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A Comparative study on the aeromechanic performances of upwind and downwind horizontal-axis wind turbines

Zhenyu Wang[1], Wei Tian, Hui Hu*

Department of Aerospace Engineering, Iowa State University, Ames, IA 50011, USA

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ABSTRACT

Traditional horizontal-axis wind turbines are mainly designed as upwind configuration. In order to avoid blade strikes, the rotor blades have to be positioned far enough away from the turbine tower and have to be designed as inflexible as possible. In addition, a complicated yaw control system is required to keep the turbine rotor facing the incoming wind. Due to these drawbacks, the turbine in downwind configuration is proposed to overcome these disadvantages because, first of all, rotor blades can be designed more flexible since there is no danger of blade strikes, and secondly, yaw control system could be eliminated if nacelle is designed appropriately to follow the incoming wind direction passively. In the present study, a comparative experimental investigation was conducted to quantify the aeromechanic performance of a downwind turbine (DWT), in comparison to that of a traditional upwind turbine (UWT). The thrust coefficient of the DWT model was found to be increased slightly in the time-averaged quantity, but have a significant augment in the fluctuations. Due to the shadow effect, the power outputs of the DWT model was found to be decreased by 3.2% when they were operated in a same atmospheric boundary layer (ABL) wind. In addition, a high-resolution particle image velocimetry (PIV) system was employed to characterize the ensemble-averaged and phase-locked wake flow structures to quantify the turbulent flow characteristics in the turbine wakes. The velocity deficit in the lower half turbine wake for the UWT case was found to be greater than that of the DWT case at the location of $X/D < 1.0$. The higher wind load fluctuations for the DWT system were found to be correlated well with the higher TKE distributions in the turbine wakes. The phase-locked PIV measurements illustrated that the wake regions can be divided into four zones, which are dominated by the vortices shedding from different turbine components. The detailed flow field measurements were correlated with the dynamic force and power measurement data to elucidate the underlying physics.

1. Introduction

Wind energy is one of the primary renewable and clean energy sources. Wind turbines are the most common system to convert the kinetic energy from wind into electrical energy. As we know that, wind turbines can be generally divided into two configurations: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). HAWT is usually more efficient and has a longer lifetime than VAWT configuration [1]. Therefore, vast majority of the large-scale wind turbines are applied as horizontal-axis designs. Traditional utility-scale HAWTs have one singular rotor with three rotating blades, and most of them are mounted in front of turbine tower. This upwind configuration is mainly for the consideration of aerodynamic performance, for instance, to reduce the tower shadow effect [2–4], etc. However, the disadvantages of this design are also prominent. Take the rotor blades as an example, the rotor has to be positioned far enough away from the turbine tower to avoid blade strike. Therefore, these rotor blades have to be designed as inflexible as possible to avert such problems, especially for the blades employed in MW-class wind turbines. As a result, this requirement would greatly increase the blade manufacturing cost. It is massive especially compared with the numerous turbines (By the end of 2016, the global cumulative installed wind power capacity expanded to 486,749 MW) [5] installed in large-scale onshore and offshore wind farms. In order to avoid blade strike occurring in the operation, people usually tilt the rotors (e.g., 2.5–8°) slightly to keep them away from turbine towers [2,3,6,7], but which would reduce the power generation in comparison to those turbines with zero tilt angle [8]. In addition, upwind wind turbines require a complicated yaw control system to keep the turbine rotor facing the incoming wind [9]. With the concerns of these drawbacks, the downwind configuration was

* Corresponding author.
E-mail address: huhui@iastate.edu (H. Hu).
[1] Current address: Simulation Innovation and Modeling Center (SIMCenter), The Ohio State University, Columbus, OH 43210, USA.

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Nomenclature

A	area of blade rotational disk [m^2]
C_P	power coefficient [–]
C_T	thrust coefficient [–]
D	diameter of turbine rotor [m]
H	turbine hub height [m]
I_u	turbulence intensity [–]
P	power output [W]
Re_D	Reynolds number based on rotor diameter [–]
TKE	turbulent kinetic energy [m^2/s^2]
TSR	tip-speed-ratio [–]
U_H	freestream velocity at turbine hub height [m/s]
α	power law exponent [–]
σ_u	root-mean-square of the turbulent velocity fluctuation [m/s]
η	efficiency of DC generator [–]
θ	blade phase angle [°]
ω_y	vorticity (out of plane) [1/s]

proposed to overcome these disadvantages existing in the upwind design [4]. As we know that, the rotor in the downwind configuration is installed behind turbine tower, which means the rotor blades can be designed more flexible since there is no danger of blade strikes. This could largely reduce the manufacturing cost and lower the weight of rotor blades, potentially resulting in a 15–20% reduction in turbine capital cost [10]. In addition, if nacelle can be appropriately designed to follow the incoming wind direction passively, there is no need to use a yaw control mechanism in the wind turbine system.

In comparison to a large amount of studies conducted to investigate the flow performance on traditional upwind HAWTs [11–15], relatively little attention is paid on the downwind design for commercial application possibly due to the concern of shadow effect. Because people found shadow effect would reduce the total power coefficient and increase turbulence and fatigue on wind turbines [2]. As a result, very few literatures on investigating downwind turbines can be found in the past several decades and the corresponding flow characteristics are still not quite clear. Therein, most of them were studied by computational methods. Janajreh et al. [16,17] numerically investigated the rotor-tower interaction of downwind turbine configuration. They found that the aerofoil shape tower has a lower resulting aerodynamic force on rotating blades and a reduced rotor wake in comparison to those in the circular tower case. However, these advantages would be diminished under highly-turbulent flows. Zhao et al. [9] used a high-fidelity CFD code U^{2}NCLE to compare two-bladed and three-bladed upwind and downwind turbines, respectively. They stated that the unsteady aerodynamic loads are higher in the downwind turbine than those in the upwind turbines, but the impact of rotor orientations (i.e., upwind or downwind) are smaller than that caused by the blade number and the rotating speed. Zhou and Wan [18] also observed that the rotor-tower interaction in downwind turbines would cause a larger thrust reduction when the rotating blades approaching turbine tower. Given that a higher flow incidence across the rotational disk and a higher axial velocity in the outboard portion of rotor blades, Frau et al. [7] found a 3% enhancement of power coefficient in the downwind configuration. However, the drawback is that the loadings on rotor blades are 14% higher than that in the upwind design. In contrast with the numerical studies on the downwind turbines, Kress et al. [6] conducted an experimental investigation to understand the unsteady torque characteristics with different rotor cone angles. They observed that the unsteadiness of rotor torque for the downwind configurations is about 38–68% higher than the values in the corresponding upwind designs, which is similar with the results shown in the aforementioned computational studies. Larwood and Chow [19]confirmed this finding through a wind tunnel study on a downwind NREL Phase VI wind turbine. However, the fatigue loads can be significantly mitigated if an aerodynamic shroud that aligned with the incoming wind direction, is amended on the turbine tower. They also stated that the downwind coning could essentially reduce the average loads for blade flap-bending, which shows a great benefit in applying the downwind design for large-scale wind turbines. Furthermore, Kress et al. [20] found the downwind rotor configuration is more suitable for yaw stability with a given wind condition, which could be easier to control turbine rotors and produce more power from the same incoming airflow.

According to the aforementioned studies, the flow characteristics of downwind rotor design, such as the rotor-tower interaction, are not fully understood because the shortage of detailed investigations. As a result, the aim of the present study is to provide a comprehensive experimental study on the flow performance of a traditional upwind turbine (UWT) and a downwind turbine (DWT). The instantaneous wind loads acting on both wind turbines were measured to quantify the fatigue analysis. The detailed velocity distributions were obtained by a planar particle image velocimetry (PIV) measurement, under the same incoming flow condition. The measured velocity and vorticity distributions were used to characterize the turbine wake characteristics and evolutions of the unsteady blade tip and root vortices. The power outputs of the model wind turbines were also measured to quantify the influence of upwind and downwind configurations in power generation.

2. Experimental setup and wind turbine models

2.1. Wind tunnel

The experimental study was conducted in a large-scale Atmospheric Boundary Layer (ABL) wind tunnel with the dimension of 20.0 m × 2.4 m × 2.3 m in the test section [21]. It is a closed-circuit wind tunnel with the capacity of generating a maximum ABL wind speed of 45 m/s and the side walls in the test section are transparent. Fig. 1 shows the wind tunnel test section and a conventional upwind HAWT model is mounted at the center of the ground. A series of aluminum chain arrays, which are perpendicular to the flow direction (i.e., *x*-direction) and with an equal spacing of 15-inch, are placed in the test section in order to generate an incoming airflow with an ABL profile usually seen in offshore wind farms. The wind tunnel ceiling can be adjusted to ensure the boundary layer growth under approximately zero pressure gradient in the streamwise direction. Further information of this wind tunnel in generating ABL wind profiles can be found in the

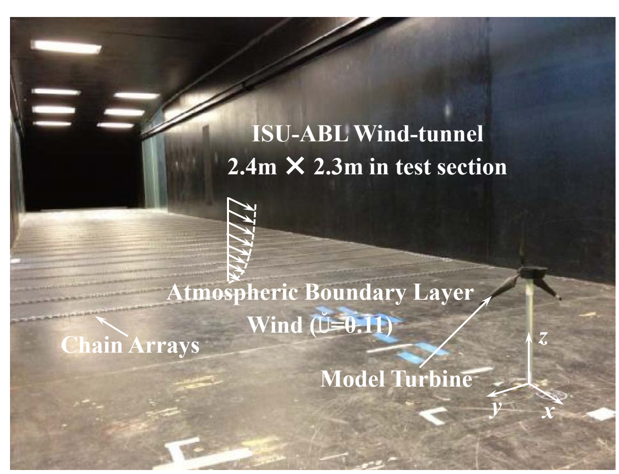

Fig. 1. The HAWT model and the test section of wind tunnel.