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Investigation into the wake aerodynamics of a five-straight-bladed vertical axis wind turbine by wind tunnel tests

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ABSTRACT

Wake characteristics have significant effects on the performance design of standalone turbines and the optimal placement of multiple turbines. In the literature to date, little experimentation has been done on the wake of vertical axis wind turbines (VAWTs), and understanding of such wake is far from adequate. In this work, systematic measurements are presented of both the near and mid-range wake of a five-straight-bladed VAWT in a wind tunnel. The blockage ratio of the VAWT was 1.8%, and no correction of the measured data was required. The wake flow fields were measured up to 10 turbine diameters (10*D*) to the downstream. The wake exhibited high asymmetry in the horizontal direction. In addition, the wake expanded more in the horizontal direction than in the vertical direction. The causes of the asymmetry were analyzed and discussed through the experimental results. An engineering wake model was proposed to characterize the wake edges and the average velocities. The existence of a pair of counter-rotating vortical structures in the wake was detected. Moreover, the integral length scale was found to steadily grow with the downstream distance. This work contributes to the knowledge of the VAWTs' wake and the application of VAWTs in wind farm layout design.

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1. Introduction

Wind energy is clean and renewable, and the use of wind power has risen massively in recent years (Kusiak and Song, 2010; Islam et al., 2013; Danao et al., 2014; Ghasemian and Nejat, 2015). The exploration of power generation by wind turbines helps to prevent the escalating depletion of fossil fuels and the degradation of the global climate (Chen et al., 2015). Wind turbines are classified into two basic types: the horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT). The presence of a wind turbine and the rotation of its blades create strong blockage effects against the approaching wind. Moreover, part of the wind's kinetic energy is converted into the mechanical energy of the wind turbine's rotation for power production. As a consequence, a wake characterized by decreasing wind velocities and rising turbulence is created behind the wind turbine (Vermeer et al., 2003).

The HAWT has been developed to a mature level through intense research efforts, and this type of turbine has been dominant in the wind power industry for the past several decades (Eriksson et al., 2008; Islam et al., 2013). Nevertheless, recent studies have shown that VAWTs have great future prospects for applications in built environments and offshore areas, which are projected to become huge sources of renewable energy (Edwards et al., 2012; Almohammadi et al., 2013; Bhuyan and Biswas, 2014; Tjiu et al., 2015; Ismail and Vijayaraghavan, 2015). VAWTs have higher potential for scalability (Peace, 2004; Islam et al., 2013), superior robustness, and lower costs compared to their HAWT counterparts (Islam et al., 2013; Tjiu et al., 2015; Ismail and Vijayaraghavan, 2015). Furthermore, some studies have indicated that VAWTs have the faster wake recovery (Dabiri, 2011; Kinzel et al., 2012; Tescione et al., 2014). This finding suggests that VAWTs may be more efficient for clustered arrays in wind farm scenarios, especially in built environments and offshore regions.

To reduce the mutual interference of turbines in a wind farm and maximize the overall power output, the wake characteristics have to be analyzed (Lam and Peng, 2016). During the past several decades, substantial research efforts have been made to qualitatively and quantitatively investigate the wake aerodynamics of HAWTs (Alfredsson and Dahlberg, 1979; Jensen, 1983; Magnusson and Smedman 1999; Hand et al., 2001; Sanderse, 2009; Abdelsalam et al., 2014). However, few studies have been done on the wake characteristics of VAWTs, especially concerning how the wake flows evolve in the far wake, even though such studies are crucial for the optimal wind farm layout design. Therefore, this study emphasizes analyses of the wake characteristics of straight-bladed VAWTs, *i.e.*, the Darrieus-type VAWTs (Darrieus, 1931).

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Rather than conducting investigations of the VAWTs' wake, most previous research efforts on VAWTs have focused mainly on the power performance and loading behavior of rotor blades. Howell and colleagues performed an experimental study on the aerodynamic performance of a VAWT (Howell et al., 2010). They found that the blade surface roughness improves the power performance below a Reynolds number of 30,000. Conversely, beyond this critical Reynolds number, a smooth blade surface enhances the turbine performance. Studies of the solidity ratios for various numbers of blades have shown that the low-solidity VAWT reaches its rated performance at a higher blade speed ratio (BSR, $\lambda = V_B/U_0$, ratio of blade rotational speed to free-stream wind speed). The solidity ratio refers to the total blade area over the swept area of rotor blades, *i.e.*, $\sigma = Nc/(\pi D)$, where N is the number of blades, c is the chord length, and D is the turbine diameter. McLaren and colleagues conducted a systematic investigation into the aerodynamic loading behavior of blades for a high-solidity three-bladed VAWT in a wind tunnel (McLaren, 2011; McLaren et al., 2012). The thrust and radial force coefficients were measured at a series of BSRs and free-stream wind speeds. Such analyses have revealed that the power coefficient, C_P, as calculated from thrust force coefficients, has an amplification effect at high BSRs, whereas the results obtained from torque coefficients are more stable. Moreover, a vibration mitigation method and a signal filtering technique were developed to eliminate the resonant effect of the structural vibration with the turbine rotation.

Simão Ferreira performed an experimental study of the near wake of a two-bladed VAWT (Ferreira, 2009). The vortices induced by the VAWT and their effects on the wake flows have been comprehensively investigated through the smoke visualization, hot-wire measurement and particle image velocimetry (PIV). Tescione and colleagues investigated the near wake aerodynamics of a two-bladed VAWT based on stereoscopic PIV tests (Tescione et al., 2014). The VAWT operated at a BSR of 4.5 at a free-stream wind speed of 9.3 m/s. Phase-locked measurements were conducted at the blade mid-span plane for examining the wake characteristics along the horizontal plane. Moreover, measurements were performed along vertical planes at the windward and leeward to inspect the three-dimensional wake behavior. The stream-wise and cross-stream velocities at the blade mid-span plane were measured up to two turbine diameters (2D) in the wake. These tests revealed asymmetrical wake patterns in the horizontal direction. The wake was shown to have a more pronounced expansion toward the windward.

A careful review of the existing literature suggests that studying the wake characteristics of VAWTs through wind tunnel tests is a highly worthwhile task. As mentioned, the mid-range and far wake characteristics of VAWTs are of critical importance for the wind farm layout design. In this study, wind tunnel tests were conducted toward developing a comprehensive understanding of how the near and mid-range wake evolves. The measurements along horizontal lines (HLs) were carried out at the height of the blade mid-span at different downstream distances. In addition, measurements along vertical lines (VLs) aligned with the tower centerline were made at various downstream distances. Apart from that, measurements on a vertical plane normal to the approaching wind were conducted. The aerodynamic properties, such as the three-component velocities, turbulence intensities, and Reynolds shear stresses were measured and calculated. Based on the measured wake characteristics, an engineering wake model was proposed to describe the wake edges and average velocities. Finally, analyses of the integral length scale in the wake were performed to further examine the evolution of turbulence structures.

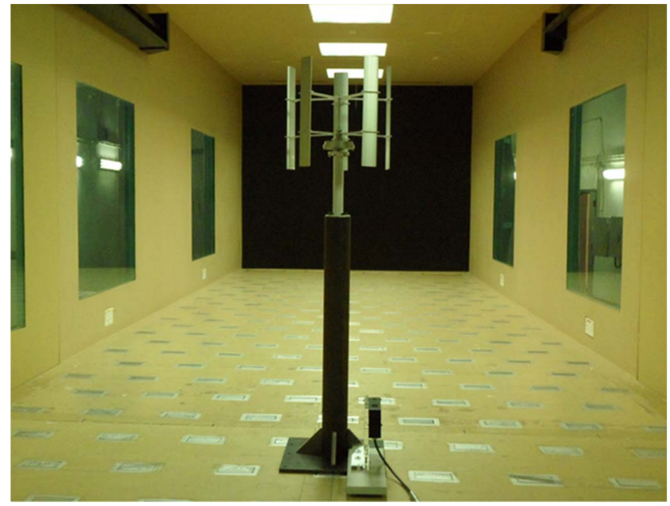

Fig. 1. VAWT prototype in the wind tunnel.

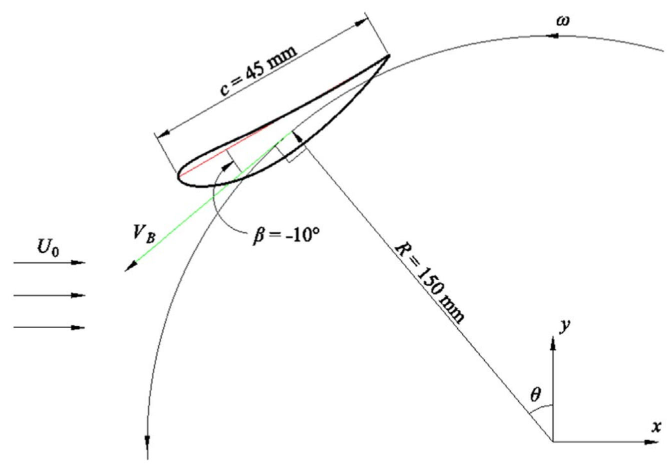

Fig. 2. Schematic of the geometrical properties of a single blade.

2. Measurement methodology

2.1. Wind turbine prototype

The wind turbine under investigation is shown in Fig. 1. This wind turbine has $N=5$ blades that extend straight outward from a cambered airfoil. The cambered airfoil is helpful in the sense that it can deflect the approaching flows onto the upper and lower surfaces and can produce lift force even at zero angle of attack (AOA, α). Therefore, the VAWT has an outstanding self-starting performance. Fig. 2 presents the schematic of the geometrical properties of one of the VAWT's blades. The VAWT rotates counterclockwise viewing from the top as shown by the angular speed, ω. Note that θ is the azimuthal angle. The turbine has a diameter, D, of 300 mm and a blade depth, H, of 300 mm. Hence, the turbine has an aspect ratio of $H/D=1.0$. The chord length, c, of the blade is 45 mm. The rotor blade is pitched at the blade mid-chord. A preset pitch angle, the angle between the blade rotational speed, V_B, and the blade chord line, is $\beta = -10°$. A solidity ratio of $\sigma = Nc/(\pi D) = 0.24$ is attained, which corresponds to a high-solidity VAWT.

2.2. Wind tunnel and measurement apparatus

The wind tunnel facility is located at City University of Hong Kong, Hong Kong. The height of the tunnel's cross-section is 2.0 m, and the width of the tunnel is 2.5 m. Thus, the blockage ratio of

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