [17]. The TDTS controlled by a computer in the controlling room was used to automatically position the cobra probe to the measured points. The data were recorded at a sampling rate of 3000 Hz, and the measurement duration was 30 s. First, the wake measurements were carried out in the low-turbulence smooth flows. The wooden grid was then installed, and the same set of measurements was conducted in the grid-turbulence flows. To make the comparisons fair, the wind speed at the turbine position was set at 10.2 m/s in both flow regimes. In the smooth flows, the free-stream turbulence intensity, I, was 2.7%, whereas I equaled 6.3% ($\Delta L = 0$ m) in the grid-turbulence flows.