Effect of Oncoming Flow Turbulence on the Kinetic Energy Transport in the Flow Around a Model Wind Turbine

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Abstract

An experimental study was conducted to investigate the effects of the atmospheric boundary layer winds on the near wake characteristics of a scaled three-blade Horizontal Axial Wind Turbine model. Both stereoscopic particle image velocimetry and two-dimensional particle image velocimetry were used to comprehensively measure the full velocity field behind the model wind turbine, including all three components of instantaneous velocity vectors from different views. Turbulence statistics derived from the measured instantaneous velocity vectors including ensemble-averaged velocities, vorticities, turbulence kinetic energies and Reynolds shear stresses are calculated to further quantify the wake characteristics. In addition, proper orthogonal decomposition is applied to identify the dominant vortex structures in the measured flow field. Our particular purpose is on the better understanding of the effect of inflow turbulence levels on the flow characteristics and unsteady vortex structures, as well as the transportation of kinetic energy in the near wake of wind turbine.

I. Introduction

Knowledge of turbulent flow in the wake of a horizontal-axis wind turbine is essential for optimizing the wind turbine performances and reducing the wake effects on the downstream wind turbines. Extensive studies have been conducted to understand the flow characteristics in the wake of a wind turbine. As pointed out by Vermeer et al. (2003), a turbine wake is usually divided into two regions. While the flow within the region from the turbine to one rotor diameter downstream is defined as near wake, the far wake refers to the region further downstream the near wake. The focus of far wake lies on velocity deficit and enhanced turbulence, which are used to develop wake model and turbulence model for the prediction of wake interference in a wind farm. Nowadays, remote sensing instruments such as light detection and ranging (LiDAR) or Sodar are widely used in field measurements to provide velocity profiles in the turbine wake, which improve understanding of the flow characteristics in far wake region. For example, Barthelmie et al. (2006) evaluated six wake models with a set of experiments to measure free-stream and wake wind speed profiles by using a Sodar at a small offshore wind farm. By using LiDAR system, Pena et al. (2008) and Aitken et al. (2012) measured the wind speed deficits and turbulence characteristics in the turbine wake for offshore (i.e., Horns Rev) and onshore (i.e., United States Great Plains) wind farms, respectively.

Compared to far wake, near wake is characterized by much more complex coupled three-dimensional (3-D) flow structures including attached or separated flows, unsteady tip and root vortices. A fine spatio-temporal resolution technique is required to fully reveal the turbulent flows in the near wake of wind turbine. However, current field measurement techniques such as LiDAR and Sodar have no ability to provide the detailed flow information at expected spatio-temporal resolution. Only Hong et al. (2014) reported a super-large-scale particle image velocimetry (SLPIV) measurements with natural snowflakes as flow tracers to obtained the turbulent flow structures around a utility-scale wind turbine. Wind tunnel experiment with high resolution technique is the only way capable of systemically obtaining

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detailed turbulent flow structures in the near wake of wind turbine. A number of wind tunnel studies have been performed to examine the flow characteristics in near wake by using PIV measurements. While previous studies performed by Whale et al. (1996, 2000), Grant and Parkin (2000), Medici and Alfredsson (2006) and Massouh and Dobrev (2007) were done with a free-stream inflow condition, recent researches are mostly focus on the turbulent boundary layer inflow conditions. Cal et al. (2010) studied the kinetic energy transportation from an atmospheric boundary layer (ABL) flow to a 3x3 array of model wind turbines. Yang et al. (2011), Hu et al. (2012) and Zhang et al. (2012) characterized the unsteady vortex structure in the near wake of a model wind turbine sited in neutral boundary layer flows. Lignarolo et al. (2015, 2016) analyzed the instability of turbine blade tip-vortex and the turbulent mixing process of the turbine near wake. Howard et al. (2015) described the meandering motions in the near wake of wind turbine by using the PIV velocity vector fields. More recently, Ozbay et al. (2016) and Wang et al. (2016) experimentally studied the wake characteristics behind twin-rotor wind turbine models.

Although many PIV measurements have been performed to reveal near wake characteristics, it still calls for a better understanding due to the fact that the near wake would be affected by numerous factors such as rotor blades geometry, mean and turbulence characteristics of ABL inflow, thermal stability, surface heterogeneity and topography. As indicated by Sheinman and Rosen (1992), ignoring the effect of inflow turbulence can lead to a considerable overestimation of turbine power output. Binh et al. (2008) pointed out that turbulence intensity also plays a direct role on both mean and fatigue loads acting on wind turbine. Lebron et al. (2012) indicated that inflow turbulence plays a central role in the energetics of a wind turbine streamtube, which determine the maximum possible power can be extracted by a wind turbine. These studies highlight the significance of a good understanding about the effect of inflow turbulence on the turbulent characteristics in the wake of wind turbine. Medici and Alfredsson (2006), Chamorro and Porte-Age (2009) and Tian et al. (2014) have shown that both near wake and far wake can be substantially changed by the turbulence levels in ABL inflow. However, previous studies related to the turbulence effect were mainly limited to pointwise techniques (Medici and Alfredsson, 2006; Chamorro and Porte-Age, 2009) or two-dimensional PIV (2DPIV) measurements (Tian et al., 2014). As indicated by Hansen and Butterfield (1993) and Zhang et al. (2012), due to the significant 3-D effect in near wake, a comprehensive knowledge of all three components of instantaneous velocity vectors in the near wake is essential to the accurate prediction of wind turbine aeromechanic performances.

In the present study, both stereoscopic PIV (SPIV) and 2DPIV were used to comprehensively measure the full velocity field behind a model wind turbine, including all three components of instantaneous velocity vectors from different views. Turbulence statistics derived from the measured instantaneous velocity vectors including ensemble-averaged velocities, vorticities, turbulence kinetic energies (TKEs) and Reynolds shear stresses are calculated to further quantify the wake characteristics. In addition, proper orthogonal decomposition (POD) is applied to identify the dominant vortex structures in the measured flow field. Our particular purpose is on the better understanding of the effect of inflow turbulence levels on the flow characteristics and unsteady vortex structures, as well as the transportation of kinetic energy in the near wake of wind turbine.

II. Experimental Setup

2.1 Atmospheric boundary layer wind

Experimental studies were performed in a large-scale ABL wind tunnel located at the Aerospace Engineering Department of Iowa State University. The wind tunnel is operated as a closed return loop, which has a contraction section with a 4.8:1 area ratio upstream of the test section along with a set of honeycombs, wire meshes, and a cooling system to provide uniform airflow into the test section. The test section of the wind tunnel is 20m long, 2.4m wide and 2.3m high. As guided by the methods proposed by Irwin (1981) and Sill (1988), triangular spires at the entrance of the test section and wooden blocks spaced on the wind tunnel floor were used to simulate the flow conditions similar to ABL wind under thermally neutral conditions. The wind tunnel ceiling can be adjusted to ensure that the simulated ABL wind has a zero pressure gradient along the flow direction.

During the experiments, two ABL winds with distinct turbulence levels (i.e., type-1 ABL wind with relatively low turbulence vs. type-2 ABL wind with relatively high turbulence) were simulated by changing the triangular spires and wooden blocks. Figure 1(a) shows the measured stream-wise mean velocity profiles of the simulated ABL winds. The friction velocities of type-1 and type-2 ABL winds are and , which are determined by the measured Reynolds shear stress (not shown here). Then, by fitting logarithmic profiles to the measured mean velocity, the surface roughness length and zero plane displacement for type-1 ABL wind were found to be and , while the corresponding values for type-2 ABL wind are and . Turbulence intensity profiles for the simulated ABL winds are given in Fig. 1(b). The turbulence intensity is calculated as , where is the root mean square (RMS) of the velocity fluctuations in the
stream-wise direction and $U_{local}$ is the time-averaged velocity at the local measurement point. It can be clearly seen that the magnitudes of the turbulence intensity in turbine rotor region for type-2 ABL wind are almost twice as those of the type-1 ABL wind.

![Fig. 1 Flow characteristics of the two simulated ABL winds (a) mean stream-wise velocity (b) turbulence intensity](image)

**2.2 Tested wind turbine model**

As shown in Fig. 2, the wind turbine model applied in the present study represents a most widely used horizontal axial wind turbine (HAWT). The turbine rotor consists of three ERS-100 blades developed by TPI Composites, Inc. A constant circular section from the root of the blade to a distance of 5% radius of the blade and three NREL airfoils (S819, S820, S821) are applied for the design of ERS-100 blade (Locke and Valencia, 2004). The diameter of the turbine rotor is $D = 280mm$ and the height of the turbine hub is $H = 225mm$. The ratio of turbine rotor area to wind tunnel cross-section area is about 1:110, which is small enough to ignore the blockage effect. More information about the turbine model can be found in Tian et al. (2014) and Ozbay et al. (2016).

![Fig. 2 The schematic of the wind turbine model](image)

As shown in Fig. 2, a small direct current (DC) generator is installed inside the turbine nacelle and attached to the three-blade turbine rotor. The angular speed of the turbine rotor can be adjusted by changing the electrical resistance that loads on the generator. During the experiments, the turbine rotor runs at the angular speed of approximately $\Omega = 1700rpm$. The corresponding tip speed ratio (TSR, $\lambda = \Omega(2\pi/60)(D/2)/U_{hub}$) is approximately 5.0. Here $U_{hub}$ is the inflow velocity at hub height of the model wind turbine, which was kept constant and set as $U_{hub} = 5.0 m/s$ in the present study. This value (i.e., $\lambda = 5.0$) falls into the range of TSR for typical utility-scale wind turbine (i.e., $\lambda = 4.0$~8.0), as suggested by Burton et al. (2001).

The chord Reynolds number based on the averaged chord length of the rotor blade and the inflow velocity at hub height was found to be approximately 9500, which is typically two to three orders of magnitude lower than that of a full-scale wind turbine. According to De Vries (1983), the minimum Reynolds number required for comparison of the model test results with the performances of full scale wind turbine such as power coefficient or thrust coefficient is of the order of $Re = 3 \times 10^5$. However, as mentioned by Medici and Alfredsson (2006) and Chamorro et al. (2011), the key flow characteristics in the turbine wake including the behaviors of the turbulent vortex structures would be almost independent to the chord Reynolds number. Instead, TSR is a key similarity parameter which determine the main flow characteristics in the near wake such as wake rotation direction, helical shape, and strength of the tip and root vortices.
2.3 Experimental setup for PIV measurements

As mentioned above, both 2DPIV and SPIV were used to measure the velocity field from different views. As shown in Fig. 3, 2DPIV is applied in the vertical stream-wise (x − z) plane passing through the central axis of the turbine rotor, while SPIV is adopted in the vertical span-wise (y − z) planes at different downstream locations (i.e., x/D = 0.5, 1.0, 2.0, 4.0). During the experiments, oil droplets with the diameter of approximately 1μm generated by a droplet generator are used as flow tracers. A double-pulsed Nd: Yag laser (Evergreen) which can produce laser pulse of 200mJ at wavelength of 532nm was adopted to illuminate the region of interest. The laser beam was shaped to a sheet by a set of spherical and cylindrical lenses. For 2DPIV measurement, in order to have a larger measurement window along the stream-wise direction, two high-resolution 16-bit CCD cameras (PCO1600, CookeCorp) were used to capture the particle images with the axis of the camera perpendicular to the laser sheet (i.e., vertical stream-wise (x − z) plane). For SPIV measurement, two PCO2000 cameras mounted on Scheimpflug mountings were used for particle image acquisition in vertical span-wise (y − z) plane. A digital delay generator (Berkeley Nucleonics, Model 565) connected with both the laser and cameras was applied to coordinate the timing of the laser illumination and the image acquisition.

![Fig. 3 Experimental setup for 2DPIV and SPIV measurements](image)

A cross-correlation algorithm was applied to calculate the instantaneous velocity vectors with an interrogation window of 32 × 32 pixels and an effective overlap of 50%. A sequence of 1000 frames of measured instantaneous velocity fields were used to obtain the turbulence statistics including mean velocities, vorticities, TKEs and Reynolds shear stresses. The measurement uncertainty for the velocity vectors was estimated to be within 2.0%, while the uncertainties for the high-order turbulence statistics such as TKE and Reynolds shear stress are approximately 5.0%.

III. Proper Orthogonal Decomposition

POD has been widely used in fluid mechanic research in recent years, especially for the complex flow phenomenon (Berkooz et al., 1993). POD algorithm is capable of identifying the principal flow structures with the most energetic contributions. The POD modes, which are represented by an orthogonal set of spatial eigenfunctions, are ranked based on their kinetic energy. Therefore, if predominant spatial structures exist in the flow, they can be extracted by POD algorithm and be represented in the first few modes. In the present study, we employed POD algorithm on instantaneous velocity vector fields obtained from PIV measurements to yield the spatial-temporal characteristics of the dominant flow structures in the near wake of a model wind turbine. A step-by-step construction of the POD algorithm is provided below:

After PIV measurements, all the fluctuating velocity components (i.e., ensemble-averaged velocity components have been removed) can be arranged in a matrix:

\[
U = \begin{bmatrix}
    u_1^1 & u_2^1 & \ldots & u_N^1 \\
    \vdots & \vdots & \ddots & \vdots \\
    u_1^M & u_2^M & \ldots & u_N^M \\
    v_1^1 & v_2^1 & \ldots & v_N^1 \\
    \vdots & \vdots & \ddots & \vdots \\
    v_1^M & v_2^M & \ldots & v_N^M \\
    w_1^1 & w_2^1 & \ldots & w_N^1 \\
    \vdots & \vdots & \ddots & \vdots \\
    w_1^M & w_2^M & \ldots & w_N^M
\end{bmatrix}
\]

(1)
where the subscript \( M \) denotes the number of spatial discrete points in PIV measurements and the superscript \( N \) denotes the number of the PIV snapshots, which represent the spatial and temporal resolutions of the PIV data, respectively. It should be noted that there is no third velocity component for 2DPIV measurements.

Then, the auto-covariance matrix can be created by:

\[
M = U^T U
\]  
(2)

The eigenvalue \( \lambda \) and eigenvector \( A \) of the matrix \( M \) can be obtained as:

\[
MA^i = \lambda^i A^i
\]  
(3)

The eigenvalues \( \lambda^i \) are ranked in a descending order to ensure that the modes with the most energetic contributions are the first few modes. Then, each POD eigenmode \( \phi^i \) can be calculated by projecting matrix \( U \) onto each eigenvector and then normalized by its norm as:

\[
\phi^i = \frac{\sum_{n=1}^{N} (A^n_i u^n)}{\| \sum_{n=1}^{N} (A^n_i u^n) \|}, \quad i = 1,2, ... N
\]  
(4)

The POD coefficients of each model can be determined by:

\[
a^n = \phi^T u^n
\]  
(5)

where \( \phi = [\phi^1, \phi^2, ..., \phi^N] \).

Reconstructing the original fluctuating velocity components can be performed by the summation of each eigenmode multiplied by the corresponding mode coefficient:

\[
u^n = \phi a^n
\]  
(6)

In addition, an \( L^{th} \) order POD reconstruction of the flow fields can be calculated by:

\[
u^{n, L} = \sum_{i=1}^{L} a^n_i \phi^i + U
\]  
(7)

where \( U \) is the ensemble-averaged velocity components.

### IV. Results and Discussion

#### 4.1 Ensemble-averaged PIV results

Kinetic energy in ABL inflow is extracted as it passing across the rotational disk of wind turbine, which leads to significant velocity deficits behind the turbine rotor. Figures 4 and 5 show the mean stream-wise velocity distributions in the turbine wake for low and high turbulence inflow cases, respectively. It can be seen clearly that for both low and high turbulence inflow cases, the inflow speed slow down greatly when it moving across the rotation disk of the turbine blades. In addition, the expansion of wake flow downstream of the wind turbine can be seen clearly from the distribution pattern of the iso-velocity contour lines.

![Fig. 4 Ensemble-averaged velocity distributions for low turbulence ABL inflow case (a) 2DPIV (b) SPIV](image-url)
The PIV measurement results shown in Figs. 4 and 5 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, in comparison with the cases with lower turbulence levels in the ABL winds.

Figures 6 and 7 shows the normalized TKE 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 for the low and high turbulence inflow cases are different due to the significant differences of the TKE levels in the turbine wake. As shown in the figures, 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.

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.

4.2 Results of POD analysis

In this study, the measurement region of the first PCO camera is selected as the region of interest (ROI) to better understand the turbulent structures in the near wake of a wind turbine. Figure 8 shows the instantaneous 2DPIV results in the turbine near wake. It can be seen that the near 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 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.

Figure 9 shows the percentage of the cumulative POD modes energy for low and high turbulence inflow cases. It can be seen that the cumulative energy for the low order modes is much higher for low turbulence inflow case, compared to that of the high turbulence inflow case. The cumulative energy of the first 6 POD modes for the low turbulence inflow case is approximately 57.4%, while for the high turbulence inflow case the value is only 35.4%.

Figure 10 presents the reconstructed instantaneous velocity and vorticity fields based on the first 6th POD modes. It can be seen that for low turbulence inflow case, the 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. As revealed in Fig. 9, these concentrated vortices contain most of the turbulent energy in the turbine wake. Therefore, the near wake flow is dominated by the evolution of these concentrated wake vortices. The existence of these concentrated vortices in the turbine wake would prevent the mixing of the flow in the other region, leading to the low recovery of the wind speed in the turbine wake.
For the high turbulence inflow case, as shown in Fig. 10(b), there are no obvious concentrated vortices in the turbine wake. The large flow structures extracted by POD algorithm only contain 35.4% of the total turbulent energy in the turbine wake. It implies that, most of the turbulent energy is contained in the smaller and weaker eddies in the turbine wake. These eddies would significantly enhance the turbulence mixing of the flow in the turbine wake region, as well as promoting the kinetic energy transportation to entrain more high-speed airflow surrounding the rotation disk of the wind turbine to re-charge the turbine wake flow.

![Normalized Vorticity ($\omega^{+\Delta t/2\mu}$)](image)

Fig. 10 Instantaneous near wake flow reconstructed by using the first 6$^{th}$ POD modes (a) Low turbulence inflow case (b) High turbulence inflow case

V. Conclusions

An experimental study was conducted to investigate the effects of the ABL winds on the near wake characteristics of a scaled wind turbine model. The experimental investigation was performed in a large-scale ABL wind tunnel. Both SPIV and 2DPIV were used to measure the flow field behind the wind turbine model. The PIV measurements reveal 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. Based on POD analysis, the faster recovery of the turbine wake for the high turbulence inflow case is caused by the reason that most of the turbulent energy is contained in the smaller and weaker eddies in the turbine wake. These eddies would highly enhance the turbulence mixing in the turbine wake.

For the low turbulence inflow case, the concentrated vortices shedding from the turbine blades contain most of the turbulent energy in the turbine wake, which would prevent the mixing of the wake flow in other region, leading to the much lower recovery of wind speed in the turbine wake.

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