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Study on power performance for straight-bladed vertical axis wind turbine by field and wind tunnel test

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ABSTRACT

In this paper, the power performance of straight-bladed VAWT is experimentally investigated by wind tunnel experiment and field test. The test rotor is two-bladed with NACA0021 airfoil profile. A survey of varying unsteady wind parameters is conducted to examine the effects of blade pitch angle, Reynolds number and wind velocity on the power performance of VAWT. Moreover, the flow field characteristics are obtained through measuring the wind velocity by Laser Doppler Velocimeter (LDV) system in the wind tunnel experiment and three-cup type anemometers in field test. Power and torque performance are obtained through a torque meter installed in rotor shaft of the wind turbine. Experimental results estimated from the measured values from field test and wind tunnel experiment are compared. In this research, power performance and flow field characteristics are discussed and the relationship between operating conditions and wind velocity are verified. These results provided a theoretical guiding significance to the development of VAWT simplified.

1. Introduction

There has been an increase of interest in small–scale wind turbines as energy sources in the built environment due to increased awareness of public in urban areas about global warming and their desire to reduce their carbon footprint. Such small scale wind turbines should be well suited within the urban landscape and Vertical Axis Wind Turbines (VAWTs) have shown the potentiality of fulfilling this requirement [1–4]. Blades of straight-bladed VAWT may be of uniform section and non-twisted, making them relatively easy to fabricate and extrude [1,5–7]. Furthermore, the transmission losses are reduced due to proximity to the demand center [6,8–10]. There is an urgent demand of this type of wind turbine with high efficiency and low cost in urban areas [6,9,11–13]. Therefore, the design research on straight-bladed VAWT has become one of the hot spots in recent wind power technology development.

In the past few decades, extensive research in the flow field characteristics and aerodynamic performance by numerical analysis or wind tunnel experimental have been conducted and great achievements have been acquired. For example, Raciti Castelli et al. [14] presented a CFD model for the evaluation of energy performance and aerodynamic forces acting on a straight-bladed vertical-axis Darrieus wind turbine. Torque and power curves were compared for the analyzed architectures, achieving a quantification of the effect of blade number on overall rotor performance. Their results were similar to investigations in Abu-El-Yazied T G. et al. [15], Wenehenubun F. et al. [16] and Roh S C. et al. [17]. Moreover, Tescione G. et al. [18] and Hofemann, C. et al. [19] aimed at understanding and quantifying the development of the near wake of a VAWT, with experimentally measuring by Particle Image Velocimetry the evolution of the tip vortices and immediately adjacent flow. It was known that the inboard movement of tip vortices is due to the curvature of the wake, and the deformation of the near wake as a function of azimuth angle and time. LI QA et al. focused on the velocity field around the straight-bladed VAWT experimentally measured by LDV technology and the pressures on the rotor blade surface were measured through the use of a multi-port pressure scanner in wind tunnel [20,21]. The authors found that the power extracted from the wind turbine mainly depended on the wind in

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Nomenclature

A	Cross-sectional area [m^2]
c	Blade chord length (=0.265) [m]
C_{power}	Power coefficient (=$Q\omega/(0.5\rho DHU_0^3)$)
D	Rotor diameter (=2.0) [m]
H	Height of rotor (=1.2) [m]
h	Hub height (=5.0) [m]
N	Number of blade (2)
P	Power output (W)
Q	Rotor torque [N•m]
R	Rotor radius (=1.0) [m]
Re	Reynolds number (=Wc/ν)
TI	Turbulence intensity
U_{ave}	Instantaneous averaged wind velocity in the wake during operation [m/s]
U'_{ave}	Instantaneous averaged wind velocity in the wake during standstill [m/s]
U'_N	Non-dimensional wind velocity in the wake
U_{wake}	Instantaneous wind velocity in the wake during operation [m/s]
U'_{wake}	Instantaneous wind velocity in the wake during standstill [m/s]
U_0	Mainstream wind velocity [m/s]
U_2	Instantaneous wind velocity measured by three cup-type anemometers in the positions of 2 [m/s]
U_3	Instantaneous wind velocity measured by three cup-type anemometers in the positions of 3 [m/s]
U_{10ave}	Averaged wind velocity in the wake at 10 min [m/s]
W	Resultant velocity to blade [m/s]
WD_{ave}	Averaged wind direction of ultrasonic anemometer A and B at one minute [deg]
WD_A	Averaged wind direction of ultrasonic anemometer A at one minute [deg]
WD_B	Averaged wind direction of ultrasonic anemometer B at one minute [deg]
x	Longitudinal coordinate [m]
y	Lateral coordinate [m]
z	Vertical coordinate [m]
α	Angle of attack [deg]
β	Blade pitch angle [deg]
θ	Azimuth angle [deg]
λ	Tip speed ratio (=$R\omega/U_0$)
ν	Kinematic viscosity [m^2/s]
ρ	Air density [kg/m^3]
ω	Angular velocity of rotor [rad/s]

upstream section. In addition, the reverse flow was generated at some locations of downstream region for the wind turbine with 4 and 5 blades. Elkhoury M. et al. [22] discussed the effects of incoming freestream velocity, turbulence intensity, fixed-pitch and variable-pitch mechanism, and airfoil shape on the power coefficient of the VAWT with experimental and numerical. As shown in this research, variable-pitch mechanism improved the performance of the VAWT and thicker symmetric airfoils performed better for high solidity VAWTs. In order to analyze the interaction between the turbine and the boundary layer flow and to understand how it influences the structure of the wake, Rolin V. et al. [23] examined the wake behind a VAWT in a turbulent boundary layer at low Reynolds numbers and a low tip speed ratio in wind tunnel experiment. The obtained results showed that the boundary layer effects may be responsible for the lower velocity deficit in the core of the wake. Furthermore, a similar research work was also performed in Chowdhury A M. et al. [24] by a comparative CFD analysis.

However, few researches have been carried out to explore the effects of tip speed ratio on the power performance and near-wake characteristic of VAWT in field test. Specifically, there have been few reports relevant to low tip speed ratio during rotation, because the flow field around VAWT rotor blade becomes so much complicated: as a result, the aerodynamic characteristics of the blades of a small straight-bladed VAWT become more difficult to understand and evaluate [13,21,25–27]. Therefore, it is a major challenge to analyze the aerodynamic characteristics of a small straight-bladed VAWT and study the wind velocity distribution in the near-wake of wind turbine operating at a low tip speed ratio [28].

As shown in Fig. 1, there is disturbed flow in the wake. In most cases, the best location for the meteorological mast will be upwind of the turbine in the direction from which valid wind is expected to come during the field test. In other cases, however, it may be more appropriate to place the mast alongside the turbine, as it is with a wind turbine on a ridge. The measurement sectors shall exclude directions having significant obstacles and other wind turbines, as

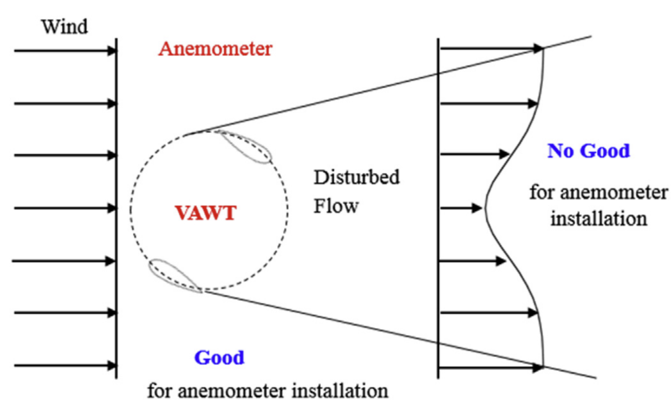

Fig. 1. Flow field characteristics in the wake for VAWT during rotation.

seen from both the wind turbine under test and the meteorological mast. For all neighboring wind turbines and obscles, the directions to be excluded due to wake effects shall be determined using the procedure. The disturbed sectors to be excluded due to the meteorological mast being in the wake of the wind turbine under experiment. To set the anemometer in the undisturbed flow region, wind velocity distribution of wake will be measured in this research. Furthermore, the power performance of straight-bladed VAWT is also investigated by field test and wind tunnel experiment.

The present paper is the first study to investigate the effects of wind velocity on the power performance of a straight-bladed VAWT by field test and wind tunnel test. The test wind turbine is two-bladed with blade sections composed from airfoil sections NACA0021. Firstly, the flow field characteristics are acquired through measuring the wind velocity distribution in the wind tunnel experiment. Furthermore, the effects of incoming freestream velocity and turbulence intensity on the power coefficient of the VAWT are investigated in field test. In addition, based on the wind speed data measured from three cup-type anemometers, the