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Experimental and numerical study of turbulence effect on aerodynamic performance of a small-scale vertical axis wind turbine

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ABSTRACT

The suitability of vertical axis wind turbines (VAWTs) in harnessing energy within a complex wind environment has increased their renewed interest. However, there still exists a huge knowledge gap about the aerodynamic performance of VAWTs operating in a turbulent flow regime. In this paper, an experimental method is presented for a deeper understanding of unsteady rotor aerodynamics under turbulent flow operating conditions. To carry out the investigation, we developed and tested a small-scale Savonius turbine in a wind tunnel. A systematic analysis of torque and power coefficients, including their variations at uniform flow, was also presented to predict the power performance. A mechanism to generate a turbulent flow was then created to analyze the effect of induced turbulence intensity on the aerodynamics and performance of the VAWT. Results revealed that the turbulence of the inflow impacted fluctuating aerodynamic loads on the turbine blade and, ultimately, its aerodynamic performance. In addition, simulations using a CFD code were performed to compare numerical data with experimental measurements. This analysis shows the effect of turbulence intensity on performance of small wind turbines, and the aerodynamics that causes the behavior.

1. Introduction

Turbulence is a complex process and can have a significant impact on the power output of wind turbines. This is particularly crucial for small wind turbines, which in practice are typically installed near buildings, trees, and other obstacles (McIntosh et al., 2008; Mcintosh, 2009; Scheurich, 2011). The vertical axis wind rotors have potential advantages under such conditions due to their ability to accept wind from any direction without yawing, low sound emission due to relatively lower tip speed ratios, increased performance in unsteady and skewed flows, ease of maintenance and low manufacturing cost, as well as potential operational safety during gust conditions (Edwards et al., 2012; Danao et al., 2013, 2014; Wekesa et al., 2014b, 2015, and references therein). Two types of VAWTs are mainly used, Savonius and Darrieus wind rotors (Wekesa et al., 2014b, 2015; Islam et al., 2008). The Savonius rotors are the simplest and cheapest designs of wind turbine rotors and have the capability to self-start at low wind speeds from any direction. Various experimental studies have been carried out to improve the aerodynamic performance of Savonius wind turbines (Mahmoud et al., 2012; Saha and Rajkumar, 2006; Jeon et al., 2015; Nasef et al., 2013; Tesch et al., 2015; Bhuyan and Biswas, 2014; Torresi et al., 2014; Gupta et al., 2008, and references therein). The studies revealed that Savonius wind turbines are an interesting technological alternative to conventional wind turbines.

There is relatively scarce literature that has attempted to characterize the effect of wind turbulence on the turbine's performance. The current power curve representations do not account for the impact of turbulence on small wind turbine energy production (Lubitz, 2014; He et al., 2013; Seguro and Lambert, 2000; Sparks and Huang, 2001). The common approach to report the turbine power curves is to determine output power as statistical averages of power measurements binned by wind speed, whereby the variance of the data is lost (Lubitz, 2014; Ahmadi-Baloutaki et al., 2015; Rogers et al., 2005; Fyrippis et al., 2010; Cao et al., 2009). This approach does not capture the effect of free-stream turbulence, thus creating an immediate need to address the influence of turbulence intensity and providing useful information in the context of wind turbine power curve.

A few studies that have attempted to characterize the effect of wind turbulence on wind turbines indicate that turbulence effect on wind turbine performance installed in urban environment is

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subjected to intensity of the turbulence as well as the size of turbulence scales (Lubitz, 2014; Ahmadi-Baloutaki et al., 2015; Sunderland et al., 2015; Pagnini et al., 2015; Maldonado et al., 2015; Kooiman and Tullis, 2012; Turk and Emeis, 2010; Mycek et al., 2014; Emejeamara et al., 2015; Bertenyi et al., 2010, and references therein). Unlike typical atmospheric performance testing works, the output data from studies in Lubitz (2014), Sunderland et al. (2015), Pagnini et al. (2015), Kooiman and Tullis (2012), and Turk and Emeis (2010) were split into smaller segments and the variance of the data was used to determine the turbulence intensity of each segment. Wind turbulence levels lower than 14% resulted into increased power output, while inconsistent trend was reported for higher turbulence levels. The authors (Lubitz, 2014) asserted that the turbine rotor energy production was altered by ambient turbulent levels, although the impact varied at different wind speeds. However, all tests were performed in an open atmospheric environment; hence there was no control on the level of free-stream turbulence.

The studies in Pagnini et al. (2015), Maldonado et al. (2015), Mycek et al. (2014), Emejeamara et al. (2015), and Mikkelsen (2013) have pointed out the significant role of the ambient turbulence intensity rate on the aerodynamic performance of wind turbines. Pagnini et al. (2015) employed two small-size wind turbines, with horizontal (HAWT) and vertical (VAWT) axis to analyze power curves in turbulent urban environment. From Pagnini et al. (2015), the VAWT became more efficient and started producing more power than HAWT quite often, especially at higher turbulence conditions. A similar study by Maldonado et al. (2015) experimentally determined the role of free-stream turbulence with large integral scale on the aerodynamic performance of a wind turbine blade. A significant increase in the lift-to-drag ratio for most angles of attack was predicted at high levels of turbulence intensity. However, although a turbulent free-stream may increase turbine power, the blades must be designed to withstand prevalent larger mean and fluctuating aerodynamic loads and thus cyclic stresses due to turbulence (Maldonado et al., 2015). In addition, Mycek et al. (2014) run experimental trials at two turbulent intensities, namely 3% and 15%, from which the wake remains pronounced. This corresponded to almost 20% velocity deficit and more than three times the upstream ambient turbulence intensity at lower turbulence intensity. While, at a higher turbulence intensity, the wake dissipated much faster.

There is no clear consensus on the effect of free-stream turbulence on wind turbine's aerodynamic performance induced by turbulence intensity as different trends have been reported in the literature. Ahmadi-Baloutaki et al. (2015) attributed these variations to different turbulent flow type studies by different researchers, complicated by varying amounts of wind shear and unsteady winds. To further understand the systematic performance of small wind turbines under controlled turbulent flow with steady and uniform wind conditions, Ahmadi-Baloutaki et al. (2015) attempted to investigate the influence of free-stream turbulence intensity on the aerodynamic performance of a Darrieus-type VAWT. A marginal increase in turbine power coefficient was predicted by increasing the turbulence intensity beyond 5% in the grid generated turbulent flows. In addition, the introduction of the external free-stream turbulence improved the self-starting capability of the vertical axis wind turbine. However, the turbine performance curves were limited to lower tip speed ratios ($\lambda < 1$) (Ahmadi-Baloutaki et al., 2015). Hence, for complete interpretation of the effect of free-stream turbulence on the wind turbine performance, there is need for extending the performance curves to tip speed ratios greater than one. In addition, generation of performance curves at greater tip speed ratios in turbulent flows still remains a challenge in research owing to limitations in wind tunnel experiments and safety considerations.

Therefore, the present study capitalizes on such aspects and employs an experimental method to investigate the influence of turbulence intensity on aerodynamic performance of a small-scale Savonius-type VAWT. A turbulence-generating mechanism has been used to generate the simplest form of turbulence. In addition, the general wind turbine model setup is discussed, and simulations using a CFD code are performed for comparison between experimental measurements and numerical data.

2. Experimental description

This section aims at giving a detailed description of the experimental setup, instrumentation, and measurement procedures used for the experiments.

2.1. The wind tunnel facility

The experiment of the VAWT model was performed in advanced wind tunnel and wave flume joint laboratory situated at Harbin Institute of Technology (HIT). The wind tunnel is a closed-loop circuit, which consists of double test sections: the small test section and the large test section. The small test section is 4.0 m (width) × 3.0 m (height) with a length of 25.0 m, and the large section is 6.0 m (width) × 3.6 m (height) with a length of 50.0 m. The turbine model tests in this study were performed in the small test section with optically transparent walls, with a background turbulence intensity of less than 0.46% at the end of the test section under normal operation. The flow with $I < 0.46\%$ in the present study is deemed 'no turbulence' or uniform flow. In addition, the wind tunnel has a characteristic of good flow field performance with test flow field inhomogeneity and mean flow angle of less than 1% and 0.5°, respectively. The maximum achievable velocities are 50 m/s and 30 m/s for the small and large empty working test sections, respectively. A wave trough is located under the large test section and separated by moving floors. The VAWT model is mounted on a fixed circular turntable 3.6 m in diameter at the center of the test section, 6 m downstream distance along the test section length; a schematic diagram of the facility is shown in Fig. 1.

Additional levels of free-stream turbulence ($9 \geq I \leq 14\%$) used in the experiments to simulate turbulent inflow conditions were generated using an active turbulence-generating wedge mechanism located at the end of the test section inlet. The turbulence levels were chosen to match the unsteady urban wind environment which is a representative of the prevailing wind characteristics of a target site in Kenya following a previous study by the authors in Wekesa et al. (2015). The turbulence-generating wedges were placed 16 m from the VAWT model along the 19 m upstream distance of the wind tunnel test section length. The active wedge mechanism consists of seven vertical elliptical shafts 0.5 m apart firmly fixed and spanning the height and width of the wind tunnel test section. Figs. 2(a) and (b), respectively, show a photograph of the active turbulence-generating mechanism and the VAWT model fixed on the test stand in a wind tunnel test section.

The flow field surrounding VAWTs is asymmetric, periodic, unsteady, separated and highly turbulent (Ahmadi-Baloutaki et al., 2015). Although wind tunnel tests provide benefit for controlled flow conditions, further sources of error due to the effect of blockage are introduced during the process. Therefore, characteristics of the flow would be altered to some extent if an obstruction is placed within the wind tunnel. The blockage ratio, BR, is defined as the ratio of the cross-sectional area of the rotor model to the maximum wind tunnel projected test section area: BR = rotor frontal area/test section area (Jeon et al., 2015). The frontal area of the present VAWT rotor as it spins is 0.49 m^2, resulting into a