Eleventh International Conference on Computational Fluid Dynamics (ICCFD11), Hawaii, USA, July 11-15, 2022

ICCFD11-2022-3402

Analysis on the flow over a vertical-axis wind turbine with varying tip-speed ratio and solidity

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Abstract: We investigate the flow around a vertical-axis wind turbine (VAWT) using large eddy simulation, and explore a quantitative relationship between the flow structures and key parameters that influence the turbine performance. We consider multi-bladed VAWTs for various tip-speed ratios. The dominant flow phenomenon with VAWTs is the dynamic stall which is closely connected to the evolution of the leading-edge vortex (LEV) with the blade rotation. The formation and evolution of the LEV are strongly affected by both the tip-speed ratio and turbine solidity. Observing the LEV developments for various tip-speed ratios and solidities, we suggest a modified tip-speed ratio with which the flow characteristics around VAWTs are better represented.

Keywords: Vertical-axis wind turbine, Tip-speed ratio, Solidity.

1 Introduction

In recent years, vertical-axis wind turbines have received increasing interests since it was reported that the power density (power extracted per unit land area) of a VAWT wind farm was higher than that of horizontal-axis wind turbines (HAWTs) [1]. Hence, the researches on VAWTs have focused on the wake and momentum recovery downstream of a VAWT [2, 3]. In contrast, the flow characteristics around the blades of the VAWTs and their influence on the power generation have not been fully examined. In the present study, we investigate the flow characteristics around the blade of a VAWT with varying tip-speed ratio and solidity.

2 Numerical Details

Fig. 1 shows the schematic diagram of the computation domain and boundary conditions, and the geometry of a VAWT used in this simulation. The geometry of a VAWT is the same as that in the experimental work [2], but the struts and rotating tower are not included. We adopt a periodic boundary condition along the spanwise direction (i.e. along the vertical axis). The Reynolds number is $Re_D = 80,000$ based on the free-stream velocity (U_0) and rotor diameter (D). The non-dimensional parameters used for characterizing the VAWT aerodynamic performance are the tip-speed ratio ($\lambda = R\Omega/U_0$) and turbine solidity ($\sigma = nc/(\pi D)$), where $R\,(= D/2)$ and Ω are the radius and rotation rate of the turbine, respectively, n is the number of blades, and c is the blade chord length. Various tip-speed ratios of 0.5 - 2.4 from 0.5 to 2.4 are considered and solidity is varied by changing the number of blades from 2 to 5.

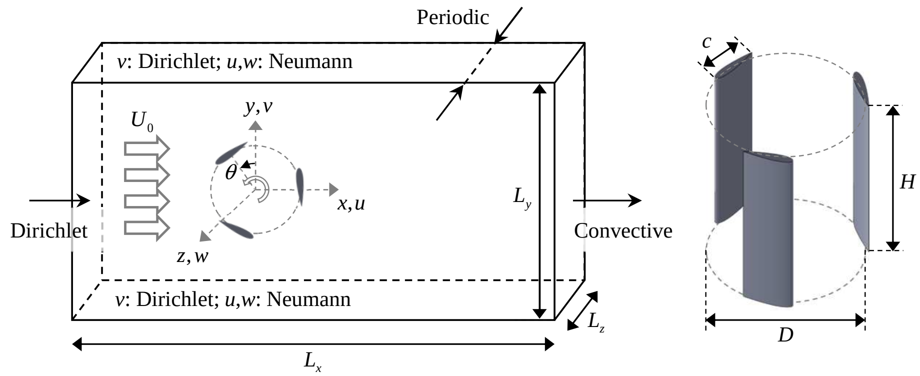

Figure 1: Schematic diagram of the computational domain and boundary conditions, and the geometry of a VAWT.

We solve the spatially filtered Navier-Stokes and continuity equations using a large eddy simulation with a dynamic global subgrid-scale model [4]. An immersed boundary method [5] is used to satisfy the no-slip condition on a VAWT. A second-order implicit fractional-step method [6] with linearization [7] and the second-order central difference method are used.

3 Results and Discussion

As the blade of a VAWT rotates, the flow separates from the trailing edge at the inner surface of the blade and the separation point moves toward the leading edge. Then, a strong leading-edge vortex (LEV) develops. Here, θ is the azimuth angle of the blade and $\theta = 0°$ is the position where the blade directly faces the inflow. We define $\theta_{\max}$ at which the phase-averaged power coefficient is maximum. We observe that the formation of the LEV begins when the blade passes through $\theta = \theta_{\max}$.

We compare the flow around the VAWT blades of different λ's and σ's. Similar values of $\theta_{\max}$ and flow phenomena around the blades are observed at different combinations of λ and σ as shown in Fig. 2. Based on this observation, we suggest a modified tip-speed ratio, $\lambda' = \frac{\lambda}{\pi(1-\sigma)}$, to identify the flow characteristics at different λ's and σ's.

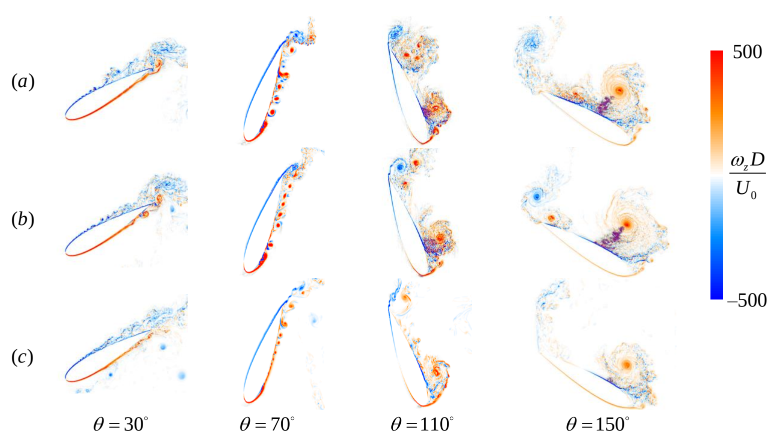

Figure 2: Contours of the instantaneous spanwise vorticity for different numbers of blades (solidities) and tip-speed ratios: (a) $n = 2$, $\lambda = 1.2$; (b) $n = 3$, $\lambda = 1.0$; (a) $n = 5$, $\lambda = 0.8$.

Acknowledgements

This work was supported by the National Research Foundation through the Ministry of Science and ICT (2016R1E1A1A02921549). We also grateful to the KISTI Supercomputing Center for providing supercomputing resources and technical support (KSC-2018-CHA-0030).

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