Effects of incoming surface wind conditions on the wake characteristics and dynamic wind loads acting on a wind turbine model

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An experimental investigation was conducted to examine the effects of incoming surface wind conditions on the wake characteristics and dynamic wind loads acting on a wind turbine model. The experimental study was performed in a large-scale wind tunnel with a scaled three-blade Horizontal Axial Wind Turbine model placed in two different types of Atmospheric Boundary Layer (ABL) winds with distinct mean and turbulence characteristics. In addition to measuring dynamic wind loads acting on the model turbine by using a force-moment sensor, a high-resolution Particle Image Velocimetry system was used to achieve detailed flow field measurements to characterize the turbulent wake flows behind the model turbine. The measurement results reveal clearly that the discrepancies in the incoming surface winds would affect the wake characteristics and dynamic wind loads acting on the model turbine dramatically. The dynamic wind loads acting on the model turbine were found to fluctuate much more significantly, thereby, much larger fatigue loads, for the case with the wind turbine model sited in the incoming ABL wind with higher turbulence intensity levels. The turbulent kinetic energy and Reynolds stress levels in the wake behind the model turbine were also found to be significantly higher for the high turbulence inflow case, in comparison to those of the low turbulence inflow case. The flow characteristics in the turbine wake were found to be dominated by the formation, shedding, and breakdown of various unsteady wake vortices. In comparison with the case with relatively low turbulence intensities in the incoming ABL wind, much more turbulent and randomly shedding, faster dissipation, and earlier breakdown of the wake vortices were observed for the high turbulence inflow case, which would promote the vertical transport of kinetic energy by entraining more high-speed airflow from above to re-charge the wake flow and result in a much faster recovery of the velocity deficits in the turbine wake. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4904375]

I. INTRODUCTION

Wind energy, as a renewable energy source, has been playing an increasingly important role in worldwide energy production portfolio in recent years. Nowadays, with rapid development of wind energy, wind turbines sited in wind farms would operate under many different terrain conditions, ranging from rather flat sites such as open ocean terrain for offshore wind farms to complex hilly terrains for onshore wind farms.

There are vast discrepancies in the flow characteristics for the incoming atmospheric boundary layer (ABL) winds over typical onshore and offshore wind farms. While the near neutral ABL
winds over offshore wind farms on relatively flat ocean surfaces are found to have relatively low ambient turbulence, the ABL winds over onshore wind farms have much higher ambient turbulence levels due to the effects of complex terrain topography, various roughness on the ground (e.g., buildings, trees, and plants), and the significant variations between highly convective daytime conditions and highly stable nocturnal conditions. As a result, the wind turbines sited in onshore wind farms would see quite different surface wind characteristics (i.e., different mean wind speed profiles with much higher turbulence levels) in comparison with those in offshore wind farms.

A number of studies have been conducted in recent years to reveal the effects of the turbulence intensity levels of the incoming surface winds on the aeromechanics performances of wind turbines as well as the characteristics of the wake flows behind the wind turbines. For example, Sheinman and Rosen1 reported that the over-estimation of turbine power output could be more than 10% if ignoring the effects of turbulence in the incoming flow. Lebron et al.2 studied the fluxes of kinetic energy on a wind turbine streamtube including the effects of turbulence. Their analysis results confirm that turbulence plays a central role in the energetics of a wind turbine streamtube. Chamorro and Porte-Agel3 showed that the effects of boundary layer turbulence on the velocity deficit and added turbulence intensity in the far wake behind a wind turbine model are not negligible even at a downwind distance of 15 times the rotor diameter. More recently, Ozbay et al.4 studied the effects of the turbulence intensity levels of the incoming airflows on the wake interferences among multiple wind turbines with different wind farm layouts. They reported that, with the same staggered wind farm configuration, the incoming surface flow with higher turbulence levels, corresponding to onshore wind farm case, would enhance the total power output of the wind farm by 6%, in comparison with the offshore wind farm case.

As described in the review article of Vermeer et al.,5 the wake behind a wind turbine is typically divided into a near wake and a far wake. In the near wake, the presence of the rotor is apparent by the number of blades, blade aerodynamics such as attached or stalled flows, 3-D effects, and tip vortices. Whale et al.,6 Grant and Parkin,7 and Massouh and Dobrev8 conducted experimental studies to investigate the flow structures in the near wakes of model turbines in airflows or water flows with uniform incoming flow velocity. Chamorro et al.5 and Yang et al.9 studied the evolution of the unsteady vortex and turbulent flow structures in the near wakes of wind turbines placed in nonhomogeneous ABL flows with rather high turbulence intensity levels. The findings reported in those previous studies reveal clearly that the turbine wake characteristics with the wind turbines placed in uniform incoming flows were found to be substantially different from those turbines sited in nonhomogeneous ABL flows with strong vertical velocity gradients and high turbulence intensity levels in the incoming flows.

As described in Massouh and Dobrev,8 the shedding of unsteady wake vortices in the near turbine wakes has been suggested as one of the important sources to induce turbine blade vibration, which is highly associated with the dynamic wind loads acting on the wind turbines. So far, the characteristics of dynamic wind loads acting on wind turbines are mainly obtained from field measurements of large-scale wind turbines. Based on analyzing the blade surface pressure distributions and local incoming flow data, Schreck and Robinson10 characterized two key dynamic stall processes for wind turbines: vortex initiation and vortex convection. In the study of Robinson et al.,11 blade surface pressure data were analyzed to characterize the impacts of three-dimensionality, unsteadiness, and flow separation effects observed to occur on downstream wind turbines. In addition, a number of numerical approaches have been implemented in order to predict the dynamic responses of wind turbines. For example, Moriarty et al.12 generated multiple samples of wind loading data under various wind conditions by using a stochastic turbulence simulator coupled with an aeroelastic code. More recently, Lee et al.13 used a two-way coupled aeroelastic tool with large eddy simulation (LES) to investigate the atmospheric and wake turbulence impacts on wind turbines.

Wind tunnel facilities have been widely used to study aeromechanics of wind turbines due to their capabilities to produce well-controlled flow conditions. Chamorro and Porte-Agel1,15 performed wind tunnel studies to investigate the effects of boundary layer turbulence as well as thermal stability on the wake of a single wind turbine sited in a boundary layer flow. The turbulence properties inside and above the aligned and staggered wind farms consisted by model wind turbines
were also systemically investigated by Chamorro and Porte-Agel.\textsuperscript{9,16} Lebron et al.\textsuperscript{17} conducted an experimental study on the interaction between a wind turbine array and turbulent boundary layer with the main objective of collecting velocity data in sufficient detail to address questions such as the mechanisms for kinetic energy entrainment into the wind turbine array field. Cal et al.\textsuperscript{18} carried out an experimental study of the horizontally averaged flow structure in a boundary layer flow including a $3 \times 3$ array of model wind turbines in order to understand the vertical transport of momentum and kinetic energy across a boundary layer flow with wind turbines. The attentions of these studies focused on wake models, wake interference, and turbulence models for far wake flows. More recently, Hu et al.\textsuperscript{19} conducted a comprehensive experimental study to quantify the dynamic wind loads and wake characteristics of a wind turbine model in an ABL wind. Zhang et al.\textsuperscript{20} reported the detailed turbulent structures in the near wake of a wind turbine, including the characterization of the wake rotation effects and coherent tip vortex shedding.

In the present study, an experimental study is conducted to investigate the effects of the incoming flow conditions on the turbine wake characteristics and dynamic wind loads acting on a same model wind turbine placed in two types of ABL winds with distinct mean and turbulence characteristics to simulate the scenario with a same wind turbine sited in a typical onshore wind farm in comparison with that in a typical offshore wind farm. In addition to measuring dynamic wind loads acting on the model turbine, a high-resolution Particle Image Velocity (PIV) system is used to conduct detailed flow field measurements to quantify the turbine wake characteristics as well as the dependence of wake vortices on the rotation of the rotor blades with the model turbine sited in different non-homogenous incoming surface winds. The detailed flow field measurements are correlated with the dynamic wind load data in order to gain further insight into the underlying physics for the optimal design of wind turbines operating in different ABL winds.

\section*{II. EXPERIMENTAL SETUP AND PROCEDURE}

The experimental study was performed in the Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel located at the Aerospace Engineering Department of Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a test section 20 m long, 2.4 m wide, and 2.3 m high. It has a capacity of generating a maximum wind speed of 45 m/s in the test section. Figure 1 shows a picture of the test section of the AABL tunnel with triangular spires and arrays of wooden blocks on the wind tunnel floor to simulate the surface flow conditions similar to those in ABL winds over typical onshore and offshore wind farms. Similar as those used by Irwin,\textsuperscript{21} Sill,\textsuperscript{22} and Jia et al.\textsuperscript{23} in their wind tunnel experiments to generate environmental boundary layer winds, five isosceles triangle shaped spires, which are equally distributed at the inlet of the test section of the AABL tunnel, were used in the present study to generate a mean velocity shear profile of the
incoming airflow in the test section. As shown in Fig. 1, a wooden plate with the height of 200 mm and thickness of 12.7 mm was mounted on the wind tunnel floor to connect to the five spires. In the present study, the spires with aspect ratios of 0.12 and 0.16 were used to generate two ABL winds with different velocity and turbulence intensity gradients. Surface roughness elements with different size and spacing were also mounted on the wind tunnel floor to generate different levels of turbulence intensity of the incoming ABL winds. By using different combinations of the roughness elements and triangle shaped spires, different ABL winds with distinct mean and turbulence characteristics can be generated in the AABL tunnel. The tunnel ceiling, which is flexible, was adjusted along the length to accommodate the boundary layer blockage to ensure a zero pressure gradient along the flow direction.

As described in Zhou and Kareem and Jain, the mean velocity profile of an ABL wind over an open terrain can usually be fitted well by using a power function. Different power-law exponents represent different types of winds over different terrains. Figure 2 gives the measured mean flow velocity and turbulence intensity profiles of the two different ABL winds generated in AABL wind tunnel for the present study. The measurement data were obtained by using a Cobra Probe Anemometry system (TFI Series 100 of Turbulent Flow Instrumentation Pty Ltd.) in the tunnel test section at the location where the model wind turbine would be mounted.

As shown in Fig. 2(a), the power-law exponent for the first type of ABL wind is about 0.11, which can be used to represent the ABL wind over offshore (open sea) terrain according to American Society of Civil Engineers (ASCE) standard. The corresponding turbulence intensity shown in Fig. 2(b) at the turbine hub height (\(Z/H = 1\)) was found to be about 9.5% for the Type-1 ABL wind (i.e., low turbulence inflow case), which is in the range of the turbulence intensity levels measured over Horns Rev offshore wind farm as reported in Hansen et al. Here, the turbulence intensity is calculated by using the expression of \(I_u = \sigma_u/U_{\text{local}}\), where \(\sigma_u\) is the root-mean-square of the turbulent velocity fluctuations, and \(U_{\text{local}}\) is the mean wind speed at the measurement point. For the second type of the ABL wind, the power-law exponent of the mean velocity profile was found to be about 0.16, which is used to represent the ABL wind over the terrain of open country with low scrub or scattered trees (e.g., the onshore wind farms in Midwest region of the USA). The turbulence intensity levels for the Type-2 ABL wind as a function of the height above the tunnel floor is also given in Fig. 2(b). The standard turbulence intensity profile of the ABL wind over an open terrain on land suggested by Architectural Institute of Japan (AIJ) was also plotted in the graph for comparison. It can be seen clearly that, the turbulence intensity levels of the Type-2 ABL wind (i.e., high turbulence inflow case) used in the present study is in a fairly good agreement with the AIJ standard.

![Flow characteristics of the two different incoming ABL winds used in the present study: (a) mean streamwise velocity profiles and (b) turbulence intensity profiles.](image-url)
The schematic of the wind turbine model used in the present study.

with the AIJ standard values for ABL over open terrain on land. It should also be noted that the turbulence intensity level at the turbine hub height for the Type-2 ABL wind is about 18.0%, which is almost twice as high as that of the Type-1 ABL wind.

The model wind turbine of the present study represents the most commonly used three-blade horizontal axial wind turbines (HAWTs) seen in modern wind farms. Figure 3 shows a schematic of the model wind turbine along with typical cross section profiles of the turbine rotor blades. The model turbine has a rotor radius of 140 mm and hub height of 225 mm. With the scale ratio of 1:320, the model turbine would represent 2 MW wind turbines commonly seen in modern wind farms with a rotor diameter of about 90 m and a tower height of about 80 m. The rotor blades of the model turbine are made of a hard plastic material by using a rapid prototyping machine. The rotor blades have the same airfoil cross sections and platform profiles as ERS-100 prototype turbine blades developed by TPI Composites, Inc. As shown in Fig. 3, the rotor blade has a constant circular cross section from the blade root to 5% blade radius ($R$), and three NREL airfoil profiles (S819, S820, S821) are used at different spanwise locations along the rotor blade. The S821 airfoil profile is used between 0.208$R$ and 0.40$R$, the S819 primary airfoil is positioned at 0.70$R$, and the S820 airfoil profile is specified at 0.95$R$. A spline function is used to interpolate the prescribed cross section profiles to generate the three dimensional model of the rotor blade using SolidWorks software. In the present study, the rotor blades were mounted on a turbine hub with a pitch angle of 3.0°. A DC electricity generator (Kysan, FF-050S-07330) was installed inside the nacelle of the model turbine, which would produce electricity as driven by the rotating blades. While primary design parameters of the model turbine are listed in Table I, further information about the ERS-100 rotor blades is available at Locke and Valencia. It should be noted that, the blockage ratio of the model turbine (i.e., the ratio of the turbine blade swept area to the cross-section area of AABL tunnel) was found to be about 1.2%, and thus, the blockage effects of the model turbine in the test section of AABL is almost negligible for the present study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R$ (mm)</th>
<th>$H_{hub}$ (mm)</th>
<th>$d_{rod}$ (mm)</th>
<th>$d_{nacelle}$ (mm)</th>
<th>$\alpha$ (°)</th>
<th>$a$ (%)</th>
<th>$a_1$ (%)</th>
<th>$a_2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>140</td>
<td>226</td>
<td>18</td>
<td>26</td>
<td>5</td>
<td>68</td>
<td>20</td>
<td>35</td>
</tr>
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</table>
During the experiments, the mean wind speed at the hub height of the model turbine was set to be about 5.0 m/s (i.e., $U_{hub}$ = 5.0 m/s). The Reynolds number based on the averaged chord length of the rotor blades ($C$) and the incoming wind speed at the hub height ($U_{hub}$) was found to be about 7000 (i.e., $Re_C \approx 7000$). It should be noted that this Reynolds number is significantly lower than those of large-scale wind turbines in the field, i.e., $Re_C \approx 7 \times 10^4$ for the present study vs. $Re_C > 1 \times 10^6$ for the large-scale wind turbines as described in Wilson.\textsuperscript{30} According to Alfredsson et al.\textsuperscript{31} and Medici and Alfredsson,\textsuperscript{32} while the chord Reynolds number of a wind turbine may have a significant effect on the power production performance of the wind turbine (i.e., the maximum power coefficient would be much lower for a small-scale model turbine operating at a lower Reynolds number), the wake characteristics and the evolution of the unsteady vortices in the turbine wake would become almost independent of the chord Reynolds number when the chord Reynolds number of the model turbine is higher enough. De Vries\textsuperscript{33} suggested a required minimum chord Reynolds number on the order of $Re_C = 3 \times 10^5$ for a reliable comparison of the model test results with full-scale data. More recently, Chamorro et al.\textsuperscript{34} conducted a comprehensive study to quantify the Reynolds number dependence of turbulence statistics in the wake flow behind a model turbine sited in ABL winds. Instead of using chord Reynolds number, the Reynolds number based on the turbine rotor diameter ($D$) and the flow velocity at the turbine hub height ($U_{hub}$), i.e., $Re_D$, was used by Chamorro et al.\textsuperscript{34} to characterize the wake measurement results. They found that fundamental flow statistics (i.e., normalized profiles of mean velocity, turbulence intensity, kinematic shear stress, and velocity skewness) in the turbine wake have asymptotic behavior with the Reynolds number. Mean velocity in the turbine wake was found to reach Reynolds number independence at a lower value compared to that of higher-order statistics (i.e., turbulence intensity, turbulent kinetic energy, and Reynolds shear stress). Reynolds number independence for mean velocity could be reached at $Re_D \approx 4.8 \times 10^4$, and that of higher order statistics started at $Re_D \approx 9.3 \times 10^4$. It should be noted that, the Reynolds number based on the rotor diameter of the turbine and the wind speed at the turbine hub height for the present study is about 90,000 (i.e., $Re_D \approx 9.0 \times 10^4$), which is in the range of the required minimum Reynolds number as suggested by Chamorro et al.\textsuperscript{34} to achieve Reynolds number independence of the turbine wake statistics.

In the present study, the rotation speed of the turbine rotor blades was adjusted by applying different electric loads to the small DC generator installed inside the turbine nacelle. The turbine rotation speed $\Omega$ can change from 0 to 2200 rpm, and the tip-speed-ratio ($\lambda = \Omega R/U_{hub}$ where $R$ is the radius of the rotor) of the model turbine is in the range from 0 to 6.5. During the experiments, a series of tip-speed-ratio values were adjusted to test the dynamic wind loads acting on model turbine. For the measurement results given in the present study, the model turbine was set to operate at the optimum tip-speed-ratio of $\lambda \approx 5.0$, i.e., at the tip-speed-ratio with the maximum power output of the model turbine. It should be noted that a typical three-blades HAWT on a modern wind farm usually has a tip-speed-ratio of $\lambda \approx 4.0 \sim 8.0$, as described in Burton et al.\textsuperscript{35}

For the model turbine used in the present study, an aluminum rod was used as the turbine tower to support the turbine nacelle and the turbine rotor blades. Through a hole on the wind tunnel floor, the aluminum rod was connected to a high-sensitivity force-moment sensor (JR3 load cell, model 30E12A-I40) to measure the dynamic wind loads (aerodynamic forces and bending moments) acting on the model turbine. The JR3 load cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is +0.25% of the full range (40 N). During the experiments, the wind load data were acquired for 120 s at a sampling rate of 1000 Hz for each test case. A Monarch Instrument Tachometer was also used to measure the rotation speed of the wind turbine blades independently.

In addition to the wind loading measurements, a high-resolution PIV system was also used in the present study to conduct detailed flow field measurements in the vertical plane passing through the symmetrical plane of the model turbine. Figure 4 gives the schematic of the experimental setup used for PIV measurements. For the PIV measurements, the incoming airflow was seeded with ~1 $\mu$m oil droplets by using a droplet generator. Illumination was provided by a double-pulsed laser adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm. The thickness of the laser sheet in the measurement region was about 1.0 mm. In order to have a
larger measurement window along the streamwise direction to reveal the turbulent flow structures behind the model turbine, two high-resolution 16-bit CCD cameras (PCO1600, CookeCorp) were used for PIV image acquisition with the axis of the cameras perpendicular to the laser sheet. The CCD cameras and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a digital delay generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition.

After PIV image acquisition, instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window of $32 \times 32$ pixels, which has a physical area of 7.4 mm $\times$ 7.4 mm. An effective overlap of 50% of the interrogation windows was employed in PIV image processing, which result in a spatial resolution of 3.7 mm $\times$ 3.7 mm for the PIV measurements. After the instantaneous velocity vectors $(u_i, v_i)$ were determined, the vorticity $(\omega_z)$ can be derived. The distributions of the ensemble-averaged flow quantities such as the mean velocity, normalized Reynolds Stress $(\tau = -\bar{u}'v'/U_{hub}^2)$, and in-plane turbulence kinetic energy $(TKE = 0.5 \left( \bar{u}'^2 + v'^2 \right) / U_{hub}^2)$ were obtained from the instantaneous PIV measurements. In the present study, a cinema sequence of 1000 frames of instantaneous PIV image pairs were obtained in order to ensure a good convergence of turbulence statistics of the PIV measurements such as TKE and Reynolds Stress. The measurement uncertainty level for the velocity vectors is estimated to be within 2%, while the uncertainties for the measurements of ensemble-averaged flow quantities such as Reynolds stress and turbulent kinetic energy distributions about 5%.

In the present study, both "free-run" and "phase-locked" PIV measurements were performed during the experiments. The "free-run" PIV measurements were conducted in order to determine the ensemble-averaged flow statistics (e.g., mean velocity, Reynolds Stress, and turbulence kinetic energy) in the turbine wake. For the "free-run" PIV measurements, the image acquisition rate was pre-selected at a frequency that is not a harmonic frequency of the rotating frequency of the turbine rotor blades in order to ensure physically meaningful measurements of the ensemble-averaged flow quantities. "Phase-locked" PIV measurements were conducted to elucidate more details about the dependence of unsteady wake vortices in relation to the position of the rotating rotor blades. For the "phase-locked" PIV measurements, a digital tachometer was used to detect the position of a pre-marked rotor blade. The tachometer would generate a pulsed signal as the pre-marked rotor blade passed through the vertical PIV measurement plane. The pulsed signal was then used as the input signal to a Digital Delay Generator (DDG) to trigger the digital PIV system to achieve the "phase-locked" PIV measurements. By adding different time delays between the input signal from the tachometer and the transistor-transistor logic (TTL) signal output from the DDG to trigger the
digital PIV system, the “phase-locked” PIV measurements at different rotation phase angles of the pre-marked rotor blade can be accomplished. At each pre-selected phase angle (i.e., corresponding to different positions of the pre-marked rotor blade related to the vertical PIV measurement plane), 200 frames of instantaneous PIV measurements were used to calculate the phase-averaged flow velocity distribution in the wake flow behind the model turbine. As shown in Fig. 4, since two CCD cameras were used for PIV image acquisition in order to have a larger measurement window along the streamwise direction, a standard linear regression method was used in the present study to determine the PIV measurement results in the overlap regions between the two PIV measurement windows. In the present study, a Cobra Probe Anemometry system (TFI Series 100 of Turbulent Flow Instrumentation Pty Ltd.), which is capable of measuring all three components of instantaneous flow velocity vector at a prescribed point with a sampling rate of up to 2.0 KHz, was also used to provide time-resolved flow velocity measurement data at the points of interest to supplement the PIV measurements.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Dynamic wind load measurement results

As described above, the JR3 force-moment sensor used in the present study can provide time-resolved measurements of all three components of the aerodynamic forces and the moment

![Graphs showing measurement results of dynamic thrust force acting on the model wind turbine.](image)
gives examples of the wind load measurement results in terms of the instantaneous thrust coefficients with the model turbine sited in two different types of ABL winds. As revealed clearly from the time histories of the measured instantaneous thrust force given in Fig. 5(a), the wind loads acting on the model turbine in turbulent ABL winds (i.e., for both the Type-1 and Type-2 ABL winds) were found to be highly unsteady with their magnitudes fluctuating significantly as a function of time. The time-averaged values were also given in the plots as the dashed lines for comparison. It can be seen that the instantaneous wind loads acting on the turbine could be significantly higher compared with their mean values. Furthermore, while the mean value of the wind loads acting on the turbine sited in the incoming ABL wind with relatively low turbulence intensity levels (i.e., $C_T = 0.470$ for Type-1 ABL wind case) is only slightly lower than that of the case with much higher turbulence intensity levels in the incoming ABL wind (i.e., $C_T = 0.511$ for Type-2 ABL wind case), the fluctuation amplitudes of the instantaneous wind loads acting on the turbine were found to become significantly higher for the high turbulence inflow case, in comparison with those of the relatively low turbulence inflow case.

Figure 5(b) shows the histograms of the measured instantaneous thrust forces acting on the model turbine, which can be used as an indicator to provide further insight about the effects of the incoming flow conditions on the dynamic wind loads acting the wind turbine. While the instantaneous wind loads acting on the model turbine were found to be highly unsteady with their magnitude fluctuating randomly as shown in Fig. 5(a), the histograms of the measured thrust force coefficients were found to be fitted reasonably well by using Gaussian functions for both the low and high turbulence inflow cases. It suggests that the standard deviation of the dynamic wind loads can be used as a quantitative parameter to evaluate the fatigue loads acting on wind turbines even though the turbines were sited in turbulent ABL winds. While the standard deviation value of the instantaneous thrust coefficient for the low turbulence inflow case was found to be about 0.14 (i.e., $\sigma \approx 0.14$), the corresponding value was found to become 0.23 (i.e., $\sigma \approx 0.23$) for the high turbulence inflow case, which is about 1.7 times of the low turbulence inflow case. The larger fluctuations of the dynamic wind loads would indicate much severe fatigue loads acting on the wind turbine when sited in onshore wind farms, which is believed to be closely related to the much higher turbulence intensity levels in the incoming ABL winds over the onshore wind farms. Such quantitative wind loading measurement results highlight the importance of taking the ambient turbulence intensity levels into account for the optimal mechanical design of the wind turbines operating in different ABL winds.

Figure 5(c) shows the power spectra of the measured instantaneous thrust forces acting on the model turbine through a fast Fourier transform (FFT) analysis procedure. For the case with relatively low turbulence intensity levels in the incoming flow, a well-defined dominant peak at $f_0 = 28$ Hz can be identified clearly in the spectrum plot, corresponding to the rotational speed of the turbine rotor blades at the optimum tip-speed-ratio of $\lambda \approx 5.0$. The rotational frequency of $f_0 = 28$ Hz based on the FFT analysis of the dynamic wind load measurements was found to agree very well with the independently measured rotational speed of the turbine blades by using a tachometer. Other peaks, representing the harmonic frequencies of the turbine blade rotational frequency $f_0$, can also be identified clearly from the spectrum plot. However, for the case with much higher turbulence intensity levels in the incoming ABL wind, no well-defined dominant peaks can be identified in the corresponding power spectrum. Since the rotational speed of the turbine rotor blades was found to fluctuate greatly in a wide frequency region (i.e., $21 \text{ Hz} < f_0 < 30 \text{ Hz}$), a group of peaks can be seen in the power spectrum for the high turbulence inflow case. The significant fluctuations in the rotational speed of the turbine rotor blades would cause much more random shedding of the tip and root vortices from the turbine rotor blades, which were visualized clearly from the “phase-locked” PIV measurements to be discussed later. The significant fluctuations in the rotational speed of the turbine rotor blades would also result in much greater variations of the
FIG. 6. Ensemble-averaged velocity distributions in the turbine wake: (a) for the low turbulence inflow case and (b) for the high turbulence inflow case.

dynamic wind loads, thereby, higher fatigue loads acting on the wind turbine for the high turbulence inflow case due to the almost doubled turbulence intensity levels in the incoming ABL wind.

B. “Free-run” PIV measurement results

As described above, “free-run” PIV measurements were conducted in the present study in order to determine the ensemble-averaged flow statistics (e.g., mean velocity, turbulence kinetic energy, and Reynolds Stress) in the turbine wake. Figure 6 shows the “free-run” PIV measurements in term of ensemble-averaged flow velocity distributions in the turbine wake for the low and high turbulence inflow cases. Figure 7 gives the transverse profiles of the mean flow velocity extracted from the PIV measurement results at the downstream locations of $X/D = 0.5, 1.0, 1.5$, and $2.0$, respectively. The mean velocity profiles of the incoming ABL winds for the two tested cases were also plotted in the graphs for comparison. It can be seen clearly that, in comparison with the flow velocity profiles of the incoming ABL winds, obvious velocity deficits can be observed in the wake flow behind the wind turbine for both the low and high turbulence inflow cases. The size of the regions with significant velocity deficits were found to be much greater than that can be expected from the stationary turbine nacelle only. The incoming airflow streams were found to decelerate greatly as they pass through the rotation disk of the turbine blades since a portion of the kinetic energy carried by the incoming ABL winds was harvested by the wind turbine.

As shown clearly in Fig. 6(a), for the case with relatively low turbulence levels in the incoming ABL wind, the region with relatively low flow velocity (i.e., $U/U_{hub} < 0.7$) in the turbine wake were found to be elongated greatly, which extends beyond the PIV measurement window of the present study (i.e., $X/D > 2.4$). The iso-velocity contour lines for $U/U_{hub} > 0.7$ in the turbine wake were found to be almost parallel to each other in the downstream region of $1.0 < X/D < 2.0$. 

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FIG. 7. Transverse velocity profiles in the turbine wake at different downstream locations: (a) for the low turbulence inflow case and (b) for the high turbulence inflow case.

As shown in Fig. 7(a), very little changes can be observed among the transverse mean velocity profiles extracted at different downstream locations. It indicates that the velocity deficits in the turbine wake would need a much longer distance to recover. However, as shown in Fig. 6(b), for the case with much higher turbulence levels in the incoming ABL wind, the size of the region with lower flow velocity (i.e., $U/U_{hub} < 0.7$) was found to become much smaller, in comparison with that of the low turbulence inflow case. The transverse mean velocity profiles extracted at different downstream locations were found to become quite different due to the much faster recovery of the velocity deficits in the turbine wake for the high turbulence inflow case.

Figure 8 shows the changes of the flow velocity of the turbine wake at the turbine hub height as a function of the downstream distance away from the rotation disk of the model turbine. The effects of the discrepancies in the incoming flow conditions on the recovery of the velocity deficits in the turbine wake can be seen more clearly from the comparison of the measurement results for the low and high turbulence inflow cases. As shown in Fig. 8, while passing thorough the recirculation zone at the downstream of the turbine nacelle, the wake flow velocity at the turbine hub height would increase very rapidly at the immediate downstream of the turbine nacelle (i.e., $X/D < 0.3$) for both the low and high turbulence inflow cases. The variations of the wake flow velocity at the turbine hub height were found to be quite different for the two compared cases at further downstream. For the low turbulence inflow case, the wake flow velocity at the turbine hub height was found to decrease slightly in the region of $0.4 < X/D < 1.5$ due to the expansion of the turbine wake and then increase slowly with the increasing downstream distance at further downstream (i.e., $X/D > 1.5$) due to the turbulent mixing in the turbine wake. For the high turbulence inflow case, while the wake flow velocity at the turbine hub height was found to have almost a constant value in the region of $0.4 < X/D < 1.0$, then increase monotonically with a much greater increase rate at further downstream (i.e., $X/D > 1.0$). As a result, the wake velocity at the turbine hub height for the high turbulence inflow case was found to become much greater than that of the low turbulence inflow case in the turbine wake further away from the wind turbine model (i.e., $X/D > 1.0$).

The PIV measurement results given above reveal clearly that, at a same given downstream distance away from the upstream wind turbine, the velocity deficits in the turbine wake would recover much faster for the high turbulence inflow case than the low turbulence inflow case. It implies that, for the same given distance between the upstream and downstream wind turbines, the power losses for the downstream wind turbines due to the effects of the wake interferences of the upstream turbines would be much less with the turbines sited in ABL winds with much higher turbulence levels (e.g., onshore wind farm scenario), in comparison with the cases with lower turbulence levels in the ABL incoming winds (e.g., offshore wind farm scenario).

Figure 9 shows the normalized in-plane Turbulence Kinetic Energy (TKE = $0.5(\overline{u'^2} + \overline{v'^2})/U_{hub}^2$) distributions in the turbine wake for the low and high turbulence inflow cases, which can provide insights to explain the differences in the wake velocity deficit recovery for the two compared cases. It should be noted that, the color bar ranges given in Figs. 9(a) and 9(b) are different due to the significant differences of the TKE levels in the turbine wake for the compared cases. As shown in Fig. 9, while the distribution pattern of the TKE in the turbine wake was found to be quite similar for both the low and high turbulence inflow cases, the absolute TKE values in the turbine
wake for the high turbulence inflow case were found to be about 2–3 times greater than those of the low turbulence inflow case. The regions with quite high $TKE$ levels were found to concentrate in the wake immediately behind the nacelle and tower of the wind turbine, which is believed to be closely related to the formation and shedding of unsteady wake vortices from the turbine nacelle and tower. The formation and shedding of unsteady wake vortices are visualized more clearly from the “phase-locked” PIV measurement results to be discussed later. $TKE$ levels were also found to be quite high at the upper region behind the rotation disk of the turbine blades, which is correlated well to the shedding paths of the unsteady tip and root vortices from the rotating rotor blades in the PIV measurement plane. The expansion of the turbine wake with the increasing downstream distance away from the turbine rotor disk can also be observed in the measured $TKE$ distributions.

As described above, the absolute levels of $TKE$ in the turbine wake for the high turbulence inflow case were found to be much higher, in comparison with those of the low turbulence inflow case. $TKE$ level can usually be used as a parameter to indicate the extent of turbulent mixing in a turbulent flow. The much higher $TKE$ levels for the high turbulence inflow case would indicate much more intensive mixing in the turbine wake, corresponding to a much faster recovery of the velocity deficits in the turbine wakes for the high turbulence inflow case, in comparison with that of the low turbulence inflow case.

Since both the turbulence levels of the incoming ABL winds and the unsteady shedding of the complex wake vortices would contribute to the elevated turbulence levels in the turbine wake, the wake-vortex-induced $TKE$ distributions in the turbine wake were determined in the present study in order to assess of the effects of the unsteady wake vortices on the characteristics of turbine wake flows more clearly. The wake-vortex-induced $TKE$ values were obtained by subtracting the $TKE$ levels of the incoming airflow from those of the measured $TKE$ values in the turbine wake (i.e., $\Delta TKE = TKE_{\text{wake flow}} - TKE_{\text{incoming ABL wind}}$). Figure 10 gives the wake-vortex-induced $TKE$ distributions for the low and high turbulence inflow cases. It can be seen that the behavior of wake-vortex-induced $TKE$ in the near wake (i.e., the region of $X/D < 1.0$) and farther downstream (i.e., the region of $X/D > 1.0$) are quite different for the two compared cases. In the near wake region (i.e., $X/D < 1.0$), the wake-vortex-induced $TKE$ levels in the region at the tip-top height of the turbine wake near to the turbine model ($X/D < 0.60$) were found to be slightly smaller for the high turbulence inflow case, in comparison with those of the low turbulence inflow case. For the high turbulence inflow case, the wake-vortex-induced $TKE$ values were found to become negative in the region downstream of the roots of the rotor blades (i.e., $Z/D \approx 0.2$). It suggests that, due to the existence of the wind turbine, the $TKE$ levels in the near region behind the wind turbine would become even smaller than those of the incoming ABL wind. A similar feature was also reported by Chamorro and Porte-Agel, who conducted wake flow measurements by using a pointwise cross-wire anemometer. In the region farther away from the wind turbine (i.e., $X/D > 1.0$), the
Wake-vortex-induced $\Delta TKE$ values were found to become much higher for the high turbulence inflow case, which is adverse to the behavior of the wake-vortex-induced $TKE$ in the near wake. Since the characteristics of the $TKE$ distributions are closely related to the behavior of the unsteady vortex and turbulent structures in the turbine wake, further analysis about the characteristics of the $TKE$ distributions in the turbine wake for the two compared cases will be given in the later section of “phase-locked” PIV measurement results.

Figure 11 gives the measured Reynolds stress distributions in the turbine wake for the low and high turbulence inflow cases. As suggested by Cal et al., a higher Reynolds stress level would play an important role in promoting the vertical transport of the kinetic energy in a turbine wake,
which will draw down more high velocity airflow from above to the boundary layer flow. As shown in Fig. 11, while the distribution features of the Reynolds stress in the turbine wake for the low turbulence inflow case were found to be quite similar to those of the high turbulence inflow case, the absolute values of the Reynolds stress in the turbine wake for the high turbulence inflow case were found to be almost three times as high as those of the low turbulence inflow, i.e., the ranges of the color bars were different in plotting Figs. 11(a) and 11(b). In addition, the expansion of the regions with high Reynolds stress values at the upper portion of the turbine wake was also found to be much more aggressive for the high turbulence inflow case, in comparison with the low turbulence inflow case.

Based on the comparisons of the TKE and Reynolds stress distributions described above, it can be summarized that, due to the significant differences in the incoming flow conditions (i.e., distinct mean velocity and turbulence characteristics) for the two compared cases, the TKE and Reynolds stress levels in the turbine wake for the high turbulence inflow case would become much higher than those of the low turbulence inflow case, which would promote the vertical transport of kinetic energy by entraining more high-speed airflow from above to re-charge the wake flow behind the wind turbine. As a result, the velocity deficits in the turbine wake for the high turbulence inflow case would recover much faster than that of the low turbulence inflow case, as shown quantitatively in Fig. 6 to Fig. 8.

C. “Phase-locked” PIV measurement results

In the present study, “phase-locked” PIV measurements were also conducted to produce “frozen” images of the unsteady vortex structures in the turbine wake at different phase angles, from which the dependence of unsteady wake vortices on the rotation of the blades can be revealed more clearly and quantitatively. Figures 12 and 13 show the phase-averaged velocity distributions in the turbine wake at four different phase angles with the model turbine operating in the two different incoming surface winds. In the present study, the phase angle is defined as the angle between the vertical PIV measurement plane and the position of a pre-marked turbine rotor blade. The pre-marked rotor blade would be in the most upward position (i.e., within the vertical PIV measurement plane) at the phase angle of $\theta = 0^\circ$. As the phase angle increases, the turbine blade would rotate out of the vertical PIV measurement plane. As shown clearly in Fig. 12, the existence

FIG. 11. Reynolds stress distributions in the turbine wake: (a) for the low turbulence inflow case and (b) for the high turbulence inflow case.
FIG. 12. “Phase-locked” flow velocity distributions for the low turbulence inflow case: (a) $\theta = 0^\circ$, (b) $\theta = 30^\circ$, (c) $\theta = 60^\circ$, and (d) $\theta = 90^\circ$.

FIG. 13. Phase-locked flow velocity distributions for the high turbulence inflow case: (a) $\theta = 0^\circ$, (b) $\theta = 30^\circ$, (c) $\theta = 60^\circ$, and (d) $\theta = 90^\circ$.

of “wave-shaped” flow structures can be observed at the tip-top height in the turbine wake for the low turbulence inflow case, which is closely related to the formation and periodical shedding of tip vortices in the turbine wakes as suggested in Hu et al.\textsuperscript{19} The “wave-shaped” flow structures were found to propagate downstream as the phase angle increases. However, as shown in Fig. 13, the periodicity of the “wave-shaped” flow structures at the tip-top height in the turbine wake was found to become much less pronounced for the high turbulence inflow case. The “wave-shaped” flow structures were found to be dissipated rapidly as they move downstream, and become almost indistinguishable in the downstream region of $X/D > 0.5$ for the high turbulence inflow case.

Figures 14 and 15 show the “phase-locked” vorticity distributions in the turbine wake, which were derived from the “phase-locked” velocity distributions at different phase angles, for the low and high turbulence inflow cases, respectively. The effects of the discrepancies in the incoming surface wind conditions on the evolution of the unsteady wake vortex and turbulent flow structures in the turbine wake can be seen more clearly from the comparisons of the “phase-locked” vorticity
distributions. As shown in the figures, the wake flow behind the wind turbine is actually a very complex vortex flow, which is fully filled with various wake vortex structures with different spatial and temporal scales. In addition to the tip vortices and root vortices shedding periodically at the tips and roots of the turbine blades, unsteady vortex structures were also found be generated on the upper and lower surfaces of the turbine nacelle as well as the von-Karman vortex streets shedding from the turbine tower. The flow characteristics in the wake behind the wind turbine were found to be dominated by the evolution (i.e., formation, shedding, and breakdown) of the unsteady wake vortices.

As described above, the pre-marked turbine blade would be within the vertical PIV measurement plane at the phase angle of $\theta = 0^\circ$. As shown clearly in Figs. 14 and 15, a tip vortex would be induced at the tip of the pre-marked turbine blade at the phase angle of $\theta = 0^\circ$. As the phase angle increases, while the pre-marked turbine blade rotates out of the vertical PIV measurement plane, the tip vortex was found to shed from the tip of the turbine rotor blade. While moving downstream,
the tip vortex was found to align itself nicely with other tip vortices induced by the other two rotor blades to form a moving tip vortex array in the wake flow. Besides the vortex array aligned nicely at the top-tip height of the rotor blades, an additional row of concentrated vortex structures were also found to be generated at the inboard of the turbine blades at approximately 50%–60% span of the rotor blades. The vortex structures were found to move outward with the expansion of the wake flow as they move downstream, and finally merge with the tip vortex structures. Similar vortex structures at approximately 50%–60% span of the rotor blades were also observed by Whale et al.\textsuperscript{9} and Hu et al.\textsuperscript{19} in their experimental studies to examine the evolution of unsteady wake vortex structures in turbine wake flows.

The influences of the different characteristics of the incoming ABL winds on the unsteady vortex structures in the turbine wake were revealed very clearly through the comparison of the “phase-locked” vorticity distributions for the low turbulence inflow case with those of the high turbulence inflow case. As shown in Fig. 14, for the low turbulence inflow case, concentrated vortices (i.e., both the tip vortices and the vortex structures at 50%–60% span of the rotor blades) shedding from the turbine rotor blades would align themselves nicely to form moving vortex arrays in the turbine wake, which were observed as the “wave-shaped” flow structures in the “phase-locked” flow velocity distributions given in Fig. 12. For the low turbulence inflow case, the wake vortex structures were found to be dissipated gradually as they move downstream, and eventually breakdown at the downstream location around $X/D \approx 0.8$.

For the high turbulence inflow case, as shown in Fig. 15, the concentrated wake vortices shedding from the turbine rotor blades (i.e., both the tip vortices and the vortex structures at 50%–60% span of the rotor blades) seem to become slightly weaker and smaller, in comparison with those of the low turbulence inflow case. The shedding of the wake vortices was also found to become much more turbulent and random for the high turbulence inflow case, due to the much higher turbulence intensity levels in the incoming airflow. All the observations are believed to be closely related to the much greater variations in the turbine rotational speed for the high turbulence inflow case, as revealed from the power spectrum analysis of the dynamic wind loads given in Fig. 5. For the high turbulence inflow case, the wake vortices, as travelling downstream, were found to be dissipated much more rapidly, and break down much earlier. As a result, the “wave-shaped” structures in the turbine wake for the high turbulence inflow case were found to become almost indistinguishable at the downstream location of $X/D \geq 0.4$ in the phase-locked flow velocity distributions, as shown in Fig. 13.

As described above, since the wake-vortex-induced TKE in the turbine wake would be determined by the behavior of the wake vortices, the wake-vortex-induced TKE and Reynolds stress levels in the turbine wake were found to be much higher in the regions along the shedding paths of the wake vortices structures. Corresponding to the weaker wake vortices in the turbine wake for the high turbulence inflow case as shown in Fig. 15, the wake-vortex-induced TKE levels in the near wake would be slightly lower than those of the low turbulence inflow case, as shown clearly in Fig. 10. Medici\textsuperscript{16} conducted an experimental study to investigate the self-induced mixing properties in a turbine wake, and suggested that the existence of concentrated tip vortices in a turbine wake would prevent the wake flow from mixing with the outer high-speed airflow. As shown in Figs. 14 and 15, the concentrated wake vortices would break down at the downstream location of $X/D \approx 0.8$ for the low turbulence inflow case and at the downstream location of $X/D \approx 0.4$ for the high turbulence inflow case. After the breakdown of the concentrated wake vortices, the TKE and Reynolds stress levels in the turbine wake were found to increase dramatically. Since the higher TKE and Reynolds stress levels in the turbine wake would suggest more turbulent and intensive mixing in the turbine wake, it will be promoting the vertical transport of kinetic energy to entrain high-speed airflow from above to re-charge the wake flow. Corresponding to the much earlier breakdown of the concentrated wake vortices and much higher TKE and Reynolds numbers levels in the turbine wake, the recovery of the velocity deficits in the turbine wake for the high turbulence inflow case were found to be much faster, in comparison with that of the low turbulence inflow case, as shown clearly and quantitatively in Fig. 6 to Fig. 8.
D. Power spectra of the turbulent flow velocity in the turbine wake

As described above, a Cobra Probe Anemometry system was also used in the present study to provide time-resolved flow velocity measurement data at the points of interest to supplement the PIV measurements. By taking the FFT of the instantaneous flow velocity \((u, v,\) and \(w)\) measured by using the Cobra Probe Anemometry system, a comparative study based on spectral analysis of the turbulent flow velocity in the turbine wake was also performed to assess the characteristics of the turbulence energy distributions across a range of frequencies for the low and high turbulence inflow cases.

Figure 16 shows the power spectra of the turbulent flow velocity fluctuations in the turbine wake with the measurement point located at the downstream location of \((X/D = 0.5, Y/D = 0.0, Z/D = 0.5)\), i.e., along the shedding path of the tip vortices in the PIV measurement plane. As visualized clearly in the “phase-locked” PIV measurement results given in Figs. 14 and 15, the measurement point would be at the upstream of the concentrated wake vortex breakdown for the low turbulence inflow case (i.e., the concentrated wake vortex breakdown at the downstream location of \(X/D \approx 0.8\) for the low turbulence inflow case). However, the same measurement point would be located at the downstream of the concentrated wake vortex breakdown position for the high turbulence inflow case (i.e., the concentrated vortex breakdown at \(X/D \approx 0.4\) for the high turbulence inflow case). Since very similar features were also seen in the power spectra of the horizontal (i.e., \(S_v\) spectra) and vertical (i.e., \(S_w\) spectra) components of the turbulent flow velocity vector, only the power spectra of the streamwise (i.e., \(S_u\) spectra) component of the turbulent flow velocity vector were presented in Fig. 16 for comparison.

As shown in the Fig. 16(a), for the case with relatively low turbulence intensity levels in the incoming flow, the classical turbulence energy production subrange and inertial subrange in the turbine wake flow, which are identified as the regions that follow power law scaling with \(-1\) and \(-5/3\) slopes, respectively, can be seen clearly in the power spectra of the streamwise (i.e., \(S_u\) spectra) component of the turbulent flow velocity. Similar features about the energy production and inertial subranges were also reported by Chamorro et al.\(^9\) and Zhang et al.\(^20\) in quantifying the flow characteristics of turbine wakes. Furthermore, since the measurement point is located at the upstream position of the concentrated wake vortex breakdown for the low turbulence inflow case, localized high-energy signatures or the tip vortices can be identified easily in the spectra plots in terms of well-defined local peak frequencies. The well-defined local peak frequencies in the spectra plots are found to correspond well to the primary shedding frequency of the tip vortices from the rotating turbine blades (i.e., \(3f_0\), where \(f_0\) is the rotational frequency of wind turbine). Other high peaks, representing the harmonic frequencies of the shedding frequency of the tip vortices, can also be identified clearly from the spectra plots.

However, for the case with much higher turbulence intensity levels in the incoming ABL wind, while the turbulence energy production and inertial subranges in the wake flow (i.e., the regions with \(-1\) and \(-5/3\) slopes in the spectrum plots) can still be seen in the spectra plot given in
Fig. 16(b), no obvious high-energy containing signatures can be seen in the spectra plot. This is because the concentrated, high-energy containing wake vortices shedding from the rotating turbine blades have already broken down and turn into much smaller turbulent eddies before reaching to the measurement point. Therefore, the signatures of the concentrated, high-energy containing wake vortices cannot be identified easily in the power spectra of the measured turbulent velocity in the turbine wake for the high turbulence inflow case.

IV. CONCLUSION

A comparative study was conducted to investigate the turbine wake characteristics and dynamic wind loads acting on a model wind turbine placed in two different types of ABL winds with distinct mean and turbulence characteristics. A scaled three-blade HAWT model was used for the comparative study to simulate the scenario with the same wind turbine sited in the two different types of ABL winds. In addition to measuring the dynamic wind loads acting on the model turbine, a high-resolution PIV system was used to make both “free-run” and “phase-locked” measurements to quantify the flow characteristics and behavior (i.e., formation, shedding, and breakdown) of the unsteady wake vortices in the turbine wake. The detailed flow field measurements were correlated with the dynamic wind loading measurements in order to gain further insight into the underlying physics for the optimal design of the wind turbines operating in different ABL winds.

While the instantaneous wind loads acting on the model turbine were found to be highly unsteady with their magnitudes fluctuating significantly, the histograms of the dynamic wind loads acting the model turbine were found to be able to be fitted reasonably well by using Gaussian functions for the two studied cases with different turbulence levels in the incoming ABL winds. In comparison to those of the case with relatively low turbulence intensity levels in the incoming flow, the dynamic wind loads acting on the model turbine were found to fluctuate much more significantly for the high turbulence inflow case, which would result in much larger fatigue loads acting on the wind turbines, due to the much higher turbulence intensity levels in the incoming surface wind.

The PIV measurements reveal clearly that, since a portion of the kinetic energy carried in the incoming airflow was harvested by the wind turbine, the speed of the incoming surface wind would be decelerated after passing through the rotation disk of the turbine blades, which results in the velocity deficits in the turbine wake. The wake characteristics behind the wind turbine were found to be dominated by the behavior (i.e., formation, shedding, dissipation, and breakdown) of the unsteady wake vortices shedding from the rotating blades, nacelle, and tower of the wind turbine. In the near wake, the regions with high TKE and Reynolds stress levels were found to concentrate mainly along the shedding paths of the unsteady wake vortices. As moving downstream, the concentrated, high-energy containing wake vortices were found to be dissipated, and eventually break down into smaller turbulent eddies, which would cause a dramatic increase of the TKE and Reynolds stress levels in the turbine wake. The higher TKE and Reynolds stress levels in the turbine wake would result in enhanced turbulent mixing to promote the vertical transport of kinetic energy by entraining more high-speed airflow from above to re-charge the wake flow, thereby, to facilitate the recovery of the velocity deficits in the wake flow behind the model turbine.

In comparison with the low turbulence inflow case, the shedding of the concentrated wake vortices from the turbine rotor blades was found to become much more turbulent and random for the high turbulence inflow case due to the much higher turbulence intensity levels in the incoming surface wind. The breakdown of the concentrated wake vortices was also found to take place much earlier for the high turbulence inflow case, which contributes to the much higher TKE and Reynolds stress levels in the turbine wake, resulting in a much faster recovery of the velocity deficits in the turbine wake for the high turbulence inflow case, in comparison with that of the low turbulence inflow case.

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An experimental study on the effects of relative rotation direction on the wake interferences among tandem wind turbines†

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An experimental study was conducted to investigate the effects of relative rotation direction on the wake interferences among two tandem wind turbines models. While the oncoming flow conditions were kept in constant during the experiments, turbine power outputs, wind loads acting on the turbines, and wake characteristics behind the turbines were compared quantitatively with turbine models in either co-rotating or counter-rotating configuration. The measurement results reveal that the turbines in counter-rotating would harvest more wind energy from the same oncoming wind, compared with the co-rotating case. While the recovery of the streamwise velocity deficits in the wake flows was found to be almost identical with the turbines operated in either co-rotating or counter-rotating, the significant azimuthal velocity generated in the wake flow behind the upstream turbine is believed to be the reason why the counter-rotating turbines would have a better power production performance. Since the azimuthal flow velocity in the wake flow was found to decrease monotonically with the increasing downstream distance, the benefits of the counter-rotating configuration were found to decrease gradually as the spacing between the tandem turbines increases. While the counter-rotating downstream turbine was found to produce up to 20% more power compared with that of co-rotating configuration with the turbine spacing being about 0.7D, the advantage was found to become almost negligible when the turbine spacing becomes greater than 6.5D. It suggests that the counter-rotating configuration design would be more beneficial to turbines in onshore wind farms due to the smaller turbine spacing (i.e., ~3 rotor diameters for onshore wind farms vs. ~7 rotor diameters for offshore wind farms in the prevailing wind direction), especially for those turbines sited over complex terrains with the turbine spacing only about 1–2 rotor diameters.

wind energy, wind turbine aerodynamics, wind turbine wake interference, complex vortex flows

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1 Introduction

Wind energy is one of the most promising renewable energy resources in the world today. While wind energy provided only approximately 2.3% of total U.S. electricity generation in 2010, a target of 20% of USA total electricity generation from wind energy by 2030 has been set up recently by the U.S. Department of Energy. To achieve the goal of 20% of electricity generation from wind energy by 2030, while more and more wind farms are being developed at the sites where wind energy source is plentiful, wind turbine dynamics, micrositing, and array effects have been identified as the most significant research topics needed for wind resource characterization and wind power generation [1].

A modern wind farm usually consists of multiple wind turbines arranged in an organized pattern or array. The wake interferences among the turbines have been found to affect
the performance of the turbines significantly. The wind turbines located in the near- and far-wake regions of upstream turbines in a typical wind farm would experience a significantly different surface wind field and wind loadings compared to the ones located upwind due to the wake interferences of the upwind turbines. Since a portion of the wind energy carried by the oncoming wind has already been harvested by the upstream turbines, significant velocity deficits would be generated in the wake flows behind the upstream turbines. As a result, downstream turbines see a considerably lower freestream velocity than the upstream turbines, and thus, less energy is available in the oncoming flows for the downstream turbines. Barthelmie & Jensen [2] reported that power losses due to wake interferences among wind turbines were found to be up to 30% of total average power for most large offshore wind farms, depending on the wind turbine array spacing and layout. Extensive experimental and numerical studies have been conducted in recent years to investigate wind turbine aerodynamics and wake interferences among multiple wind turbines in order to gain insight into the underlying physics for higher total power yield and better durability of the wind turbines [3–14]. For example, Hu et al. [7] conducted a comprehensive experimental study to quantify the dynamic wind loads and wake characteristics of a wind turbine model in an atmospheric boundary layer (ABL) wind. Zhang et al. [8] reported the detailed turbulent structures in the near wake of a wind turbine, including the characterization of the wake rotation effects and coherent tip vortex shedding. Some previous numerical work, e.g., Porté-Agel et al. [9] and Wu & Porté-Agel [10], showed that the wake flow properties cannot be well reproduced in numerical models, unless the effect of turbine induced rotation is taken into account, to parameterize the wind turbine forces. The recovery rate of the velocity deficits and the turbulence characteristics of the wake flows were found to affect the power production and wind loadings acting on the downstream wind turbines greatly. Ross and Ainslie [11] conducted an experimental study to quantify the wake flows in clusters of model wind turbines by using laser Doppler anemometry technique. They found that the wake velocity deficit would recover rapidly, up to 50%, within the first two rotor diameters (i.e., 2D) behind the upstream turbines, and then recovered gradually to reach the extent of nearly 70% and 75% at the downstream distances of 6D and 8D, respectively. They suggested that the region within the first 6D downstream is where the velocity deficits in the wake flows would recover rapidly. Based on the field measurements in offshore wind farms, Barthelmie et al. [12] reported that, with spacing between the wind turbines in the offshore wind farms being 1.7D–7.4D, the wake velocity deficit recovery that can be achieved is in the range of 10%–45%. They also found that the wake velocity deficit would recover very slowly when the spacing exceeds 6.5D. More recently, Hu et al. [13] conducted a comprehensive experimental study to investigate the effects of turbulence level of the oncoming ABL winds on the recovery rate of the wake velocity deficit behind wind turbines. They reported that the wake velocity deficit would recover much faster with a higher turbulence level in the oncoming flow (i.e., for the cases in typical onshore wind farms), compared with that with relatively low turbulence level (i.e., for the cases in typical offshore wind farms).

In spite of the extensive studies that have been conducted to investigate wake interferences among multiple wind turbines for wind farm optimization [14,15], the spacing and layout of wind turbines in a wind farm is still more an art than a science. The spacing between wind turbines is usually based on the diameter of the area swept by the turbine blades. For a modern offshore wind farm, wind turbines are generally spaced between 6–10 rotor diameters in the prevailing wind direction and 3–5 rotor diameters in the cross-wind direction [4,5]. Recently, Meyers and Meneveau [16] even suggested that “for realistic cost ratios, the optimal average turbine spacing may be considerably higher (up to 15 D) than conventionally used in current offshore wind farms (~7D)”. Typical turbine spacing used in wind turbine wake research can also be found in Calaf et al. [17], Markfort et al. [18], Wu and Porté-Agel [19]. Such large spacing between the wind turbines is intended to minimize the wake interference effects to allow for the downstream turbines to draw as much energy from the oncoming wind as possible - up to the Betz limit of 59% - without interfering with other turbines sited in upwind. Even small improvements in quantifying wake losses for given array configurations and atmospheric climates are economically significant. According to Barthelmie & Jensen [2], at current costs an increase in power output of 1% of a 100 MW wind farm is equivalent to approximately $0.5 million in revenue increase annually. Their analyses also indicate that, for realistic turbine spacing in a wind farm, power output of the wind farm was directly related to turbine spacing (i.e., 1.3% average increase in power for an increase of 1.0 rotor diameter spacing). It should be noted that, a practical turbine spacing in a wind farm is usually also constrained by many other factors, such as land use, landownership and the cost of increased cabling associated with increased turbine spacing.

Besides the studies to evaluate the effects of turbine spacing on the wake interferences among multiple turbines, a number of investigations have also been conducted to assess the effects of the turbine layout (i.e., staggered turbine layout vs. aligned turbine layout) to optimize wind farm design. It was found that, compared with the aligned turbine layout design that is most commonly used in practice, staggered wind farm design may lead to improved total power production performance for a given wind farm. Chamorro et al. [20] suggested that the difference in total power production between a staggered wind farm and an aligned wind farm with the same oncoming flow is on the order of 10% when the turbines are spaced 5D and 4D in the streamwise and spanwise directions, respectively. Similar results were
also reported by Tian et al. [21], who revealed that 12% power increase can be achieved when the staggered layout was adopted with spacing of 3D in both streamwise and spanwise directions for an onshore wind farm settings with a relatively high turbulence level in the oncoming ABL wind.

A method by controlling the yaw angles of the upstream and downstream wind turbines for a better total power production performance has also been suggested recently. As demonstrated by Adaramola & Krogstad [22], by operating the upstream turbines slightly outside the optimum setting or yawing the upstream turbines, the power output from the downstream turbines can be significantly improved. As a result, the total power production of the turbines could be increased up to 12% by operating the upstream turbines in a yawed condition. They also suggested that, by operating the upstream turbine at an appropriate yaw angle and using a relatively small distance of separation between the turbines, the efficiency of the wind farm would be comparable to that with much greater spacing between the turbines and the upstream turbine not yawed. Therefore, operating the upstream turbine at a suitable yaw angle will not only improve the total wind farm power output, but will also reduce the spacing required for a given wind farm. Ozbay et al. [23] confirmed the effectiveness of using yaw angle control method, and reported that the benefit of yaw angle control method is strongly dependent on the turbulence intensity level of the oncoming wind. With the upstream turbine operating at 10° yaw angle relative to the oncoming wind with a relatively low turbulence intensity level (i.e., for the situations of offshore wind farms), the total power output of the wind farm could be improved up to 6% for the case with a 3D spacing between the turbines. However, yawing the upstream turbine was found to have a negative impact on the overall efficiency of the wind farm when the turbulence level of the oncoming ABL is relatively high (i.e., for the cases of onshore wind farms).

While most of the wind turbines in modern wind farms are Single Rotor Wind Turbine (SRWT) systems, the concept of Counter-Rotating Wind Turbine (CRWT) systems has been suggested in recent years. While the maximum energy conversion efficiency for a conventional SRWT is about 59% according to Betz law [15], in practice, the best designed SRWT system can only extract less than 40% wind energy because of various associated losses, such as viscous loss, three dimensional loss, and transmission loss [24]. As a result, nearly 60% of the potential wind energy carried by the oncoming wind has not been harnessed by SRWT systems. Part of this energy may be further extracted by installing a second rotor in the near wake. Because the downstream wake is found to rotate in the opposite direction to the upstream rotor, the downstream rotor should rotate in the same direction as the swirling wake flow in order to extract wind energy in the wake flow more efficiently [24,25]. Based on such an idea, a CRWT concept with two rotors in the near wake that rotate at different directions was proposed and proved aerodynamically more efficient than the conventional SRWT design (i.e., the maximum energy conversion efficiency obtained by two rotors having the same area would be increased to 64% [26,27]. A prototype of 6 kW CRWT was built in California and field testing was completed in 2003. The results indicated that CRWT system could extract additional 30% more power from the same wind stream, compared with a conventional SRWT design. Jung et al. [28] performed other field measurements of a 30 kW prototype CRWT, and found that the power increase of the CRWT system reached about 21% over a conventional SRWT system at a rated wind speed of 10.6 m/s. More recently, Habash et al. [29] conducted a wind tunnel study with a small-scale CRWT system, and found that the CRWT system could produce up to 60% more energy than a SRWT system of the same type and was capable of reducing cut-in speed while maintaining turbine performance. An et al. [30] found that the wake flow of a CRWT system was more stable and the turbulence intensity level in the wake flow would become lower than that of SRWT. Farahani et al. [31] showed that the dynamic response of a CRWT system was more stable than a conventional SRWT system, and a CRWT system can produce more energy in a short period after the electric network frequency drops.

So far, while almost all the previous attempts to use CRWT to improve wind energy utilization are focused on near wake characteristics, most of the previous studies on the wake interferences among multiple turbines are limited to SRWT systems with all the turbine blades rotating in the same direction. As described above, while a CRWT system was found to have quite different wake characteristics compared with those of conventional SRWT systems, the interferences among wind turbines with different rotation directions in a wind farm have never been investigated. With this in mind, we performed a comprehensive experimental study to assess the effects of the relative rotation directions of two tandem wind turbines on the power production performance, the flow characteristics in the wake flows behind the two wind turbines, and the resultant wind loads (both static and dynamic loads) acting on the turbines. The experimental study was performed in a large-scale Aerodynamics/Atmospheric Boundary Layer (AABL) Wind Tunnel located at the Aerospace Engineering Department of Iowa State University. As shown schematically in Figure 1, while the oncoming flow was kept constant during the experiments, two turbines were set to operate in either co-rotating (i.e., the downstream wind turbine has the same rotation direction as the upstream turbine) or counter-rotating (i.e., the downstream wind turbine has an opposite rotation direction in relation to the upstream wind turbine) configuration. The turbine power outputs, the wind loads (i.e., both the aerodynamic forces and bending moments) acting on the wind turbines, and the flow characteristics in the near wake (i.e., within the first rotor diameter, $D/2<1D$ and far wake (up to $7.8D$ downstream) behind the wind turbines.
were measured and compared quantitatively for wind turbines in both co-rotating and counter-rotating configuration. It should be noted that, while our first report on this topic with some preliminary results was presented in a conference paper [32], the work included in the present study adds much more detailed measurement results, extensive discussions and considerable analysis to elucidate the underlying physics, which is far beyond the scope of the previous conference presentation.

2 Experimental setup and test models

2.1 Atmospheric boundary layer wind tunnel

The experimental study was performed in the Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel located at the Aerospace Engineering Department of Iowa State University. The AABL wind tunnel is a closed-circuit wind tunnel with a test section of 20 m long, 2.4 m wide and 2.3 m high, optically transparent side walls, and a capacity of generating a maximum wind speed of 45 m/s in the test section. Spirestructures, chains and/or arrays of wood blocks were installed on the wind tunnel floor at the upstream of the test wind turbine models in order to generate a turbulent boundary layer flow to simulate a typical atmospheric boundary layer (ABL) wind seen in wind farms. The boundary layer growth of the simulated ABL wind under zero pressure gradient condition was achieved by adjusting the ceiling profile of the test section of the wind tunnel.

It is well known that the velocity profile of an ABL wind can usually be fitted well by using a power function, i.e.,

\[ U(z) = U_{zc} \left( \frac{z}{Z_G} \right)^D \]

where \( U_{zc} \) is the wind speed at a reference height of \( Z_G \) [33]. The value of the power-law exponent \( D \) is determined by the terrain roughness, i.e., \( D \approx 0.35 \) over a large city with tall buildings and well developed industrial areas, \( D \approx 0.25 \) over suburban area, small towns or well wooded areas; \( D \approx 0.10 \) over open sea, ice or tundra desert [34]. Figure 2 shows the measured velocity profiles of the oncoming flow in the test section for the present study. While the horizontal axis in Figure 2(a) represents the non-dimensional averaged wind velocity \( U/U_{hub} \) with \( U_{hub} \) being the reference velocity at the hub height of the wind turbine, the vertical axis of the figure is the non-dimensional height \( Z/H \) about the floor of the wind tunnel test section, where \( H \) is the height of the wind turbine hub. As shown clearly in Figure 2(a), the power law exponent of the curve fitting to the measurement data was found to be \( D \approx 0.11 \). It indicates that the oncoming velocity profile of the simulated ABL wind used for the present study is very similar to those seen in offshore wind farms over open sea. Figure 2(b) gives the corresponding turbulence intensity profile of the oncoming flow in the test section of the AABL wind tunnel.

2.2 The wind turbine models used in the present study

The wind turbine models used for the present study represent the most commonly used three-blade horizontal axial wind turbines (HAWTs) seen in modern wind farms. Figure 3 shows a schematic of the wind turbine model along with typical cross section profiles of the turbine rotor blades. All
the wind turbine models used in the present study have the same rotor radius of 127 mm and hub height of 225 mm. With the scale ratio of 1:350, the wind turbine models would represent large-scale 2 MW wind turbines commonly seen in modern wind farms with a rotor diameter of about 90 m and a tower height of about 80 m. It should be noted that the blockage ratio of the wind turbine models (i.e., the ratio of the turbine blade swept area to the cross-section area of the AABL tunnel) was found to be about 1.2%, and thus, the blockage effects of the wind turbine models in the test section would be almost negligible for the present study.

The rotor blades of the model wind turbines used in the present study are made of a hard plastic material by using a rapid prototyping machine. The rotor blades have the same airfoil cross sections and platform profiles as ERS-100 prototype turbine blades developed by TPI Composites, Inc. As shown clearly in Figure 3, the rotor blade has a constant circular cross section from the blade root to 5% blade radius (R), and three NREL airfoil profiles (S819, S820, S821) are used at different spanwise locations along the rotor blade. The S821 airfoil profile is used between 0.208R and 0.40R, the S819 primary airfoil is positioned at 0.70R, and the S820 airfoil profile is specified at 0.95R. A spline function is used to interpolate the prescribed cross section profiles to generate the three-dimensional model of the rotor blade using SolidWorks software. In the present study, the rotor blades were mounted on the turbine hub with a pitch angle of 3.0 degrees (i.e., θ = 3.0°). A DC electricity generator (Kysan, FF-050S-07330) was installed inside the nacelle of the wind turbine model. As the rotation speed of the wind turbine blades changed from 0 to 1700 rpm, the corresponding TSR of the wind turbine (i.e., TSR = (ΩR)/Uhub, where Ω is the angular speed of rotation, R is the radius of the rotor blades, and Uhub is the speed of the oncoming wind at the hub height) changed from 0.0 to about 4.5. For the present study, the optimal pitch angle of the wind turbine blades was found to be about 3.0°, and the corresponding TSR was about 3.7. It should be noted that a typical three bladed HAWT on a modern wind farm usually has a tip-speed-ratio of TSR = 4–6 [33].

2.3 Measurements of the turbine power outputs, wake flow characteristics, and dynamic wind loads acting on the wind turbines

In the present study, turbine power outputs, wake flow characteristics, and the resultant wind loads acting on the wind turbines were measured quantitatively in order to assess the effects of the relative rotation direction of the tandem turbines on the interferences among the wind turbines.

The turbine power output measurements were achieved by measuring the voltage outputs of the small DC generator installed in the nacelles of the wind turbines and the corresponding electrical loadings applied to the electric circuits. During the experiments, the voltage outputs of each DC generator were acquired through an A/D board plugged into a host computer at a data sampling rate of 1 kHz for two minutes. The power coefficient of a wind turbine is usually defined as $C_{P_{WT}} = \frac{P_{WT}}{\frac{1}{2} \rho U_{hub}^3 \pi R^2}$, where $P_{WT}$ is the measured power output of the wind turbine, $\rho$ is the air density. The measured power coefficients of the wind turbine models used in the present study were found to be 25%–30% based on direct mechanical torque measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R$ (mm)</th>
<th>$H_{hub}$ (mm)</th>
<th>$\delta_{root}$ (mm)</th>
<th>$\delta_{nacelle}$ (mm)</th>
<th>$\gamma$ (°)</th>
<th>$a$</th>
<th>$a_1$</th>
<th>$a_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>127</td>
<td>226</td>
<td>18</td>
<td>26</td>
<td>5°</td>
<td>68</td>
<td>20</td>
<td>35</td>
</tr>
</tbody>
</table>
which agrees well with the values reported in Kang & Meneveau [38] for small turbine models. The power coefficients of the small turbine models were found to be smaller than those of large-scale wind turbines (i.e., 40%–50%), which is believed to be closely related to the much lower Reynolds number of the wind turbine models (i.e., \( Re \approx 8000 \) for the present study vs. \( Re \approx 1 \times 10^6 \) for the large-scale wind turbines), as suggested by Alfredsson et al. [35].

While the absolute values of the power coefficients of the wind turbine models used in the present study were found to be smaller compared with those of the large-scale wind turbines, the power outputs of the wind turbine models used in the present study were found to vary greatly when the turbine models were operated in different test conditions. Instead of using the absolute values of the power coefficients, the normalized power output of the model turbines (i.e., normalized by the maximum power output of the upstream turbine) was used in the present study to assess the effects of the relative rotation direction of the turbines on the power production performance of the wind turbines when they were operated in either co-rotating or counter-rotating configuration, as shown in Figure 1.

For the wind turbine models used in the present study, aluminum rods were used as the turbine towers to support the turbine nacelles and the rotor blades. Through holes in the wind tunnel floor, the aluminum rods were connected to high-sensitivity force-moment sensors (JR3, model 30E12A-I40) to measure the wind loads (aerodynamic forces and bending moments) acting on the wind turbine models. The JR3 load cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is ±0.25% of the full range (40 N). While the force-moment sensor mounted at the bottom of each turbine tower can provide time-resolved measurements of all three components of the aerodynamic forces and the moment (torque) about each axis, only the measured thrust coefficient, \( C_T \), and bending moment, \( C_{My} \), are given in the present study. The thrust coefficient (i.e., aerodynamic force coefficient along \( X \)-direction for the Cartesian coordinate system defined in Figure 1) and bending moment coefficient (i.e., the moment coefficient along \( Y \)-direction) were defined by using the expressions of

\[
C_T = \frac{T}{\frac{1}{2} \rho U_{hub}^2 \pi R^2},
\]

and

\[
C_{My} = \frac{M_y}{\frac{1}{2} \rho U_{hub}^2 \pi R^2 H}.
\]

During the experiments, the wind load data were acquired for 60 s at a sampling rate of 1000 Hz for each tested case. A Monarch Instrument Tachometer was also used to measure the rotation speed of the wind turbine blades.

In the present study, the turbulence characteristics of the wake flows in the plane of symmetry of the wind turbines were measured by using a Cobra Probe Anemometry system (TFI Series 100 of TurbulentFlow Instrumentation Pty Ltd). The Cobra Probe Anemometry system is capable of measuring all three components of instantaneous flow velocity vector at a prescribed point at a sampling rate of up to 2 kHz. Other flow quantities such as the turbulence intensity, turbulence kinetic energy, Reynolds stresses and other higher order terms can also be derived based on the instantaneous measurement results. During the experiments, the Cobra Probe Anemometry system was mounted on a rigid steel frame and controlled by a motorized traverse system at the prescribed downstream locations. At each measurement point, the instantaneous flow velocity data were acquired for 60 seconds at a data sampling rate of 1.25 kHz.

3 Measurement results and discussions

3.1 The power output measurements of the model wind turbines in either co-rotating or counter-rotating configuration

As described above, since the rotor blades of the counter-clockwise-rotating wind turbines were made by mirroring those of the clockwise-rotating rotor blades, the clockwise-rotating wind turbines are expected to have the same power generation performance as those of the clock-wise-rotating turbines when placed in the same oncoming flow. Figure 4 shows the normalized power outputs of the clockwise-rotating turbine and counter-clockwise-rotating turbine as a function of the tip-speed-ratio (i.e., TSR) of the wind turbines when the turbines were mounted in the same oncoming flow individually. It can be seen clearly that, within the TSR range covered in the present study, the power outputs of the wind turbine models with different rotation directions were found to be almost identical, as expected. The maximum difference of the power outputs between the clockwise-rotating and counter-clockwise-rotating turbines was found to be less than 2.0%, which is
within the measurement uncertainty for the power output measurements. It can also be seen that the wind turbine models used in the present study were found to produce the maximum power outputs when they were operated at TSR=3.7 (i.e., the corresponding electric loading being 28.6Ω). Therefore, the power output of the upstream turbine at the optimum operation condition of TSR=3.7 was selected in the present study as the baseline to determine the normalized power outputs of the wind turbines (i.e., \( P/P_{\text{max}} \)) in both clockwise-rotating and counter-clockwise-rotating configuration.

After the power production performance of each turbine model with different rotation directions was characterized individually, two wind turbines were mounted in tandem in the wind tunnel test section in order to investigate the effects of relative rotation direction of the turbines on the interferences among the wind turbines. As shown clearly in Figure 1, the wind turbine models were set to operate in either co-rotating (i.e., the downstream turbine has the same rotation direction as the upstream turbine) or counter-rotating (i.e., the downstream turbine has an opposite rotation direction in relation to the upstream wind turbine) configuration. The measured power outputs of the two wind turbines as a function of the electric loadings applied to the turbines are given in Figure 5, with the spacing between the two turbines being 0.7\( D \) for both the co-rotating and counter-rotating configuration. Since the oncoming ABL wind was kept constant during the experiments, the power output of the upstream turbine was found to be almost independent of the rotation direction of the downstream turbine, as expected. Since the downstream wind turbine was in the wake of the upstream turbine, the power output of the downstream turbine was found to be only about 55%–70% of those of the upstream turbine due to the wake interference. It can also be seen clearly that the downstream turbine in counter-rotating configuration would produce much higher power output compared with the co-rotating case.

In order to reveal the advantage of the counter-rotating configuration in power production over the co-rotating configuration more clearly, the ratios of the power outputs of the downstream turbine in counter-rotating to those in co-rotating under the same applied electric loading were calculated, which is given in Figure 6. It can be seen clearly that, within the entire test range included in the plot, the downstream turbine in counter-rotating configuration was found to produce at least 10% more power than the co-rotating case. While the maximum advantage value of the counter-rotating configuration over the co-rotating case could be as high as 20%, the downstream turbine in counter-rotating configuration was found to produce about 17% more power compared with the co-rotating turbine at the peak power output condition (i.e., the applied electric loading being 28.6Ω) with the spacing between the two tandem turbines being 0.7\( D \). Further analysis and discussions about the experimental observations will be given later in sect. 3.2.

A set of experiments were also conducted to investigate effects of the spacing between the two turbines on the advantage of the counter-rotating configuration over the co-rotating configuration in power production. During the experiments, while the upstream wind turbine was set to be at its optimum operation condition (i.e., TSR=3.7), the downstream turbine was mounted in the wake of the upstream turbine at different downstream locations. The same optimum electric loading was applied to the downstream turbine in either counter-rotating or co-rotating configuration. Since the power production performance of the upstream turbine was found to be almost independent of the rotation direction of the downstream turbines, only the power outputs of the downstream turbines in either co-rotating or counter-rotating configuration are given here for the quantitative comparison.

Figure 7 shows the ratios of the power outputs of the downstream turbine in counter-rotating to those in co-rotating as a function of the spacing between the two tandem turbines. It can be seen clearly that the advantage of the
counter-rotating configuration in power production would decrease monotonically as the spacing between the turbines increases. With spacing smaller than $2.0D$, the downstream turbine in counter-rotating configuration produces at least 10% more power than the co-rotating turbine. However, as the spacing between the turbines increases to about $5.0D$, the advantage of the counter-rotating configuration was found to be reduced to only about 4.0%. With this decay rate, the advantage of the counter-rotating configuration is expected to become almost negligible (i.e., <1.0%) when the spacing between the two turbines becomes greater than $6.5D$.

It should be noted that, on the practical relevance in wind farm design, count-rotating configuration may not be beneficial to offshore wind farms since the spacing between wind turbines is usually about ~7 rotor diameters in the prevailing wind direction for offshore wind farms [12,14]. However, counter-rotating configuration could be very useful for some onshore wind farms, where the spacing between the turbines is usually much smaller (i.e., ~3D). It will be especially useful for the turbines sited over mountains/hills, such as those sited on Alta Wind Energy Center wind farm in California’s Tehachapi Mountains, with the spacing between the turbines only about 1–2 rotor diameters.

3.2 The wake characteristics behind the wind turbines in either counter-rotating or co-rotating configuration

The characteristics of the wake flows behind the wind turbines in either counter-rotating or co-rotating configuration can be used to explain why the two turbines in counter-rotating configuration can harvest more wind energy from the same oncoming flow compared with those in co-rotating. For all of the measurement results presented in this section, while the upstream turbine was set to operate at its optimum operation condition, i.e., $\text{TSR}=3.7$, the same optimum electric loading was applied to the downstream turbines in either counter-rotating or co-rotating configuration. The spacing between the two tandem turbines was fixed as $0.7D$ during these experiments. The flow characteristics in the wakes behind the turbines at different downstream locations were compared quantitatively in order to elucidate the underlying physics.

Figure 8 shows the measured streamwise velocity (i.e., the $U$-component) profiles at three typical downstream locations in the wake flows behind the two turbines. The
measurement results at the same downstream locations for the case with only a single turbine mounted in the same oncoming wind (i.e., the case with only the upstream turbine mounted in the test section and the downstream turbine being removed), along with the velocity profile of the oncoming flow were also given in the same plots for quantitative comparison. Since a portion of the wind energy carried by the oncoming flow was harvested by the turbines, streamwise velocity deficits (i.e., the differences between the velocity profiles of the oncoming ABL wind and those of the wake flows) were observed in the wake flows. Since the cases with two turbines in either counter-rotating or co-rotating configuration would harvest more wind energy from the same oncoming flow, the velocity deficits in the wakes behind the two turbines were found to be much greater than those of the single turbine case. The velocity deficits in the wake flows were found to decrease gradually as the downstream distance increases, as expected.

In order to reveal the recovery of the streamwise velocity deficits in the wake flows more clearly and quantitatively, the streamwise velocity data in the wake flows at a prescribed height (i.e., at the height of 40% rotor span above the turbine hub) were extracted from the measurement result, and plotted in Figure 9 as a function of the downstream distance. In Figure 9, while \( U_{40\% \text{ rotor span, wake}} \) indicates the measured streamwise velocity in the wake flows at the prescribed height, \( U_{40\% \text{ rotor span, free}} \) represents the speed of the oncoming flow at the same height. It can be seen clearly that, for the case with only single turbine, the streamwise velocity at the downstream location of 2.0\( D \) was found to be about 70% of the oncoming flow at the same height (i.e., 30% streamwise velocity deficit at the downstream location of \( X/D=2.0 \)). As the downstream distance increases to about 8.0\( D \), the streamwise velocity was found to recover to 85% of the oncoming flow speed at the same height (i.e., only 15% streamwise velocity deficit at the downstream location of \( X/D=8.0 \)). While the streamwise velocity deficit in the wake flow was found to recover gradually with increasing downstream distance, the recovery rate in the region of \( X/D<4.0 \) was found to be much greater than that further downstream (i.e., \( X/D>4.0 \)).

Since the two wind turbines would harvest more wind energy from the same oncoming airflow compared with the case with only single turbine, the velocity deficits in the wake flows behind the two turbines were found to become much greater at the same downstream locations. The streamwise velocity deficits were found to become 46% and 22% (vs. 30% and 15% for the single turbine case) at the downstream locations of \( X/D=2.0 \) and \( X/D=8.0 \), respectively. It is interesting to note that, while the two tandem turbines in counter-rotating configuration was found to be able to harvest more wind energy (up to 20% more) from the same oncoming flow, compared with the case in counter-rotating, as shown clearly in Figures 8 and 9, the evolution of the streamwise velocity profiles and the recovery characteristics of the streamwise velocity deficits in the wake flows were found to be almost identical whether the turbines were operated in either counter-rotating or co-rotating configuration. This result implies that the better power production performance for the case with the turbines in counter-rotating has nothing to do with the evolution of the streamwise velocity profiles and the recovery characteristics of the velocity deficit in the wake flows.

Figure 10 gives the measured azimuthal velocity (i.e., \( V \)-component in the measurement plane) profiles at the same downstream locations in the wake flows, which can be used to explain why the turbines in counter-rotating configuration can harvest more wind energy from the same oncoming flow compared with the case in co-rotating configuration. In order to exclude the effects of the turbine tower on the evolution characteristics of the azimuthal velocity in the wake flows, only the measured results above the turbine hub height are given in the plots. As shown clearly in Figure 10, while the azimuthal velocity in the wake flow for the case with the two turbines in counter-rotating configuration was always found to be very small, significant azimuthal velocity components were found in the wake flows for the cases with only single turbine and with two turbines in co-rotating configuration. The negative sign of the azimuthal velocity indicates that the direction of the azimuthal velocity is opposite the rotation direction of upstream wind turbines, which was visualized clearly from the phase-locked PIV measurements of Hu et al. [7]. Figure 11 shows the measured azimuthal velocity at the prescribed height (i.e., at the height of 40% rotor span above the turbine hub) as a function of the downstream distance, which reveals the evolution characteristics of the azimuthal velocity in the wake flows more clearly and quantitatively. It is noted that \( U_{hub} \) in the figures indicates the speed of the oncoming flow at the hub height of the wind turbines.

As shown clearly in Figure 11, the azimuthal velocity in the wake region of \( X/D<4.0 \) for the single turbine case was found to be significant, i.e., the azimuthal velocity at the

![Figure 9](image_url) (Color online) The evolution of the streamwise velocity in the wake flows at the prescribed height.
The azimuthal velocity profiles in the wake flows at different downstream locations are shown in Figure 10. The azimuthal velocity was found to be amplified in the wake flow for the case with the two turbines in co-rotating configuration, becoming almost two times greater than that of the single turbine case at the same downstream locations. In comparison, the azimuthal velocity in the wake flow was always found to be very small, almost negligible, for the case with the two turbines in counter-rotating configuration. The significant difference in the evolution characteristics of the azimuthal velocity in the wake flows is believed to be the reason why the turbines in counter-rotating configuration would have a better power production performance compared with those in co-rotating configuration.

As described above, since the direction of the azimuthal velocity in the wake flow would be opposite the rotation direction of the upstream turbine, the negatively pre-rotating velocity in the oncoming flow would amplify the azimuthal velocity in the wake flow behind the downstream turbine when it was set to have the same rotation direction as the upstream turbine, as shown clearly in Figure 10. This result indicates that the kinetic energy associated with the significant azimuthal velocity in the wake flow of the upstream turbine could not be harvested by the downstream turbine when the turbines were operated in co-rotating configuration. However, for the case with the turbines in counter-rotating configuration, the azimuthal velocity in the wake flow behind the upstream turbine would be in the same direction as the rotation direction of the downstream turbine. The positively pre-rotating velocity relative to the downstream wind turbine was found to result in a much smaller azimuthal velocity in the wake flow behind the downstream turbine, as shown quantitatively in Figure 10. This result indicates that, while the streamwise velocity deficits in the wakes of the upstream turbines were found to be almost the same for the co-rotating and counter-rotating configurations as shown in Figure 8, the extra kinetic energy associated with the azimuthal velocity in the wake flow was harvested by the downstream turbine when it was counter-rotating relative to the upstream turbine. As a result, the turbines in counter-rotating configuration would be able to harvest more wind energy from the same oncoming flow, compared with the counter-rotating case.

As shown in Figure 11, the magnitude of the azimuthal velocity in the wake at the downstream location of $X/D=0.7$ behind the upstream turbine was found to be about 11% of the oncoming flow speed at the hub height. The kinetic en-
nergy associated with the significant azimuthal velocity is the source for the counter-rotating downstream turbine to produce extra power output over the co-rotating turbine. Since the azimuthal velocity in the wake flow was found to become smaller as the downstream distance increases, the advantage for the counter-rotating configuration over the co-rotating configuration in power production would become less and less as the spacing between the two turbines increases. The azimuthal velocity in the wake flow was found to become very small, almost negligible, when the downstream distance increases to $X/D > 6.5$. As a result, the advantage of the counter-rotating configuration over the co-rotating configuration would vanish as the spacing between the turbines becomes greater than $6.5D$, which was confirmed quantitatively from the power output measurements given in Figure 7.

Figure 12 shows the schematic of the velocity vector triangles when the turbines were in either co-rotating or counter-rotating configuration, which can be used to elucidate the underlying physics associated with the observation described above more clearly, i.e., to explain why the counter-rotating configuration can have a better power production performance than the co-rotating configuration. As described previously, the clockwise-rotating rotor blades were made in mirror symmetry to the counter-clockwise-rotating rotor blades. For the upstream turbine in either clockwise-rotating or counter-clockwise-rotating, the incoming ABL wind has no apparent azimuthal velocity component when approaching the turbine. As shown in Figure 12 in dashed lines, the velocity vector triangles for the rotor blades with different rotation directions will be symmetric. The intake angle $\phi_0$, thereby, the corresponding effective angle of attack of the oncoming flow approaching the turbine rotor blades, will be the same whether for the turbine in clockwise-rotating or counter-clockwise-rotating. As a result, the aerodynamic forces (i.e., the lift and drag forces) acting on the turbine would be the same regardless of its rotation direction. This is the reason why the counter-clockwise rotating turbine was found to have almost the same power production performance as the clockwise-rotating turbine when placed individually in the same oncoming flow, as shown quantitatively in Figure 4.

The situation would become much more complicated for cases with multiple wind turbines arranged in tandem. Since the downstream turbines would be in the wakes of the upstream turbines, non-zero azimuthal velocity component in the oncoming flows would become inevitable for the downstream turbines. Even though the clockwise-rotating rotor blades were made in mirror symmetry to the counter-clockwise-rotating rotor blades, the velocity vector triangles for the downstream turbine in co-rotating configuration relative to the upstream turbine would become different from those in counter-rotating configuration due to the existence of the azimuthal velocity component in the oncoming flow. As shown in Figure 12(a) in solid line, for the downstream turbine co-rotating relative to the upstream turbine, the azimuthal velocity in the oncoming flow would be opposite the rotation direction of the downstream turbine. The so-called “negative pre-rotating flow effect” would decrease the intake angle of the oncoming flow in relation to the rotor blades of the downstream turbine (i.e., $\phi_{\text{co-rotating}} < \phi_0$). It will result in a smaller effective angle of attack for the rotor blade in relation to the oncoming flow. Thus, the direction of the lift acting on the turbine blade would be changed with a smaller fraction of the lift in the turbine’s rotation direction, which reduces the torque to drive the wind turbine rotor. As a result, the power output of the downstream wind turbine in co-rotating configuration would be decreased compared with the case with no apparent azimuthal velocity in the oncoming flow, even though the streamwise velocity (i.e., $U$-component) of the oncoming flow was kept constant.

However, for the downstream turbine in counter-rotating related to the upstream turbine, the azimuthal velocity in the oncoming flow would be in the same direction as the turbine rotation direction. The so-called “positive pre-rotating flow effect” would increase the intake angle of the oncoming flow in relation to the turbine rotor blades (i.e., $\phi_{\text{co-rotating}} > \phi_0$).
$\phi_{\text{counter-rotating}} > \phi_0$, as shown clearly in Figure 12(b). The greater intake angle of the oncoming flow would result in a larger effective angle of attack of the effective inflow vector for the counter-rotating turbine rotor blade compared with the case with no apparent azimuthal velocity in the oncoming flow. The direction of the lift force acting on the turbine blade would be changed correspondingly, causing a larger fraction of the lift being oriented in the turbine’s rotation direction. This would increase the torque to drive turbine blade and thus the power generation of the counter-rotating downstream turbine. Therefore, the counter-rotating downstream turbine would produce more power compared with the co-rotating downstream turbine (i.e., up to 20% more power production when the spacing between the turbines is $0.7D$ according to the measurement results given in Figure 6), even though the streamwise velocity (i.e., $U$-component) distributions of the oncoming flows were found to be almost identical for the two compared cases.

The evolution of the turbulence characteristics in the wake flows behind the turbines in either co-rotating or counter-rotating configuration were also assessed in the present study. Figure 13 shows the measured turbulence intensity profiles at the same downstream locations in the wake flows with spacing between the turbines of $0.7D$. The measurement results for the case with only a single wind turbine placed in the same oncoming flow were also given in the plots as a baseline for the quantitative comparison. As described above, only the measured data above the turbine hub height were given in the plots in order to exclude the effects of the turbine tower on the turbulence characteristics of the wake flows. It can be seen clearly that both the turbulence intensity levels in the wake flows for the cases with two turbines (in either co-rotating or counter-rotating configuration) would be much higher than those with only single turbine placed in the same oncoming flow, as expected. It can also be seen that the turbulence intensity levels in the wake flow for the case with the turbines in counter-rotating were found to be slightly lower than those of the co-rotating case. The differences were found to become smaller and smaller as the downstream distance increases, and became almost indistinguishable in the far wake regime of $X/D > 5.0$.

3.3 Measurement results of the wind loadings acting on the turbines

In the present study, the resultant wind loads acting on the turbines in either co-rotating or counter-rotating configuration were also measured in order to assess the effects of the relative rotation direction of the turbines on the static and dynamic wind loads acting on the wind turbines. While both aerodynamic forces and bending moments acting on the wind turbines were quantified in the present study, Figure 14 shows only the time sequences of the instantaneous thrust forces acting on the turbines in terms of thrust coefficient $C_T$ with the turbines in either co-rotating or counter-rotating configuration and a spacing between the turbines of $0.7D$. Since the turbines were placed in the same oncoming flow, the wind loads (both static and fatigue loads) acting on the upstream turbines were found to be almost independent of the rotation direction of the downstream turbines. As shown clearly from the measurement data given in Figure 14, the instantaneous wind loads acting on the both upstream and downstream turbines were found to be highly unsteady with their magnitudes fluctuating significantly as a function of time. The time-averaged thrust coefficients were also plotted in the graphs as the dashed lines for comparison. It should be noted that, while time-averaged wind loads (i.e., static wind loads) were traditionally used for the mechanical design of wind turbines, the effects of the unsteady turbulence flow and associated dynamic wind loads are paid more and more attention in recent years for optimal mechanical design of modern wind turbines. The measurement results given in Figure 14 reveal clearly that the instantaneous wind loads acting on the wind turbines
could be significant compared with the time-averaged values (i.e., about 2–3 times higher). The quantitative measurement results of the present study highlight the importance of taking the dynamic fluctuations of the wind loads into account for the mechanical design of wind turbines in order to improve the fatigue lifetime of the wind turbines operating in turbulent ABL winds.

Based on the time sequences of the instantaneous aerodynamic forces acting on the wind turbines, the corresponding power spectrum can also be obtained through a fast Fourier transform (FFT) analysis procedure. The rotation frequencies of the rotor blades identified based on the FFT analysis were found to agree well with the rotation speeds of the turbine rotor blades measured independently by using a tachometer. Other peak frequencies, which represent the harmonic frequencies of the rotation frequency of the turbine rotor blades, can also be identified clearly from the power spectrum plots, as expected.

The measured values of the time-averaged thrust coefficients, $C_T$, bending moment coefficient, $C_{My}$, and the standard deviations of the thrust and bending moment coefficients ($\sigma_{CT}$ and $\sigma_{CM_y}$) of the wind turbines are listed in Table 2, which can be used to assess the effects of the relative rotation direction of the wind turbines on the static and fatigue wind loads acting on the turbines more clearly. Since the oncoming flow velocity for the downstream turbine would be smaller compared with that of the upstream turbine due to the velocity deficits in the wake flow behind the upstream turbine, the mean values of the wind loads acting on the downstream turbine (i.e., time-averaged thrust and bending moment coefficients) were found to be smaller than those of the upstream turbine, as expected. Since the turbulence intensity levels in the wake flow behind the upstream turbine would be much higher compared with the oncoming flow, the fluctuation amplitudes of the instantaneous wind loads acting on the downstream turbine (i.e., the standard deviations of the thrust and bending moment coefficients) were found to be much greater than those of the upstream turbine. The measurement results of the present study confirmed that the downstream wind turbines operating in the wakes of upstream turbines would experience much higher fatigue wind loads (i.e., greater standard deviations of the instantaneous aerodynamic forces and bending moments), thereby, resulting in a reduced fatigue lifetime for the

| Table 2 | The wind loads acting on the turbines in either co-rotating or counter-rotating configuration |
|-----------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
|                | Upstream turbine | Downstream turbine in co-rotating configuration | Downstream turbine in counter-rotating configuration |
| Mean thrust coefficient, $C_T$ | 0.33 | 0.21 | 0.22 |
| The standard deviation of the thrust coefficient, $\sigma_{CT}$ | 0.124 | 0.178 | 0.168 |
| Mean bending moment coefficient, $C_{My}$ | 0.39 | 0.24 | 0.26 |
| The standard deviation of the bending moment coefficient, $\sigma_{CM_y}$ | 0.119 | 0.191 | 0.174 |
downstream turbines due to the wake interferences.

From the comparisons of the measurement results for the downstream turbine in co-rotating configuration with those in counter-rotating configuration, it can be seen clearly that the downstream turbine in counter-rotating would experience slightly higher static wind loads (i.e., slightly higher time-averaged thrust and bending moment coefficients) corresponding to better power production performance, compared with those of the co-rotating downstream turbine. More interestingly, the standard deviations of the instantaneous wind loads acting on the counter-rotating downstream turbine (i.e., the standard deviations of the thrust and bending moment coefficients) were found to be smaller than those of the co-rotating downstream turbine. The smaller fatigue loads acting on the counter-rotating downstream turbine are believed to be closely related to the smaller turbulence intensity and Reynolds stress levels in the wake flow, as shown quantitatively in Figure 13. The smaller fatigue loads acting on the counter-rotating downstream turbine (i.e., the smaller standard deviations of the thrust and bending moment coefficients) would indicate a better working condition and longer fatigue lifetime for the downstream turbine, which are highly desirable for wind farm design optimization. In summary, the measurement results of the present study suggest that the turbines in counter-rotating configuration would be able to not only produce more power from the same oncoming flow by harvesting extra wind energy associated with the azimuthal velocity in the wake flow, but also reduce the fatigue loads acting on the downstream turbines, thereby, improving the working condition and extending the fatigue lifetime of the downstream turbines.

4 Conclusion

A comprehensive experimental study was conducted to quantify the effects of the relative rotation direction of two tandem wind turbines on the wake interferences among the turbines. The experimental study was performed in a large-scale Aerodynamic/Atmospheric Boundary Layer (AABL) Wind Tunnel with scaled Horizontal Axial Wind Turbine (HAWT) models. While the oncoming flow was kept constant during the experiments, the model turbines were set to operate in either co-rotating (i.e., the downstream turbine has the same rotation direction as the upstream turbine) or counter-rotating (i.e., the downstream turbine has an opposite rotation direction in relation to the upstream turbine) configuration. The turbine power outputs, the static and dynamic wind loads (i.e., aerodynamic forces and bending moments) acting on the turbines, and the turbulence characteristics in the wake flows behind the turbines were measured and compared quantitatively.

The measurement results reveal clearly that, while the power production performance and wind loads acting on the upstream turbine were found to almost independent of the rotation direction of the downstream turbine, the relative rotation direction of the downstream turbine was found to greatly affect the power production performance and the wind loads (both static and fatigue loads) as well as the turbulence characteristics in the wake flows behind the downstream turbine. The counter-rotating turbines were found to be able to harvest more wind energy from the same oncoming flow, compared with the co-rotating case. While the evolution of the streamwise velocity and the recovery characteristics of the streamwise velocity deficits in the wake flows were found to be almost identical whether the turbines were set to operate in either co-rotating or counter-rotating configuration, the significant differences in the evolution of the azimuthal velocity in the wake flow are believed to be the reason why the counter-rotating turbines would have a better power production performance compared with the co-rotating turbines. While the co-rotating downstream turbine would amplify the azimuthal velocity in the wake flow, the counter-rotating downstream wind turbine was found to be able to harvest the additional kinetic energy associated with the azimuthal velocity in the oncoming flow, thereby, making the azimuthal velocity in the wake flow become almost negligible. The wind load measurements reveal that the counter-rotating configuration can also reduce the fatigue wind loads acting on the downstream turbines, i.e., better working conditions and longer fatigue lifetimes for the downstream turbines, in addition to improving power production performance.

Since the azimuthal velocity in the wake flow was found to decrease monotonically with the increasing downstream distance, the benefit of the counter-rotating configuration was found to decrease gradually as the spacing between the turbines increases. While the counter-rotating downstream turbine was found to be able to produce up to 20% more power compared with the co-rotating downstream turbine when the spacing between the turbines was 0.7 rotor diameters (i.e., 0.7D), the advantage of the counter-rotating configuration was found to be reduced to only about 4.0% when the spacing between the turbines was increased to about 5.0D. Since the azimuthal flow velocity in the wake flow was found to become almost negligible in the further downstream region, the benefits of the counter-rotating configuration were found to die away (i.e., <1.0%) when the spacing between the turbines becomes greater than 6.5D. It suggests that, on the practical relevance of wind farm design, counter-rotating configuration would be more beneficial to onshore wind farms, compared with offshore wind farms, due to the much smaller spacing between the turbines (i.e., ~3 rotor diameters for onshore wind farms vs. 6–10 rotor diameters for offshore wind farms), especially for those turbines sited over the mountains/hills with the spacing between the turbines only about 1–2 rotor diameters.

It should be noted that the present experimental study was conducted in an ABL wind tunnel with scaled HAWT...
models, the corresponding Reynolds number of the scaled turbine models is about 2–3 orders lower than those of the full-scale wind turbines. As a result, the measured power coefficients of the scaled turbine models were found to be much smaller than those of the full-scale wind turbines due to the inherent limitations of the wind tunnel tests with scaled model turbines. While we believe that the findings derived from the present study on the effects of the relative rotation direction of wind turbines on the wake interferences among multiple turbines are meaningful and helpful to gain further insight into the characteristics of the dynamic wind loads and wake interferences among multiple wind turbines for higher total power yield and better durability of the wind turbines in general, much more research studies are needed in generalizing the observed effects and measured numbers for the cases of full-scale wind turbines.

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Dynamic wind loads and wake characteristics of a wind turbine model in an atmospheric boundary layer wind

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Abstract An experimental study was conducted to characterize the dynamic wind loads and evolution of the unsteady vortex and turbulent flow structures in the near wake of a horizontal axis wind turbine model placed in an atmospheric boundary layer wind tunnel. In addition to measuring dynamic wind loads (i.e., aerodynamic forces and bending moments) acting on the wind turbine model by using a high-sensitive force-moment sensor unit, a high-resolution digital particle image velocimetry (PIV) system was used to achieve flow field measurements to quantify the characteristics of the turbulent vortex flow in the near wake of the wind turbine model. Besides conducting “free-run” PIV measurements to determine the ensemble-averaged statistics of the flow quantities such as mean velocity, Reynolds stress, and turbulence kinetic energy (TKE) distributions in the wake flow, “phase-locked” PIV measurements were also performed to elucidate further details about evolution of the unsteady vortex structures in the wake flow in relation to the position of the rotating turbine blades. The effects of the tip-speed-ratio of the wind turbine model on the dynamic wind loads and wake flow characteristics were quantified in the terms of the variations of the aerodynamic thrust and bending moment coefficients of the wind turbine model, the evolution of the helical tip vortices and the unsteady vortices shedding from the blade roots and turbine nacelle, the deceleration of the incoming airflows after passing the rotation disk of the turbine blades, the TKE and Reynolds stress distributions in the near wake of the wind turbine model. The detailed flow field measurements were correlated with the dynamic wind load measurements to elucidate underlying physics in order to gain further insight into the characteristics of the dynamic wind loads and turbulent vortex flows in the wakes of wind turbines for the optimal design of the wind turbines operating in atmospheric boundary layer winds.

1 Introduction

With the oil and gas supply security and climate change emerging as high concerns, the need for renewable energy sources to alleviate dependence on hydrocarbons and reduce carbon dioxide (CO₂) emissions is becoming increasingly urgent. Wind energy is one of the cleanest renewable power sources in the world today. While wind energy provided only approximately 1.0% of total U.S. electricity generation in 2008, a target of 20% of USA total electricity generation from wind energy by 2030 has been set up recently by the U.S. Department of Energy. To achieve the goal of 20% of electricity generation by 2030, the total wind power capacity in USA will need to exceed 300 gigawatts (Schreck et al. 2008). Suppose if each wind turbine could generate about 2.0 MW, which corresponds to the large wind turbines with the hub height about 80 m and rotor blade diameters about 80–100 m, it would require at least 150,000 additional large wind turbines installed in onshore or/and offshore wind farms in order to meet the 20% electricity generation goal. Wind turbine dynamics, micrositing, and array effects have been identified the most significant research topics needed for wind resource characterization and wind power generation (Schreck et al.
More specifically, detailed measurements and modeling to characterize the surface wind energy resources and turbulent wake flows of wind turbines are highly desirable in order to provide more accurate estimations of the power generation and fatigue wind loads for the optimal design of the wind turbines.

As described in the review article of Vermeer et al. (2003), the wake of a wind turbine is typically divided into a near and a far wake. The near wake refers to the region from the turbine to approximately one rotor diameter downstream. In the near wake, the presence of the rotor is apparent by the number of blades, blade aerodynamics such as attached or stalled flows, 3-D effects, and tip vortices. A significant feature in the near wake of a wind turbine is the helical tip vortices induced by the rotating blades. The evolution of helical tip vortices downstream of the wind turbine significantly. The tip vortices were also recognized as an important source of noise generation and blade vibration (Massouh and Dobrev 2007). The far wake is the region beyond the near wake, where the actual rotor shape is less important. The main attentions to far wake flows are usually drawn in wake models, wake interference, turbulence models, and topographical effects.

A good physical understanding about the characteristics of the turbulent vortex flows in the wakes of wind turbines and the resultant dynamic wind loads acting on the wind turbines is essential for the optimal design of the wind turbines. This requires a detailed knowledge about the dynamic wind loads and transient behavior of the unsteady vortex and turbulent flow structures in the wakes of wind turbines. Although a number of experimental studies have been conducted recently to investigate wind turbine wake aerodynamics, most of the previous studies were performed based on qualitative flow visualization and/or using pointwise flow measurement techniques, such as hot-wire anemometry, hot-film anemometry, and laser Doppler velocimetry, to conduct flow velocity measurements at limited points of interest (Alfredsson and Dahlberg 1979; Tsustui and Matsumya 1987; Ebert and Wood 1997; Vermeer 2001; Medici and Alfredsson 2006; Chamorro and Porte-Agel 2009). A common shortcoming of such pointwise flow measurements is the incapability of providing spatial correlation of the turbulent vortex structures to effectively reveal the transient behavior of the unsteady vortex structures in the wake flows. Temporally synchronized and spatially resolved flow field measurements are highly desirable in order to elucidate the underlying physics to improve our understanding about the characteristics of the turbulent vortex structures in wakes of wind turbines. Contemporary flow diagnostic techniques, such as particle image velocimetry (PIV) to be used in the present study, are capable of providing such information.

Surprisingly, only very few experimental studies were conducted recently to provide flow field measurements to quantify the transient behavior of the unsteady vortex structures in the wakes of wind turbines. Whale et al. (2000) studied the tip vortices generated by an untwisted two-bladed rotor in a water tank by using a PIV system. Based on the comparison of the PIV measurements with the numerical simulation results using a rotor vortex lattice method, they reported a good qualitative agreement between the wake structures obtained from the PIV measurements and the numerical simulations, particularly in regard to the shape of the wake boundary, including features such as wake expansion and contraction, despite the difference in Reynolds numbers of the experiments and numerical simulations. They also suggested that “…the fundamental behavior of the helical tip vortices would be almost insensitive to the blade chord Reynolds number as long as the similarity of the tip-speed-ratio (TSR) of the wind turbine is observed”. Grant and Parkin (2000) used a digital PIV system to measure the flow velocity fields downstream of a two-bladed wind turbine model in a low-speed wind tunnel. The PIV measurements reveal clear pictures of the turbine wake flows, including the size and persistence of the velocity deficit and tip vortices in the wake as well as the wake deflection in yaw, both aligned into the incoming wind direction and at a range of yaw angles, up to approximately 5 rotor diameters downstream. More recently, Massouh and Dobrev (2007) conducted a wind tunnel study to characterize the wake flow downstream of a small wind turbine model based on phase-locked PIV and hotwire measurements. The evolution of the helical tip vortices downstream of the wind turbine model was revealed clearly from the measurement results. While useful information has been uncovered by those previous studies, it should be noted that most of those experimental studies were conducted with the wind turbine models installed in air or water flows with homogenous, uniform incoming flow velocity, and relatively low turbulence intensity levels. However, in reality, most of the wind turbines operate in atmospheric boundary layer winds with significant variations in both mean wind speed and turbulence intensity levels along vertical directions. The effects of the significant variations in both the mean wind speed and turbulence intensity levels of the atmospheric boundary layer winds on the dynamic wind loads and the evolution of the unsteady vortex and turbulent flow structures in the wakes of wind turbines have not been fully explored.

In the present study, an experimental study was conducted to characterize the dynamic wind loads and evolution of the unsteady vortex structures in the near wake of a horizontal axis wind turbine (HAWT) model installed in an atmospheric boundary layer wind. The experimental study was performed in a large-scale aerodynamic/atmospheric
boundary layer (AABL) Wind Tunnel available at Iowa State University. In addition to measuring dynamic wind loads acting on the wind turbine model by using a high-sensitive force-moment sensor unit, a high-resolution PIV system was used to make both “free-run” and “phase-locked” PIV measurements to quantify the transient behavior of the unsteady vortex and turbulent flow structures in the near wake of the wind turbine model. The detailed flow field measurements were correlated with the dynamic wind load measurements to elucidate the underlying physics in order to gain further insight into the characteristics of the dynamic wind loads and turbulent vortex flows in the wakes of wind turbines for the optimal design of the wind turbines operating in atmospheric boundary layer winds.

2 Experimental setup and wind turbine model

2.1 Atmospheric boundary layer wind tunnel

Wind tunnel facilities have been widely used for wind turbine studies due to their capabilities to produce well-controlled flow environments. In the present study, a large-scale AABL wind tunnel located at the Aerospace Engineering Department of Iowa State University was used to perform the experimental investigations. The AABL wind tunnel is a closed-circuit wind tunnel with a test section of 20 m long, 2.4 m wide, and 2.3 m high, optically transparent side walls, and a capacity of generating a maximum wind speed of 45 m/s in the test section.

Figure 1 shows a picture of the test section of the AABL wind tunnel with a three-blade, HAWT model (at a scale ratio of 1:350) mounted in the center of a turn-table. Spike structures and arrays of wood blocks were installed at the upstream of the wind turbine model in order to generate a turbulent boundary layer flow to simulate the atmospheric boundary layer winds usually seen in wind farms. Figure 2 shows the measured mean velocity and turbulence intensity profiles at the center of the turn-table, i.e., the location where the wind turbine model would be installed, by using a hotwire anemometer probe. It is well known that the wind speed at the elevation height of 10 m above the ground is widely used to characterize atmospheric boundary layer winds. The horizontal axis in Fig. 2a represents non-dimensional mean velocity $U/U(z_{10})$, where $U(z_{10})$ is the reference velocity at a height of $z_{10} = 28.6$ m above the floor of the AABL tunnel, which is equivalent 10 m elevation height above the ground in a wind farm based on the scale ratio of 1:350. It has been suggested that the mean velocity profile of an atmospheric boundary layer flow over an open terrain can usually be fitted well by using a logarithmic function or a power function (Jain 2007), therefore, the logarithmic and power curves fitting to the measurement data were also given in Fig. 2a for comparison. It can be seen clearly that the measurement data can be represented reasonably well by either the logarithmic function or the power function. It should also be noted that, while the power law exponent for an atmospheric boundary layer wind over an open terrain in nature usually ranges from 0.1 to 0.2 according to ASCE standard (ASCE 2005), the power law exponent of the curve fitting to the present measurement data was found to be 0.165, which is well within the range of those of an atmospheric boundary layer wind over an open terrain. Figure 2b shows measured turbulence intensity of the turbulent boundary layer flow generated inside the AABL tunnel as a function of the height above the floor of the AABL tunnel. The standard turbulence intensity profile of an atmospheric boundary layer wind over an open terrain as suggested by Architectural Institute of Japan (AIJ 1996) was also plotted in the figure for comparison. It can be seen clearly that the turbulent boundary layer flow generated inside the AABL tunnel can be used to simulate the atmospheric boundary layer wind over an open terrain in nature reasonably well.

2.2 The tested wind turbine model

The wind turbine model used for the present study represents the most widely used three-blade horizontal axial wind turbines (HAWT) found in on-shore and off-shore wind farms. As shown in Fig. 3, the rotor radius of the wind turbine model is 127 mm and the height of the turbine nacelle is 225 mm above the wind tunnel floor. With the scale ratio of 1:350, the test model would represent a wind turbine in a wind farm with the rotor diameter about 90 m and tower height about 80 m. It should be noted that the blockage ratio of the wind turbine model (i.e., the ratio of the turbine blade swept area to the cross-section area of the AABL tunnel) was found to be about 1.2%. Thus, the block
The effects of the wind turbine model would be very small, which is almost negligible, for the present study. The rotor blades of the wind turbine model used in the present study are MA0530TE blades (Windsor Propeller Inc.), which are twisted blades with the pitch angle ranging from 20° at the root to 10° at the tip of the blades. The blades have a chord length of 12 mm at tip, 19 mm in the middle, and 16 mm at root. The airfoil cross-section of blades has a concave pressure surface and is well adapted for low Reynolds number applications. Since they were originally designed for propeller applications, the blades were mounted reversely with the pressure side of the blades facing the incoming airflow during the experiments in order to improve their aerodynamic performance when used as wind turbine blades. A small electricity generator was installed inside the nacelle of the wind turbine model, which would produce electricity as driven by the rotating blades. The primary design parameters of the wind turbine model are listed in Table 1.

During the experiments, while the wind turbine model was installed in the simulated atmospheric boundary layer wind, the mean wind speed at the hub height of the wind turbine model was set to be 4.0 m/s (i.e., $V_o = 4.0$ m/s). The corresponding chord Reynolds number (i.e., based on the averaged chord length of the rotor blades and the wind speed at hub height) was found to be about 6,000, which is significantly lower than those of the wind turbines in wind farms. It should be noted, according to Alfredsson et al. (1982), the chord Reynolds number would have significant effects on the characteristics of wind turbine performance. For example, the maximum power coefficient would be much lower for the wind turbine models operating at much lower Reynolds numbers.
lower Reynolds numbers. However, as suggested by Medici and Alfredsson (2006), the behaviors of the unsteady vortex and turbulent flow structures in the wake of wind turbines would be almost independent to the chord Reynolds numbers of the wind turbines. The wind turbines with similar tip-speed-ratio (TSR) would produce very similar near wake characteristics such as helical shape, rotation direction, and strength decay of the tip vortices.

In the present study, while the incoming atmospheric boundary layer wind was kept constant during the experiments, the rotating speed of the turbine blades was adjusted by applying different electric loads to the small electricity generator installed inside the turbine nacelle. With the rotation speed of the wind turbine blades changed from 0 to 1,700 rpm, the corresponding tip-speed-ratio of the wind turbine model (i.e., \( \lambda = (\Omega R)/V_o \), where \( \Omega \) is the angular speed of rotation, \( R \) is the radius of the rotor blades, and \( V_o \) is the wind speed at the hub height) was found to be changed from 0.0 to about 4.5 for the present study. It should be noted that a typical three-bladed HAWT on a wind farm usually has a tip-speed-ratio of \( \lambda = 4-6 \).

### 2.3 Experimental setup for dynamic wind load and flow field measurements

In the present study, an aluminum rod was used as the turbine tower to support the nacelle and the rotor blades of the wind turbine model. Through a hole on the wind tunnel floor, the aluminum rod was connected to a high-sensitivity force-moment sensor (JR3, model 30E12A-I40) to measure the dynamic wind loads (both aerodynamic forces and bending moments) acting on the wind turbine model. The JR3 load cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is \( \pm 0.25\% \) of the full range (40 N). While the force-moment sensor mounted at the bottom of the turbine tower can provide time-resolved measurements of all three components of the aerodynamic forces and the moment (torque) about each axis, only the measured thrust coefficient, \( C_T \), and bending moment, \( C_M \), are presented in the present study. The thrust coefficient (i.e., aerodynamic force coefficients along X-direction as shown in Fig. 4) and bending moment coefficient (i.e., the moment coefficient along Z-direction) were defined by using the expressions of

\[
C_T = \frac{T}{\rho V_o^2 R}, \quad \text{and} \quad C_M = \frac{M}{\rho V_o^2 R^2 \Omega}
\]

where \( \rho \) is the air density, \( V_o \) is the mean wind speed at the hub height, \( H \). During the experiments, the wind load data were acquired for 60 s at the sample rate of 1,000 Hz for each tested case.

In addition to the wind load measurements, a high-resolution digital PIV system was used to achieve detailed flow field measurements to quantify the characteristics of the turbulent vortex flow in the wake of the wind turbine model. Figure 4 shows the schematic of the PIV system used in the present study. For the PIV measurements, the airflow was seeded with \( \sim 1 \mu m \) oil droplets by using a droplet generator. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm. The laser beam was shaped to a sheet by a set of mirrors along with spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 1.5 mm. A high-resolution 12-bit CCD camera (PCO2000, CookeCorp) was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a digital delay generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition.

After PIV image acquisition, instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window of 32 \( \times \) 32 pixels. An effective overlap of 50\% of the interrogation windows was employed in PIV image processing. After the instantaneous velocity vectors \((u_i, v_i)\) were determined, the vorticity \((\omega_i)\) can be derived. The distributions of the ensemble-averaged flow quantities such as the mean velocity, normalized Reynolds Stress \((\tau = -u'v' / U_\infty^2)\), and turbulence kinetic energy \((\text{TKE} = 0.5 \left( \bar{u}^2 + \bar{v}^2 \right) / U_\infty^2)\) were obtained from a cinema sequence of about 1,000 frames of instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors is estimated to be within 2\%, while the uncertainties for the measurements of ensemble-averaged flow quantities such as Reynolds stress and TKE distributions about 5\%.

In the present study, both “free-run” and “phase-locked” PIV measurements were performed during the
experiments. The “free-run” PIV measurements were conducted in order to determine the ensemble-averaged flow statistics (e.g., mean velocity, Reynolds Stress, and TKE) in the near wake of the wind turbine model. For the “free-run” PIV measurements, the image acquisition rate was pre-selected at a frequency that is not a harmonic frequency of the rotating frequency of the turbine rotor blades in order to ensure physically meaningful measurements of the ensemble-averaged flow quantities.

“Phase-locked” PIV measurements were also conducted in the present study in order to elucidate more details about the evolution of unsteady vortex structures in the wake of the wind turbine model in relation to the position of the rotating rotor blades. As shown in Fig. 4, a digital tachometer was used to detect the position of a pre-marked rotor blade in order to perform the “phase-locked” PIV measurements. The tachometer would generate a pulsed signal as the pre-marked rotor blade passed through the vertical PIV measurement plane. The pulsed signal was then used as the input signal to a digital delay generator (DDG) to trigger the digital PIV system for the “phase-locked” PIV measurements. By adding different time delays between the input signal from the tachometer and the TTL signal output from the DDG to trigger the digital PIV system, the “phase-locked” PIV measurements at different rotation phase angles of the pre-marked rotor blade can be accomplished. At each pre-selected phase angle (i.e., corresponding to different positions of the pre-marked rotor blade related to the vertical PIV measurement plane), 160 frames of instantaneous PIV measurements were used to calculate the phase-averaged flow velocity distribution in the wake of the wind turbine model.

3 Results and discussions

3.1 Dynamic wind load measurement results

Figure 5 shows the typical measurement results of the dynamical wind loads acting on the wind turbine model in the terms of thrust coefficient $C_T$ and bending moment coefficient $C_M$ with wind turbine operating at the tip-speed-ratio of $\lambda = 3.0$. As shown clearly in Fig. 5a, b, the instantaneous wind loads (both thrust and bending moment) acting on the wind turbine model were found to be highly unsteady with their magnitudes fluctuating significantly as a function of time. The time-averaged values of the measured thrust and bending moment coefficients were also plotted in the graphs as the dashed lines for comparison. It should be noted that, while time-averaged wind loads were traditionally used for the mechanical design of wind turbines, the effects of the unsteady turbulence flow and associated dynamic wind loads are paid more and more attention in recent years for optimal design of modern wind turbines. The measurement results given in Fig. 5a, b reveal clearly that the instantaneous wind loads acting on a wind turbine operating in a turbulent atmospheric boundary layer wind could be significant compared with the time-averaged values (i.e., about 2–3 times higher). The quantitative measurement results of the present study highlight the importance of taking the dynamic fluctuations of the wind loads into account for the mechanical design of wind turbines in order to improve the fatigue lifetime of wind turbines operating in turbulent atmospheric boundary layer winds.

Figure 5c, d shows the histograms of the measured dynamic thrust and bending moment acting on the wind
turbine model. While the instantaneous wind loads acting on the wind turbine model were found to be highly unsteady with their magnitude fluctuating randomly, the histograms of the measured aerodynamic thrust and bending moment coefficients were found to be fitted reasonably well by using Gaussian functions. While the standard deviation of the aerodynamic thrust coefficient was found to be 0.11 with the mean value at $C_T = 0.31$, the standard deviation of the bending moment coefficient was 0.15 with the mean value of $C_M = 0.35$. Figure 5e, f shows the power spectrum of the measured aerodynamic thrust and bending moment obtained through a fast Fourier transform (FFT) analysis procedure. A dominant peak at $f_0 = 17.0$ Hz can be identified in the spectrum plots, which corresponds to the rotation speed of the rotor blades of the wind turbine model at the tip-speed-ratio of $\lambda = 3.0$. The rotation frequency of $f_0 = 17.0$ Hz based on the FFT analysis of the wind load measurements was found to agree well with the independently measured rotation speed of the rotor blades by using a tachometer. Other peaks, which represent the harmonic frequencies of the rotation frequency of the turbine rotor blades, $f_0$, can also be identified clearly from the power spectrum plots.

It is well known that the tip-speed-ratio (often known as TSR) of a wind turbine is of vital importance in the design of wind turbines. In the present study, the effects of the tip-speed-ratio of the wind turbine on the dynamic wind loads and the flow characteristics in the wake of the wind turbine model were investigated systematically. As described above, during the experiments, while the incoming atmospheric boundary layer wind was kept constant, the rotating speed of the rotor blades of the wind turbine model was adjusted by applying different electric loads to the small electricity generator mounted inside the turbine nacelle. It should be noted that, while the variations of the power output coefficient as a function of the tip-speed-ratio of a
wind turbine have been reported in previous studies (Boeing 1982; Jain 2007), very little can be found in the literature about the variations of the wind loads (e.g., aerodynamic thrust and bending moment) acting on wind turbines as a function of the tip-speed-ratio of the wind turbines, even though wind load data are very critical for the mechanical design of wind turbines operating in turbulent atmospheric boundary layer winds.

Figure 6 gives the measured mean thrust, \( C_T \), and bending moment coefficient, \( C_M \), of the wind turbine model as a function of the tip-speed-ratio of the wind turbine model, \( \lambda \). The profiles of the mean thrust and bending moment coefficients were found to follow a similar trend as the tip-speed-ratio of the wind turbine model increases. As shown in the figure, the mean thrust and bending moment coefficients were found to increase gradually as the tip-speed-ratio increases while the tip-speed-ratio, \( \lambda \), is still relatively small (i.e., \( \lambda < 3.0 \)). They were found to reach their peak values at the tip-speed-ratio of \( \lambda \approx 3.0 \), then, began to decrease with the increasing tip-speed-ratio when the tip-speed-ratio becomes relatively big (i.e., \( \lambda > 3.5 \)). Similar trends were also reported by Boeing (1982) and Jain (2007) to investigate the variations of the power coefficients of wind turbines as a function of the tip-speed-ratio.

The variations of the resultant flow velocity and effective angle of attack of the incoming airflow related to the turbine blade at different tip-speed-ratios may be used to qualitatively explain certain aspects of the experimental observation described above. Figure 7 shows the schematic of the flow velocity vectors relative to the cross-section of a turbine blade at different tip-speed-ratios. As shown in the figure, the magnitude of the resultant velocity of the airflow related to the turbine blade, \( V_{\text{total}} \), and the effective angle of attack of the resultant velocity, \( \alpha_{\text{eff}} \), would change significantly as the tip-speed-ratio of the wind turbine model increases. The lift and drag forces acting on the turbine blade were used to deduce a resultant aerodynamic force, which is indicated by the dashed black vector in the figures. While the projection of the resultant aerodynamic force along the direction normal to the rotation disk of the wind turbine (i.e., along X-axis direction) was measured as the aerodynamic thrust force acting on the wind turbine model, \( C_T \), while the effective angle of attack of the resultant velocity related to the turbine blade would be quite high. Airfoil stall could be expected at the high effective angle of attack, and large-scale flow separation would take place over the suction side of the turbine blade. Due to the airfoil stall along with the small resultant flow velocity, the resultant aerodynamic force acting on the turbine blade would be quite small when the tip-speed-ratio of the wind turbine is relatively small. As a result, the aerodynamic thrust force acting on the turbine blade would be small at relatively small tip-speed-ratio of the wind turbine, which was confirmed by the wind load measurements shown in Fig. 6. Spera (1994) also suggested that the performance of a wind turbine will be mainly controlled by the blade stall when the tip-speed-ratio of the wind turbine is relatively small.

As the tip-speed-ratio of the wind turbine increases, the magnitude of the resultant velocity, \( V_{\text{total}} \), would increase, while the effective angle of attack of the airflow related to the turbine blade, \( \alpha_{\text{eff}} \), would decrease continuously. In an optimal operating condition, a favorable effective angle of attack will be achieved right before the occurrence of airfoil stall. As shown in Fig. 7b, a significant resultant aerodynamic force would be generated due to the favorable effective angle of attack and the larger resultant flow velocity related to the turbine blade. As a result, the aerodynamic thrust acting on the wind turbine model, which is the projection of the resultant aerodynamic force along the direction normal to the rotation disk of the wind turbine, would reach its peak value as the wind turbine operating at the optimum tip-speed-ratio (\( \lambda \approx 3.0 \) for the present study as shown in Fig. 6).

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**Fig. 6** Variations of the time-averaged wind loads as a function of the tip-speed-ratio. a Time-averaged thrust coefficient. b Time-averaged moment coefficient.
As the tip-speed-ratio of the turbine blades keeps on increasing, the effective angle of attack of the airflow velocity with respect to the turbine blade would become smaller and smaller. As a result, the resultant aerodynamic force acting on the blade could become quite small, as shown in Fig. 7c. This would result in the decreasing trend of the measured aerodynamic thrust coefficient for cases with relatively big tip-speed-ratios, as revealed at the right-hand side of the profile shown in Fig. 6.

3.2 “Free-run” PIV measurement results

As described above, the flow field in the vertical plane passing the rotation axis of the wind turbine was measured by using a high-resolution PIV system. Figure 8 shows typical “free-run” PIV measurement results with the tip-speed-ratio of the wind turbine model at $\lambda \approx 3.0$. As expected, a row of tip vortex structures, which aligned themselves well in the downstream of the tips of the turbine blades, were revealed clearly from the instantaneous PIV measurement result given in Fig. 8a. A large flow separation zone can be found downstream of the turbine nacelle with its size being much greater than the diameter of the nacelle body. A series of vortex structures shedding periodically from the roots of the rotating turbine blades can also be found at the external boundary of the separation zone surrounding the turbine nacelle. The existence of the root vortex structures was also reported by Massouh and Dobrev (2007). It should also be noted that, additional flow structures were found to appear at the inboard of the blades tips at approximately 50–60% span in the form of concentrated vortex structures in the wake region. The vortex structures were found to move outward under the influence of wake expansion as they travel downstream, and finally merging with the tip vortex structures at approximately 2.0R downstream. A similar flow feature was also reported by Whale et al. (2000).

As shown clearly in the ensemble-averaged PIV measurement result given in Fig. 8b, the incoming airflow was found to slow down greatly as it flows across the rotation disk of the turbine blades. Obvious velocity deficits (i.e., local wind speed is much lower than that of the incoming airflow) can be observed in the region downstream of the rotation disk of the turbine blades. It indicates that a portion of the kinetic energy of the airflow associated with the velocity deficits has been harvested by the wind turbine and turned into electric power through the electric generator inside the turbine nacelle. The expansion of the wake flow downstream of the wind turbine can be seen clearly from the distribution pattern of the iso-velocity contour lines shown in Fig. 8b. As expected, a recirculation region with much lower velocity (i.e., larger velocity deficits) was found in the downstream of the turbine nacelle.

Figure 8c, d shows the measured TKE and Reynolds shear stress distributions in the wake of the wind turbine model. It can be seen clearly that, corresponding to the shedding of the unsteady tip vortices in the wake flow, the TKE levels along the shedding path of the tip vortex structures were found to be quite high. The wake flow downstream of the turbine nacelle was also found to be highly turbulent (i.e., with very high TKE). The high TKE levels in the regions are believed to be closely related to the generation of the unsteady root vortices and flow separation around the turbine nacelle, as revealed clearly from the
instantaneous PIV measurement results. Turbulent vortex structures were also found to appear in the wake of the turbine tower, via shedding unsteady Karman vortices. As shown in Fig. 8, the high TKE levels in the region under the turbine nacelle could be attributed to the interference between the turbulent wake flow of the turbine tower and unsteady vortex structures induced by the rotating turbine blades.

As revealed clearly from the measured Reynolds stress distribution given in Fig. 8d, the regions with high levels of the Reynolds shear stress were found to concentrate in the shedding paths of the tip vortices and the root vortex structures as well as in the wake regions downstream of the turbine nacelle and tower. As suggested by Cal et al. (2010), the high Reynolds stress in the wake of a wind turbine would play an important role in promoting the vertical transport of the kinetic energy in the wake of the wind turbine, which will draw down more high velocity wind from above to the boundary layer flow, resulting in a fast recovery of the velocity deficit in the wake of a wind turbine. The findings revealed from the PIV measurement results are found to agree well with the observations of Chamorro and Porte-Agel (2009), who conducted flow measurements by using a pointwise cross-wire anemometer.

In the present study, the effects of the tip-speed-ratio of the wind turbine model on the flow characteristics in the wake of the wind turbine model were also examined. Figure 9 shows the ensemble-averaged PIV measurement results with the tip-speed-ratio of the turbine model changing from $\lambda = 3.0$ to $\lambda = 4.5$. While the PIV measurement results reveal a very similar wake flow pattern, some obvious differences can still be identified from the comparison of the plots at different tip-speed-ratios. It can be seen clearly that, as the airflow passes the rotation disk of the turbine blades, the velocity deficits in the wake region (i.e., the loss of the kinetic energy) were found to be much smaller for the cases with relatively high tip-speed-ratios (i.e., for the cases of $\lambda = 4.0$ or $\lambda = 4.5$) compared with those with relatively low tip-speed-ratios (i.e., the cases of $\lambda = 3.0$ or $\lambda = 3.5$). It indicates that wind turbine could harvest much less wind energy if the tip-speed-ratio of the wind turbine model was too high, which confirmed the analysis described above and shown schematically in Fig. 7.
In order to elucidate the effects of the tip-speed-ratio of the wind turbine more clearly and quantitatively, the transverse profiles of the ensemble-averaged wind speed and the TKE at the downstream location of $X/R = 1.0$ as a function of the tip-speed-ratio of the wind turbine model are shown in Fig. 10. The mean velocity profile of the incoming atmospheric boundary layer wind was also plotted in the figure for comparison. It can be seen clearly that, compared with the velocity profile of the incoming airflow, significant velocity deficits were found to be generated in the wake flow due to the installation of the wind turbine model in the atmospheric boundary layer wind. The size of the regions with significant velocity deficits were found to be much greater than that can be expected from the turbine nacelle only. It indicates that the incoming airflow would be decelerated greatly as they pass through the rotation disk of the turbine blades. According to the momentum and energy conservation laws, while the aerodynamic drag force acting on the wind turbine is proportional to the square of the velocity deficits, the power output of the wind turbine model (i.e., the wind energy harvested by the wind turbine model) would be proportional to the cube of the velocity deficits. Larger velocity deficits in the transverse velocity profiles would indicate stronger aerodynamic loads acting on the wind turbine model as well as more wind energy harvested by the wind turbine model. As revealed from the transverse mean velocity profiles shown in Fig. 10, the largest velocity deficit in the wake flow was found at the tip-speed-ratio $\lambda \approx 3.0$ for the present study. It would suggest that the wind turbine model would experience the maximum wind loads as well as have the best wind energy harvesting capability when it was operated at the tip-speed-ratio $\lambda \approx 3.0$. The finding was confirmed quantitatively from the independent wind load measurement results given in Fig. 6. The normalized TKE profiles shown in Fig. 10b also revealed clearly that the wake flow downstream of the turbine nacelle would be highly turbulent (i.e., with very high TKE levels), corresponding to the shedding of the unsteady root vortex structures and flow separation around the turbine nacelle as revealed clearly from the PIV measurement results described above. A region with high turbine kinetic energy levels can also be found along the shedding path of the tip vortices in the wake of the wind.
turbine model. The high turbulence level in the wake flow would indicate a highly unsteady wind loads acting on the wind turbine model, which would affect the mechanical strength and fatigue lifetime of the wind turbine model significantly. The findings derived from the present study are found to agree well with the observations of Chamorro and Porte-Agel (2009).

3.3 Phase-locked PIV measurement results

“Phase-locked” PIV measurements were conducted to produce “frozen” images of the unsteady wake vortex structures at different phase angles, from which the evolution of the unsteady wake vortex structures can be revealed more clearly and quantitatively. In the present study, the angle between the vertical PIV measurement plane and the position of a pre-marked rotor blade (i.e., blade #1) is defined as the phase angle. Figure 11 shows the phase-locked PIV measurement results with the tip-speed-ratio of the wind turbine model being $\lambda = 3.0$ and phase angle changing from $0^\circ$ to $120^\circ$. As shown in the figures, the pre-marked turbine blade would be in the most upward position (i.e., within the vertical PIV measurement plane) at the phase angle of $\theta = 0^\circ$. As the phase angle increases, the turbine blade would rotate out of the vertical PIV measurement plane. The second turbine blade would rotate into the PIV measurement plane at the phase angle of $\theta = 120^\circ$. One of the obvious flow features that can be identified from the “phase-locked” PIV measurements is the existence of “wave-shaped” flow structures at the tip height of the wake flow, which were found to propagate downstream as the phase angle increases. The generation of “wave-shaped” flow structures is actually due to the periodic shedding of the tip vortex structures, which are
revealed more clearly in Fig. 12 and will be discussed in detail later. It can also be seen that, as the phase angle increases (i.e., as the pre-marked turbine blade was rotating out of the PIV measurement plane), high-speed airflows (i.e., the region with red color contour) would intrude more deeply down into the boundary layer flow in the region downstream of the rotation disk of the wind turbine model. It indicates that the wind energy of the airstreams within the PIV measurement plane would be harvested only when the turbine blades were rotated into the plane, as expected. Similar findings were also reported in the study of Massouh and Dobrev (2007).

Figure 12 shows the vorticity distributions in the wake of the wind turbine model, which were derived from the “phase-locked” PIV measurements at different phase angles, in order to reveal the evolution of the unsteady wake vortex structures more clearly. As described above, the pre-marked turbine blade would be within the vertical PIV measurement plane at the phase angle of $\theta = 0^\circ$. It can be seen clearly that a tip vortex would be induced at the tip of the pre-marked turbine blade at $\theta = 0^\circ$. As the phase angle increases, while the pre-marked turbine blade would rotate out of the vertical PIV measurement plane, the tip vortex was found to shed from the tip of the turbine blade and move downstream, as indicated by the red dashed line in the figure. It can also be seen that the tip vortex induced by the pre-marked blade (i.e., the 1st blade) would align itself nicely with the other tip vortices induced by the 2nd and 3rd turbine blades to form a moving tip vortex array in the wake flow. The relative velocity vectors (i.e., after subtracting the velocity of the incoming airflow at the tip height of the turbine blade from the measured flow velocity...
fields) at phase angle $\theta = 0^\circ$ and $\theta = 60^\circ$ were also given in the figure in order to visualize the formation and evolution of the tip vortex array more clearly. It can be seen clearly that the periodic shedding of the tip vortex array would cause the formation of “wave-shaped” structures at the tip height, as shown clearly in the “phase-locked” PIV measurement results given in Fig. 11. It should also be noted that, in addition to the tip vortex array, the periodic shedding of the unsteady vortex structures at the roots of the rotating blades and the flow separation around the turbine nacelle were also visualized clearly from the “phase-locked” PIV measurement results.

It should be noted that the PIV measurement results presented above represents only a plane view of a complex 3-D wake vortex flow within the vertical measurement plane. It is highly desirable and much more effective to elucidate underlying physics if a 3-D view of the wake vortex flow can be reconstructed. In the present study, a 3-D view of the wake vortex structures in the wake of the wind turbine model was reconstructed based on the “phase-locked” PIV measurement results, which is shown in Fig. 13. The trajectories of the tip vortex structures, which were determined by tracking the centers of the tip vortices induced by the three turbine blades at different phase angles, were added in the figure in order to elucidate the helical motion of the tip vortices more clearly. It can be seen clearly that the tip vortices originated from the tips of the rotor blades would form three helical vortex tubes as they moved downstream. The helical motion of the tip vortices was found to be reverse to the rotation direction of the turbine blades. The gap between the helical vortex tubes was found to be a function of the tip-speed-ratio of the wind turbine model, which can be seen more clearly in Fig. 15. While the helical tip vortex structures in the wakes of wind turbines were visualized qualitatively with smoke in previous studies (Anderson et al. 1982; Vermeer 2001; Hand et al. 2001), the 3-D view of the PIV measurement results given in the present study is believed to be the first to elucidate the formation and evolution of the helical tip vortex structures quantitatively.

Fig. 12 Evolution of the tip vortex structures at the tip-speed-ratio of $\lambda = 3.0$

Fig. 13 A 3-D view of the tip vortex structures in near wake of the wind turbine model
The strength of the helical tip vortices, which can be determined quantitatively based on the “phase-locked” PIV measurements, was also found to change significantly as they moved downstream. Figure 14 shows the decay profile of the peak vorticity of the tip vortices with the wind turbine model operating at the tip-speed-ratio of $\lambda = 3.0$. The measurement data shown in the figure were obtained by tracking the maximum vorticity of the tip vortices revealed from the “phase-locked” PIV measurement results at different phase angles. It can be seen clearly that the strength of the tip vortices would decay rapidly as they travelled downstream. The tip vortex structures were found to have only about 35% of their original strength as they travelled to the downstream location of $X/R = 1.0$. As shown in the figure, the strength decay profile of the tip vortices can be fitted well by using a power law function. It indicates that the strength of the tip vortices would decay rapidly following a power law in the near wake of the wind turbine model.

Figure 15 shows the typical “phase-locked” PIV measurement results with the wind turbine model operating at four different tip-speed-ratios. The effects of the tip-speed-ratio of the wind turbine model on the evolution of the unsteady vortex flow structures in the wake of the wind turbine model were revealed clearly from the comparison of the PIV measurement results. It can be seen clearly that

\[ y = a \times x^b; \quad a=0.323, \quad b=-0.197 \]

**Fig. 14** The strength decay of the tip vortices versus downstream distance at $\lambda = 3.0$

**Fig. 15** The evolution of the wake vortex structures at different tip-speed-ratios. a $\lambda = 3.0$, b $\lambda = 3.5$, c $\lambda = 4.0$, d $\lambda = 4.5$
the distance between the neighboring tip vortices (i.e., the pitch gap between the helical tip vortex tubes as shown in Fig. 13) would decrease almost linearly as the tip-speed-ratio of the wind turbine model increases. The strength of the tip vortices was found to become much weaker as the wind turbine model operated at a higher tip-speed-ratio. This observation is believed to be closely related to the formation mechanism of the tip vortices. It is well known that the generation of tip vortices is due to the pressure differences between the pressure and suction sides of the wind turbine blades. As the tip-speed-ratio of the wind turbine model increases, the effective angle of attack of the incoming airflow with respect to the airfoil cross-section would become smaller and smaller, as illustrated in Fig. 7. The smaller pressure difference between the pressure and suction sides of the turbine blades at smaller effective angles of attack would result in weaker tip vortices, as revealed clearly in Fig. 15. It can also be found that the unsteady vortices shedding from the roots of the turbine blades and turbine nacelle would become much bigger and stronger as the tip-speed-ratio increases. As a result, the flow separation regions around the turbine nacelle were found to increase with the increasing tip-speed-ratio of the wind turbine model, as revealed clearly in the time-averaged PIV measurement results shown in Fig. 9. It should also be noted that the additional row of the unsteady vortex structures shedding at approximately 50–60% span of the turbine blades were found to be more distinct for the cases with higher tip-speed-ratio, while they were still found to merge with the tip vortex structures at further downstream.

As described above, while the strength of the tip vortices was found to decay rapidly in the wake of the wind turbine model, the tip vortices were also found to wander around as they travelled downstream. Figure 16 shows the instantaneous center positions of the tip vortices in the wake of the wind turbine model, which were derived from 100 instantaneous frames of “phase-locked” PIV measurement results at the same phase angle of \( \theta = 0^\circ \). The phase-averaged trajectory lines of the helical tip vortex tubes were also shown in the plots for reference. The wandering feature of the tip vortices was revealed clearly from the scatterings of the instantaneous center positions of the tip vortices at different time instances (i.e., different rotation cycles) but with the same phase angle of \( \theta = 0^\circ \). It should be noted that, while the instantaneous centers of the tip vortices were found to be wandering around their phase-averaged centers randomly, further data reduction reveals that the probability density function (pdf) of the instantaneous locations of the tip vortex centers could be represented well by using Gaussian functions. The wandering range of the tip vortices were indicated by the circles plotted in the figures. It can be seen clearly that the wandering range of the tip vortices would become larger and larger as they moved further away from the turbine blade tips. The larger wandering range of the tip vortices at further downstream locations is believed to be closely related to the weaker strength of the tip vortices and higher TKE level of the wake flow in those locations, as revealed clearly and quantitatively from the PIV measurement results given above.

Based on the comparison of the test cases with the tip-speed-ratio of the wind turbine model at \( \lambda = 3.0 \) and \( \lambda = 4.0 \), it can be seen clearly that the tip-speed-ratio of the wind turbine model would have observable effects on the wandering of the tip vortices in the wake flow. The wandering of the tip vortex structures was found to become less pronounced as the tip-speed-ratio of the wind turbine model increases. As shown in Fig. 16, at the same downstream location of \( X/R \approx 2.0 \), the wandering range was found to be about 40 mm for the test case with the tip-speed-ratio of \( \lambda = 3.0 \), while the wandering range was found to become only about 30 mm for the case with the

![Fig. 16 The wandering of the tip vortices at different tip-speed-ratios. a \( \lambda = 3.0 \), b \( \lambda = 4.0 \)](image-url)
tip-speed-ratio of \( \lambda = 4.0 \). The wandering of the tip vortex structures is believed to be closely related to the turbulence characteristics of the atmospheric boundary layer winds as well as the wake meandering as investigated by Bingol et al. (2007) and Larsen et al. (2008).

4 Conclusion

A wind tunnel study was conducted to quantify the unsteady wind loads acting on a HAWT model and the evolution of the turbulent vortex structures in the near wake of the wind turbine model. In addition to measuring dynamic wind loads acting on the wind turbine model by using a high-sensitive force-moment sensor, a high-resolution PIV system was used to make both “free-run” and “phase-locked” measurements to quantify the flow characteristics in the near wake of the wind turbine model.

The measurement results reveal clearly that, while the instantaneous wind loads (i.e., both aerodynamic forces and bending moments) acting on the wind turbine model would be highly unsteady with their magnitudes being about 2–3 times greater than the time-averaged values, the histograms of the dynamic wind loads were found to be fitted reasonably well by using Gaussian functions. The wind loads acting on the wind turbine model were found to increase with the increasing tip-speed-ratio at first, reach their peak values at the tip-speed-ratio of \( \lambda \approx 3.0 \), and then decrease gradually at \( \lambda > 3.0 \) for the present study. The variations of the resultant flow velocity and effective angle of attack of the incoming airflow related to the turbine blade at different tip-speed-ratios were used to qualitatively explain the wind load measurement results.

“Free-run” PIV measurements were conducted to determine the ensemble-averaged flow statistics (e.g., mean velocity, Reynolds Stress, and TKE) in the near wake of the wind turbine model. It was found that incoming airflow would be decelerated rapidly passing through the rotation disk of the turbine blades. The largest velocity deficits of the wake flow were found to occur at the tip-speed-ratio of \( \lambda \approx 3.0 \). It implies that the wind turbine model would experience the maximum wind loads as well as have the best wind energy harvesting capability when it operated at the tip-speed-ratio of \( \lambda \approx 3.0 \) for the present study, which was confirmed by the independent wind load measurements. As expected, the regions with high TKE and Reynolds stress levels were found to concentrate in the regions along the shedding paths of the unsteady tip vortices and root vortex structures as well as the wake regions downstream of the turbine nacelle and tower. The findings revealed from the PIV measurements were found to agree well with the observations of previous studies based on pointwise hotwire anemometer or/and LDV measurements.

The evolution of the unsteady vortex and turbulence flow structures in the wake of the wind turbine model in relation to the position of the rotating rotor blades were elucidated clearly from the “phase-locked” PIV measurements. It was found that the tip vortices would form three helical vortex tubes in the wake flow as they travelled downstream. The helical motion of the tip vortex tubes was found to be reverse to the rotation direction of the turbine blades. The tip-speed-ratio of the wind turbine was found to have significant effects on the evolution of the tip vortex structures. While the gap between the helical tip vortex tubes was found to decrease almost linearly with the increasing tip-speed-ratio of the wind turbine, the tip vortices were found to become much weaker as the wind turbine model operates at higher tip-speed-ratios. The unsteady vortices shedding from the roots of the turbine blades and turbine nacelle were found to become bigger and stronger as the tip-speed-ratio of the wind turbine model increases. The strength of the tip vortices was found to decay rapidly following a power law in the near wake of the wind turbine model. The tip vortices were also found to wander around as they travelled downstream. The wandering range of the tip vortices was found to become larger and larger as they moved further away from the rotation disk of the turbine blades. The wandering of the tip vortices is believed to be closely related to the high turbulence levels of the atmospheric boundary layer winds and could also be linked to the wake meandering phenomena reported in previous studies.

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