Journal of Wind Engineering & Industrial Aerodynamics 180 (2018) 19–33

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Performance analysis of a small-scale Orthopter-type Vertical Axis Wind Turbine

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ARTICLE INFO

Keywords:
Orthopter-type Vertical Axis Wind Turbine
Solidity
Delayed detached eddy simulation

ABSTRACT

Orthopter-type Vertical Axis Wind Turbines (O-VAWT) are energy capturing devices which are suitable for micro-generation in urban areas. This paper aims to study the effect of number of blades (solidity), Aspect Ratio (AR), and wind speed on the performance of a small-scale O-VAWT using experimental and numerical techniques. Wind tunnel experiments were carried out to measure the torque of two-, three, and four-bladed turbine, each at a set of different wind speeds and blade aspect ratios. Increasing solidity was achieved by either decreasing the blade aspect ratio or increasing the number of blades, both resulting in a higher peak power coefficient ($C_{p,max}$) of the VAWT. The startup characteristics of the O-VAWT were also examined at different aspect ratios, and showed its capability to start-up even at low wind speeds. In addition, numerical simulations were carried out using an unsteady three-dimensional Delayed Detached Eddy Simulation (DDES) with Spalart Allmaras model. Numerical results of power coefficient were validated by comparison against available experimental data. Moreover, velocity and vorticity contours for the two-, three-, and four-bladed turbines, and pressure contours at different span-wise locations were thoroughly analyzed to link the flow field aerodynamics to relevant changes in power coefficient for different rotor solidities.

1. Introduction

Wind energy has been gaining more popularity as a reliable renewable energy source. Power harvesting has been relying on Horizontal- and Vertical-Axis Wind Turbines. Small-scale designs of the latter have been recently capturing considerable interest due to their capability of harvesting wind energy in all directions at a lower noise levels compared to the HAWTs, making them very suitable candidates for urban areas. In addition, micro-VAWTs are usually placed near obstacles such as buildings and trees, therefore causing unsteadiness in the wind inflow to the turbine. Wekesa et al. (2017) conducted a study on the energy content in unsteady winds and concluded that the highest frequency of wind fluctuations suitable for wind turbine applications is 1 Hz. In addition, numerical and experimental studies on the unsteady rotor performance have been investigated by various researchers (Wekesa et al., 2015, 2016; Danao et al., 2014).

VAWTs are divided into two main categories, Darrieus-type (D-VAWT), a lift based turbine, and Savonius-type (S-VAWT), which is a drag based turbine. Various configurations of Darrieus- and Savonius-type turbines have been recently investigated by researchers in an attempt to improve their performance. Jin et al. (2015) conducted a review on basic experimental and numerical research methods employed to assess the performance of Darrieus Vertical Axis Wind Turbines (D-VAWTs). Bhutta et al. (Aslam Bhutta et al., 2012) discussed the advantages and disadvantages of different VAWT configurations, including various techniques used to optimize their designs.

Rezaeiha et al. (2017a) investigated the effect of pitch angle as a potential way to enhance the performance of a VAWT. Computational Fluid Dynamics (CFD) results suggested that this parameter highly influences the load distribution between upwind and downwind halves of the turbine, thereby making dynamic pitching an encouraging approach to optimize the performance. Solidity is yet another important parameter that influences the turbine performance. However, limited studies were dedicated to investigating its effect on the power coefficient and aerodynamic characteristics of the VAWT. There is no clear evidence that the effect of solidity is similar for different VAWT types. In addition, solidity can be manipulated by altering the blade chord length, the blade number or the rotor radius, with no proof that changing any of these parameters will lead to analogous results.

Li et al. (2016) performed wind tunnel experiments to understand the

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https://doi.org/10.1016/j.jweia.2018.07.008
Received 11 April 2018; Received in revised form 3 July 2018; Accepted 9 July 2018

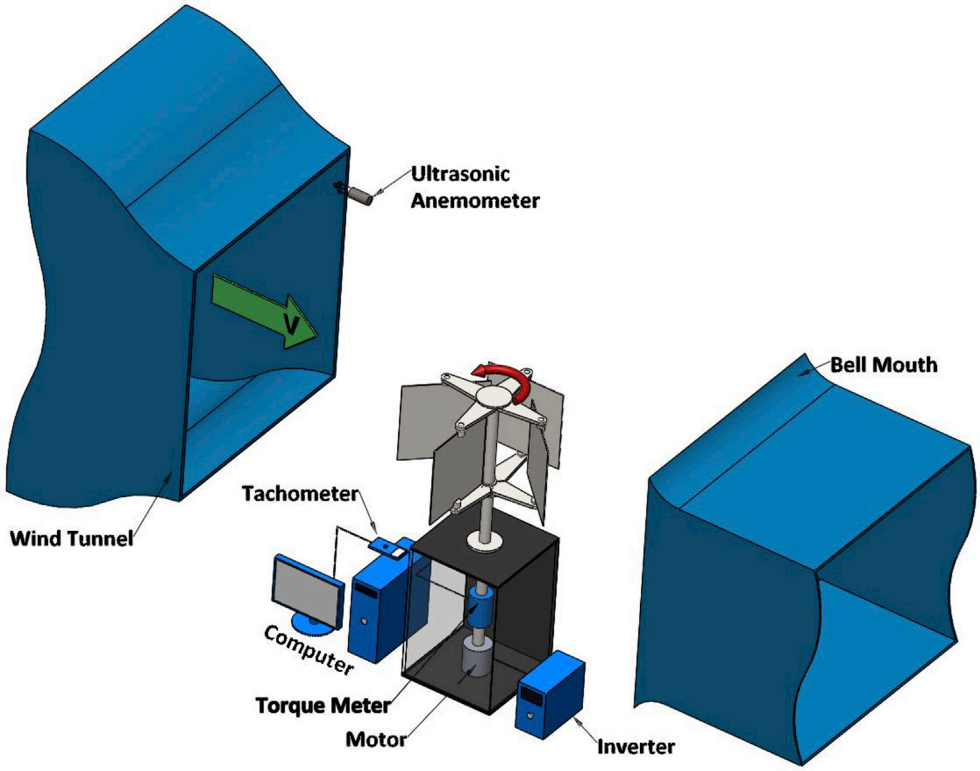

Fig. 1. Schematic diagram of the wind tunnel and the experimental apparatus.

effect of solidity at different number of blades on aerodynamic forces around a straight-bladed VAWT. It was concluded that power coefficient decreases when solidity increases, while torque coefficients increase. Similarly, Abu-El-Yazeid et al. (Abu-el-yazied et al., 2015) investigated the effect of number of blades on the performance of D-VAWT. It was found that the maximum power coefficient is obtained with the lowest number of blades (2 blades). However, decreasing the number of blades contributes to an increase in the radial cyclic aerodynamic forces, a structurally undesirable effect. Another numerical study aiming to reduce the torque variation by manipulating the number of blades on a D-VAWT was conducted by Raciti Castelli et al. (2012). Similar to the previously-mentioned findings by Abu-El-Yazeid et al. (Abu-el-yazied et al., 2015) and Li et al. (2016) an increase in number of blades causes a decrease in the radial component of the aerodynamic forces. Moreover, an increase in solidity is unfavorable since it results in reducing the power coefficient.

Previous results on the reduction in power coefficient at higher solidities are not in line with the findings of other researchers. Eboibi et al. (2016) conducted an experimental investigation of the influence of solidity on the performance of VAWTs. However, unlike previously mentioned studies, solidity was manipulated by altering the blade chord instead of blade number. Authors claimed that irrespective of the parameter altered, the effect of solidity on VAWT performance is similar. It is worth noting that since the chord length directly affects the Reynolds number, hence, the two designs were tested at different velocities to maintain similar Reynolds numbers. Increasing solidity did not affect the peak power output significantly. Nevertheless, the maximum power coefficient is attained at lower Tip Speed Ratio (TSR) for higher solidities. Cheng et al. (2017) studied the dynamics of floating straight-bladed VAWT with a number of blades ranging from two to four. The main advantage that was obtained by increasing the number of blades from 2 to 3 is in the reduction of the tower base bending moment, therefore reducing the fatigue damage. Further improvement by increasing the number of blades to 4 was not observed. Furthermore, increasing the chord length results in an increase in the power coefficient up to a maximum value after which it rapidly decreases. Delafin et al. (2016) conducted CFD simulations to understand the effect of number of blades and solidity on the performance of Ø-shape VAWT. The number of blades was increased from 2 to 4 while keeping the solidity constant with no observed benefit related to increasing power coefficient. Yet, it is desirable since it results in a decrease in torque, thrust and radial cyclic aerodynamic forces. Subramanian et al. (2017) investigated the effect of solidity on the power produced by two and three-bladed small-scale H-type D-VAWTs using three-dimensional CFD simulations. Results showed that the three-bladed configuration having a higher solidity performs better at low tip speed ratios (TSR) due to better interception of blades with wind. On the other hand, vortex-blade interaction at higher TSR reduces the power generation capability of the three-bladed VAWT thereby making lower solidity more favorable.

S-VAWTs are drag-driven devices that perform better than D-VAWTs at low wind speeds. Their solidity is usually altered by changing the number of arc-type blades used. Wenehenubun et al. (2015) conducted experiments on one, two, three and four-bladed S-VAWTs. It was concluded that the turbine with highest solidity performs best at lower TSR, but the three-bladed configuration outperforms it at higher TSR. On the contrary, experimental results of Mahmoud et al. (2012) showed a better performance for the two-bladed configuration at all TSR. Mao et al. (Lee et al., 2016) investigated the effect of blade arc angle on the performance of S-VAWT, and concluded that arc angle of 160° produced the highest power coefficient for the studied VAWT configuration.

Unlike D-VAWT and S-VAWTs, Orthepter-type vertical axis wind turbine (O-VAWT) have received very few consideration. In addition, studies focusing on improving their performance are insufficient. Bayeul-Laine et al. (Annie-Claude et al., 2010) confirmed that this type of turbines performs better than classical VAWTs for some specific blade stagger. Two blade shapes (elliptical and straight) were examined with no clear conclusions about a favorable shape could be drawn since the performance is highly dependent on the TSR range. Cooper and Kennedy (Cooper et al., 2004) tested a symmetric-blade O-VAWT design and obtained a maximum power coefficient of 0.25 with a high startup torque,