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Effect of Solidity on Aerodynamic Performance of Vertical Axis Wind Turbines

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Abstract

Vertical axis wind turbines (VAWTs) are promising for wind energy harvesting in the urban environment mainly because of their omnidirectional capability. However, currently their aerodynamic performance is not comparable with horizontal axis wind turbines (HAWTs). Therefore, to make them an ideal candidate, they need to be further improved. The aerodynamic performance of VAWTs depends on several geometrical parameters, such as solidity. However, the impact of solidity on blade aerodynamics and turbine wake has not yet been comprehensively investigated. Therefore, the current study intends to systematically study the effect of solidity on aerodynamic performance of VAWTs with different number of blades operating at various tip speed ratios to provide a deeper insight into its impact on dynamic loads on blades, turbine performance and wake. High-fidelity unsteady Reynolds-averaged Navier-Stokes (URANS) simulations extensively validated with experimental data are employed. The results show that for fixed-rotational-speed urban VAWTs, which frequently operate at high tip speed ratios, a low solidity value is more favorable. On the other hand, an optimal VAWT is a high-solidity variable-rotational-speed (fixed λ) rotor operating at a low tip speed ratio regime.

1 Introduction

Vertical axis wind turbines have recently received growing interest for wind energy harvesting in the urban environment mainly due to their omni-directional capability (Hui et al., 2018; Miller et al., 2018; Rezaeih, Kalkman, & Blocken, 2017b; Rezaeih, Kalkman, Montazeri, et al., 2017; Rezaeih et al., 2018a). However, their aerodynamic performance is currently lower than HAWTs and they require performance improvement (Rezaeih, Pereira, et al., 2017). Solidity (defined as σ = nc/d, where d is turbine diameter, n number of blades and c blade chord length) is an important geometrical parameter, which significantly affects the aerodynamic performance of VAWTs. An optimal rotor design (i.e. optimal σ) will maximize the output power. However, the optimal σ is highly dependent on the operating conditions, i.e. tip speed ratio λ. The impact of σ has been numerically and experimentally studied (Eboibi et al., 2016; Li et al., 2016; Rezaeih et al., 2018c, 2019c). However, to the best of our knowledge, (i) the studied range of σ was very limited, (ii) the dependency of σ on λ was not well addressed, and (iii) the focus was mainly on the average turbine performance rather than detailed analyses of blade aerodynamics and turbine wake. Therefore, the current study intends to address these gaps to support optimal design of VAWTs. High-fidelity CFD simulations extensively validated with experimental data are employed.

2 Computational settings and parameters

H-type VAWTs with the symmetric NACA0018 airfoil, d = 1 m, n = 2-4, c = 2.25-18 cm, and σ = 0.09-0.36 are studied. The freestream velocity is 9.3-18.6 m/s. The turbine rotational velocity is 46.5-102.3 rad/s corresponding to λ = 2.5-5.5. Chord-based Reynolds number is 0.77×10⁵ – 6.4×10⁵. The approach-flow and incident-flow total turbulence intensities are 5% and 4.42%, respectively. The turbulent length scale is 1 m. The two-dimensional computational domain is 35d × 20d. The distance from the turbine center to domain inlet and outlet are 10d and 25d. The blockage ratio (d/W) is 5 %. The computational grid consists of approximately 400,000 quadrilateral cells with a maximum and average y⁺ value of 3.8 and 1.4, respectively. The boundary conditions are uniform velocity inlet, zero gauge pressure outlet, symmetry sides, no-slip walls and sliding grid interface for the rotating grid. Incompressible URANS simulations are performed using ANSYS Fluent 16.1 with the 4-equation transition SST turbulence model, due to the transitional nature of the flow (Langtry et al., 2006; Menter et al., 2006; Rezaeih et al., 2019a, 2019b).
order discretization in time and space and SIMPLE scheme for pressure-velocity coupling are employed. The transient simulations are performed with azimuthal increment of 0.1° for 20 revolutions of the turbine to ensure the results have reached a statistically steady state condition. The results are sampled at the 21st turbine revolution. Extensive solution verification and validation are presented in Ref. (Rezaeiha, Kalkman, & Blocken, 2017a; Rezaeiha et al., 2018b).

3 Results and conclusions

Fig. 1 shows the power coefficient versus λ and σ for a 2-bladed VAWT. Fig. 1a reveals that a low-solidity VAWT will operate optimally at high λ while a high-solidity VAWT is optimum at low λ. The optimal λ decreases by increasing σ. This implies that a fixed-rotational-speed VAWT (i.e. the dominant design) is operating sub-optimally under the majority of operating conditions. In addition, for an urban VAWT, which most frequently operates at high λ regime due to low mean wind speed in the urban environment, a low solidity is favorable. Note that for fixed-rotational-speed urban VAWTs, high λ is unavoidable because, given their small size, they are preferred to rotate relatively fast to keep a sufficiently high Re (>10^5) and avoid the unwanted consequences of operating at low Re regime, i.e. large laminar separation bubble on blade and the consequent load fluctuations. Fig. 1b shows that the optimal σ decreases by increasing λ. In addition, the value of C_P delivered at the optimal σ slightly decreases for higher λ. This implies that, from an aerodynamic point of view, an optimal VAWT is a variable-rotational-speed rotor (fixed λ) with high solidity operating at a low λ regime. For the case of small-size urban VAWTs, the high solidity (high c) will help to keep Re in the desired regime. Fig.1c exhibits turbine C_P in λ-σ space which can serve as a design guide for VAWTs for different operating conditions. Further and more detailed results and discussion for the 2-, 3- and 4-bladed VAWTs will be presented in the full paper.

The conclusions of this study are: (i) low solidity is favorable for fixed-rotational-speed urban VAWTs due to their inevitable high tip speed ratio, (ii) solidity of fixed-rotational-speed VAWTs needs to be selected with special attention to the wind conditions of potential installation sites and (iii) the optimal design for VAWTs needs to include variable rotational speed, high solidity and low tip speed ratio. The results of this study can help to design optimum VAWTs and more widespread wind energy harvesting.

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