An Experimental Investigation on the Wake Characteristics of a Wind Turbine in an Atmospheric Boundary Layer Wind

Zifeng Yang1, Partha Sarkar2 and Hui Hu3 (✉)
Department of Aerospace Engineering, Iowa State University, Ames, IA, 50010

An experimental study is conducted to characterize the dynamic wind loads and evolution of the turbulent vortex and flow structures in the wake of a horizontal axis wind turbine (HAWT). In addition to measuring dynamic wind loads (both aerodynamic forces and moments) acting on a wind turbine model, a high-resolution Particle Image Velocimetry (PIV) system was used to make “free-run” and phase-locked flow field measurements to quantify the time evolution of the turbulence vortex and flow structures in the wake of the wind turbine model. The detailed flow field measurements were correlated with the dynamic wind load measurements to elucidate the underlying physics associated with power generation and fatigue loads acting on wind turbines operating in an atmospheric boundary wind.

Nomenclature

\[ D \quad \text{Diameter of the rotor} \]
\[ H \quad \text{Hub height} \]
\[ R \quad \text{Radius of the rotor} \]
\[ c \quad \text{Blade chord} \]
\[ U(z) \quad \text{Wind speed at height } z \]
\[ U_0 \quad \text{Wind speed at hub height} \]
\[ U_\infty \quad \text{Free stream wind speed} \]
\[ x \quad \text{Axial coordinate} \]
\[ y \quad \text{Vertical coordinate} \]
\[ z \quad \text{Transverse coordinate} \]
\[ z_0 \quad \text{Roughness height} \]
\[ \Omega \quad \text{Rotational speed of the rotor} \]
\[ \lambda \quad \text{Tip speed ratio}, \lambda = (\Omega R) / U_\infty \]
\[ \rho \quad \text{Air density} \]
\[ C_D \quad \text{Drag coefficient}, C_D = \frac{1}{2} \rho V_0^2 \pi R^2 \]
\[ C_{M_z} \quad \text{Bend moment coefficient along z direction}, C_{M_z} = M_z / \frac{1}{2} \rho V_0^2 \pi R^2 H \]
I. 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 provides only approximately 1.0% of total U.S. electricity generation in 2008, a target of 20% of US total electricity generation from wind energy by 2030 has been set up recently by the U.S. Department of Energy (DoE). To achieve the goal of 20% of electricity generation by 2030, the total wind power capacity in U.S.A. will need to exceed 300 gigawatts (Schreck et al., 2008). Suppose if each wind turbine could generate about 2.0MW, which corresponds to large wind turbines with the hub-height about 60 – 100 m and rotor blade diameters about 70 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 amongst the most significant research topics needed for wind resource characterization and wind power generation (Schreck et al., 2008). 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 acting on wind turbines required for the optimal wind turbine designs.

The wake of a wind turbine is typically divided into a near and a far wake. The near wake is referred 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 the helical tip vortices has been found to affect the behavior of the turbulent wake flow structures behind a wind turbine significantly. The tip vortices were also recognized as an important source of noise generation and blade vibration (Massouh & Dobrev, 2007). The far wake is the region beyond the near wake, where the actual rotor shape is less important. The main attentions for far wake flows are usually drawn in wake models, wake interference, turbulence models, and topographical effects (Vermeer, 2003).

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 wind turbines. This requires a detailed knowledge about transient behavior of the turbulent flow structures in the wakes of wind turbines and the evolution of the helical tip vortices induced by the rotating turbine blades. Although a number of experimental studies have been conducted to investigate wind turbine wake aerodynamics, most of the previous studies were carried out based on qualitative flow visualization and/or 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 et al., 1979; Tsustui & Matsumya, 1987; Ebert & Wood, 1997; Vermeer, 2001; Medici & Alfredsson, 2006; and Chamorro and Porte'-Agel, 2009). A common shortcoming of such pointwise flow measurements is the incapability of providing spatial correlation of the turbulent wake flow structures to effectively reveal the transient behavior of the helical tip vortices. Temporally-synchronized and spatially-resolved flow field measurements are highly desirable in order to elucidate the underlying physics to improve our understanding about the turbulent wake flow characteristics and the transient behavior of the helical tip vortices in wakes of wind turbines. Advanced 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 can be found in literature to provide whole-field measurements to quantify the transient behavior of the helical tip vortices 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 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 at the downstream of a two-bladed wind turbine model in a low-speed wind tunnel. The PIV measurement results 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 & Dobrev (2007) conducted a wind tunnel study to characterize the wake flow downstream of a small wind turbine model based on the phased-locked PIV and hotwire measurements. The evolution of the helical tip vortices downstream of the wind turbine 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. However, in reality, most of the wind turbines operate in atmospheric boundary layer winds with significant variations in both incoming wind speed and turbulence intensity. The effects of the significant variations in mean and turbulence characteristics of the atmospheric boundary layer winds on the power productivity, dynamic wind loads and the evolution of the unsteady tip vortices in the wakes of wind turbines have not been fully explored.

In the present study, an experimental study was conducted to characterize the turbulent flow structures and the evolution of the helical tip vortices in the near wake of a horizontal axis wind turbine (HAWT) model placed 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 (both aerodynamic forces and moments) acting on the wind turbine model using a high-sensitive six-component load cell, a high-resolution digital Particle Image Velocimetry (PIV) system was used to achieve detailed flow field measurements to quantify the characteristics of the turbulent wake flow and evolution of the helical tip vortex structures in the 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, turbulence intensity, Reynolds Stress, and turbulence kinetic energy distributions in the wake flow, phased-locked PIV measurements were also conducted to elucidate details about the time evolution of the helical tip vortices in relation to the position of the rotating turbine blades. 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 turbulent wake flows and evolution of the helical tip vortex structures in the wakes of wind turbines for the optimal design of the wind turbines operating in more realistic environments.

II. 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 Aerodynamic/Atmospheric Boundary Layer (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 20m long, 2.4m wide and 2.3m high, optically transparent side walls and a capacity of generating a maximum wind speed of 55m/s in the test section.

![Fig. 1: A picture of the test section of the AABL wind tunnel](image-url)
Fig. 1 shows a picture of the test section of the AABL wind tunnel with a three-blade, horizontal axis wind turbine (HAWT) model (at a scale ratio of 1:350) mounted in the center of a turntable. Arrays of wood blocks were mounted at the upstream of the wind turbine model as the roughness elements to generate a turbulent boundary layer flow to simulate the atmospheric boundary layer wind usually seen in a wind farm. The wood blocks are 0.076m tall with a square cross section of 0.038 × 0.038m. The blocks were arranged in a staggered pattern with 30 rows along the flow direction, starting at 12.89m and ending at 1.46m upstream of the tested wind turbine model. The space between the blocks was 0.38m in both streamwise and spanwise directions. The odd rows of the blocks started 0.076m from the side walls of the tunnel, while the even rows of the blocks started 0.28m from the side walls of the tunnel.

Fig. 2 shows the measured mean velocity and the turbulence intensity profiles at the center of the measurement region, 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 10m elevation height above the ground is widely used to characterize an atmospheric boundary layer wind. The horizontal axis in Fig. 2(a) represents non-dimensional mean velocity $U/U(z_{10})$, where $U(z_{10})$ is the reference velocity at a height of $z_{10}=28.6$mm about the wind tunnel ground floor, which is equivalent 10m elevation height in nature 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 (ASCE, 2005). The logarithmic and power curves fitting to the measurement data were also shown in Fig. 2(a) for comparison. It can be seen clearly that the measurement data can by 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 open terrain atmospheric boundary layer wind found 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. Fig. 2(b) shows the measured the turbulence intensity of the turbulent boundary layer flow generated inside the wind tunnel as a function of the evaluation height above the wind tunnel floor. 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 wind tunnel for the present study can be used to simulate an atmospheric boundary layer wind found in nature reasonably well.

Fig. 2: The measured profiles of the atmospheric boundary layer wind
2.2 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/or 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 blade swept area to the tunnel cross section area) was found to be about 1:90. Thus, the block 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 for the present study are MA0530TE (5 × 3 three-blade) propeller blades of Windsor Propeller Inc. The blades are twisted with the pitch angle of 14 deg at 75% radius, which is ranging from 20 deg at root to 10 deg at tip. The blades have a 12 mm chord length 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 wind streams 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 turbine blades. The primary design parameters of the wind turbine model are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R</th>
<th>H</th>
<th>( d_{\text{rod}} )</th>
<th>( d_{\text{nacelle}} )</th>
<th>( \alpha )</th>
<th>a</th>
<th>a1</th>
<th>a2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>127</td>
<td>225</td>
<td>18</td>
<td>28</td>
<td>6°</td>
<td>100</td>
<td>15</td>
<td>70</td>
</tr>
</tbody>
</table>

During the experiments, while the wind turbine model was installed in the simulated atmospheric boundary layer wind, the wind speed at the hub height was found to be 4.0 m/s (i.e., \( V_0 = 4.0 \text{ m/s} \)). 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 significant lower than those of the wind turbines installed in a wind farm. According to Alfredsson et al., (1982), the chord Reynolds number would have significant effects on the characteristics of the wind turbine performance. For example, the maximum power coefficient would be much lower for the wind turbine models operating at much low Reynolds numbers. However, as suggested by Medici & Alfredsson (2006), the fundamental behavior of the helical tip vortices and turbulent wake flow structures at the downstream of wind turbines would be almost independent to the chord Reynolds number. The wind turbines with similar tip-speed-ratio (TSR) would produce similar near wake characteristics such as helical shape, rotation and tip vortices. In the present study, while the incoming atmospheric boundary layer wind was kept in constant during the experiments, the rotation speed of the wind turbine model was adjusted by applying different electric loads to the small electricity generator inside the turbine nacelle. With the rotation speed of the wind turbine blades changed from 0 to 1700rpm, the corresponding tip-speed-ratio of the wind turbine model (i.e., $\lambda = \text{blade tip rotation speed/wind speed}$) was found to be changed from 0.0 to about 4.5.

2.3 Experimental setup for dynamic wind load and flow field measurements

In the present study, an aluminum rod was used as the tower to support the nacelle and rotor blades of the wind turbine model. Through a hole on the wind tunnel ground, the aluminum rod was connected to a high-sensitivity force-moment sensor (JR3, model 30E12A-I40) in order to measure the dynamic wind loads (both force and moment) 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 ±0.25% of the full range (40N). In the present study, the thrust coefficient (i.e., aerodynamic force coefficients along X –direction) and bending moment coefficient (i.e., the moment coefficient along Z-direction) of the wind turbine model were calculated by using the expressions of

$$C_T = \frac{2T}{\rho U_0^2 \pi R^2}, \quad C_{M_z} = \frac{2M_z}{\rho U_0^2 \pi R^2 H},$$

where $\rho$ is the air density, $U_0$ is the mean flow velocity at the hub height, $H$. During the experiments, the wind loads data were acquired for 60 seconds at the sample rate of 1,000 Hz for each tested case.

In addition to the wind load measurements, a high-resolution digital Particle Image Velocimetry (PIV) system was used to achieve detailed flow field measurements to quantify the characteristics of turbulent wake flow the transient behavior of the unsteady tip vortices at the downstream of the wind turbine model. Fig. 4 shows the schematic of the PIV system used in the present study. For the PIV measurements, the flow was seeded with ~ 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 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. During the experiments, “free-run” PIV measurements were conducted at first in order to determine the ensemble-averaged wake flow statistics (e.g., mean velocity, turbulence intensity, Reynolds Stress, and turbulence kinetic energy) at the downstream of the wind turbine model. It should be noted that the data acquisition rate for the “free-run” PIV measurements was pre-selected at a frequency that is not a harmonic frequency of the rotation frequency of the rotor blades in order to ensure a meaningful determination of the ensemble-averaged flow quantities.

Phased-locked PIV measurements were also conducted to elucidate more details about the time evolution of the helical tip vortices in relation to the position of the rotating rotor blades. In order to achieving the phase-locked PIV measurements, as shown in Fig. 4, a digital tachometer was used to detect the position of a pre-marked rotor blade (i.e., named blade #1). The tachometer would generate a pulsed signal as the pre-marked rotor blade passed through the vertical PIV measurement plane. The pulsed signal was used as the input signal to a Digital Delay Generator (DDG) to trigger the digital PIV system for the phased-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 phased-locked PIV measurements at different rotation phase angles of the pre-marked rotor blade (i.e., corresponding to different rotating positions of the pre-marked rotor blade) can be accomplished. At each pre-selected phase angle, 160 frames of the instantaneous PIV measurements were used to calculate the phase-averaged flow velocity distribution in the wake of the wind turbine model.

In the present study, 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 32x32 pixels. An effective overlap of 50% of the interrogation windows was employed in PIV image processing. After the instantaneous velocity vectors \( (u, v) \) were determined, the vorticity \( \omega \) can be derived. The distributions of the ensemble-averaged flow quantities such as the mean velocity, turbulence intensity, Reynolds Stress, and turbulence kinetic energy were obtained from a cinema sequence of about 1000 frames of the instantaneous PIV measurements. The measurement uncertainty level for the velocity vectors is estimated to be within 2% and 5% for the turbulent velocity fluctuations, Reynolds stress, and turbulent kinetic energy calculations.

### III. Results and Discussion

#### 3.1 Dynamic wind load measurement results

Figure 5 shows the typical measurement results of the wind loads acting on the wind turbine model with the tipspeed-ratio of the wind turbine being 3.2. While Fig. 5(a) and Fig. 5(b) give the measured instantaneous thrust force and bending moment acting on the wind turbine model, Fig. 5(c) and Fig. 5(d) show the histograms of the measured instantaneous thrust force and bending moment. It can be seen clearly, while the instantaneous wind loads acting on the wind turbine model were found to be highly unsteady, the histograms of both the dynamic thrust force and bending moment acting on the wind turbine model were found to be fitted reasonably well by using Gaussian functions. While the standard deviation of dynamic thrust force coefficient was found to be 0.103 with the mean value at \( C_T = 0.337 \), and the standard deviation of instantaneous bending moment coefficient was 0.152 with the mean value of \( C_M = 0.351 \). Fig. 5(e) and Fig. 5(f) show the Fast Fourier Transform (FFT) power spectrum analysis of the measured dynamic thrust force and bending moment. A dominant peak at \( f_0 = 17.0 \text{ hz} \) can be identified clearly 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 \( \lambda = 3.2 \). The rotation frequency of \( f_0 = 17.0 \text{ hz} \) based on the FFT analysis of the wind load measurements were found to agree very well with the independently measured rotation speed of the rotor blades by using the digital tachometer. Other peaks, which correspond to the harmonic frequencies of the rotation frequency of the rotor blades, \( f_0 \), can also be clearly identified from the power spectrum plots.
Fig. 5: Measured wind loads acting on the wind turbine model with the tip-speed-ratio, $\lambda=3.2$.
It is well known that the tip-speed-ratio (often known as the TSR) of a wind turbine is of vital importance in the design of the wind turbine generators. In the present study, the effects of tip-speed ratio of the wind turbine on the aerodynamic force and wake flow structures of the wind turbine were investigated systematically. As described above, during the experiments, while the incoming atmospheric boundary layer wind was kept in constant, the rotation 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. With the rotation speed of the wind turbine blades changed from 0 to 1700rpm, the corresponding tip-speed-ratio of the wind turbine model was changed from 0.0 to about 4.5 (i.e., $\lambda = 0 \sim 0.45$). It should be noted that, while the variations of the power coefficients of a wind turbine model as a function of the tip-speed-ratio have been reported in several previous studies (Boeing, 1982), very little can be found in the literature about the variations of the wind loads (i.e., thrust and bending moment) acting on the wind turbine as a function of the tip-speed-ratio of the wind turbine even though the wind load data are very important and critical for the mechanic design of wind turbines for better wind energy harvesting performance and long fatigue lifetime of the wind turbines operating in turbulent atmospheric boundary layer winds. Fig. 6 shows the variations of the measured mean (i.e., time-averaged) thrust and bending moment coefficients of the wind turbine model as a function of the tip-speed-ratio, $\lambda$. It can be seen clearly that the profiles of mean thrust and bending moment coefficients were found to have a very similar trend as the tip-speed-ratio of the wind turbine model increases. The mean thrust and bending moment coefficients would increase gradually with the increasing tip-speed-ratio of the wind turbine model when the tip-speed-ratio is still relatively small (i.e., $\lambda < 3.0$). The mean thrust and bending moment coefficients were found to reach their peak values at the tip-speed-ratio of $\lambda \approx 3.2$. Then, the mean thrust and bending moment coefficients of the wind turbine would decrease with the increasing of the tip-speed-ratio of the wind turbine when the tip-speed-ratio of the wind turbine model becomes relatively large (i.e., $\lambda > 3.5$). The similar trend was also reported in the experimental study of Boeing (1982) to investigate of the power coefficient of the wind turbine models as a function of the tip-speed-ratio of the wind turbines.

Fig. 7 shows the schematic of the flow velocity vectors relative to the cross-section of the turbine blade at different tip-speed-ratio. As suggested by Spera (1994), the left-hand side of the curve in Fig. 6(a) (i.e., with the tip-speed-ratio being relatively small) is controlled by blade stall. Local angles of attack (angles between the relative velocity and the blade chord line) are relative large. As shown in Fig. 7 (a), when the rotation speed of the turbine blade is relatively low (i.e., the tip-speed-ratio being relatively small), the airflow would be stalled due to the large angle of attack and a large separation region behind the blade is expected. As the rotor blade starts rotating faster, the rotation speed contributes significantly in the relative velocity respect to the blade. In an optimal operating condition, a desired angle of attack is achieved that would enable the large relative velocity to generate tremendous aerodynamic lift as shown in Fig. 7 (b). A significant part of the lift is projected into the thrust, which is even larger than the drag generated by the blade stall. The other part of the lift would provide rotation-wise driven force on the blade. With the increasing tip-speed-ratio, the angle of attack of the relative flow with respect to the blade would
decrease dramatically. As a result, the aerodynamic lift as well as the thrust acting on the blade would decrease to a small value as shown in Fig. 7(c) that explains the dropping trend at the right-hand side of the curve in Fig. 6(a).

![Image](image-url)

Fig. 7: Schematic of the flow velocity vectors relative to the cross-section of the turbine blade

### 3.2 Free run PIV measurement results

As described above, the flow field in the vertical central plane of the wind turbine with the yaw angle fixed at zero degree was measured using a high-resolution PIV system. The PIV measurement results of the present study are presented in mainly two different ways: (i) “free-run” flow field measurement results, and (ii) phase-locked flow filed measurement results. In the “free-run” PIV measurements, the data acquisition rate was pre-selected at a frequency that is not a harmonic frequency of the rotation frequency of the rotor blades in order to ensure a meaningful determination of the ensemble-averaged flow quantities.

Fig. 8 shows the “free-run” PIV measurement results at the tip-speed-ratio of the wind turbine of \( \lambda \approx 3.0 \). As clearly revealed in the instantaneous PIV measurement result, the contour plots describe the expected pattern from a cross-section of a helical tip vortex system. The instantaneous PIV contour plot also reveals separate regions of slightly concentrated vorticity in the wake, located inboard of the tip at approximately 70% span, moving under the influence of wake expansion, and finally merging with the tip vortex system at approximately 2.0R downstream. A similar flow feature was also observed by Whale et al. (2000) with separated regions located inboard of the tip at approximately mid-span merging with the tip vortex system at 2.0R. Note that the fluid separation zone at the downstream of the nacelle has much greater diameter than it can be expected from the nacelle body only. Because a series of root vortex structures due to the rotation are present on the external boundary of the separation zone which was also observed by Massouh and Dobrev (2007). As shown clearly in the ensemble-averaged velocity distribution given in Fig. 8(b), obvious velocity deficits were observed in the wake. The loss of the kinetic energy of the flow was transferred into electric power by the wind turbine. The lowest velocity region has been observed right behind the nacelle, and it starts recovering rapidly by absorbing the energy from the surrounding flow. This behavior induces the expansion of the wake as revealed by the joint contour boundaries in Fig. 8(b).

Fig. 8(c) and Fig. 8(d) show the measured turbulent intensity in streamwise (U-component) and vertical direction (V-component) respectively. A slight increment of the turbulent intensity in U-component was observed in the flow passing the blade tip, but it showed an increasing trend with the distance downstream of the wind turbine. In contrast, a distinct increment of the turbulent intensity in V-component was observed near the tip, but decreasing with the distance. The difference is attributable to the fact that the existence of the blade tip has more effects on the V-component of the flow. Moreover, the high background turbulent intensity (about 17%) in streamwise made the increment invisible to some extent. The nacelle and cylinder-shaped tower also induced intense turbulent intensity mainly due to the vortex shedding. Especially in the region under the nacelle, the high turbulence could be attributable to the interference from the tower on the wakes of turbine blades.
Fig. 8: PIV measurement results at the tip-speed ratio of $\lambda = 3.0$
Fig. 8 (e) and (f) show the normalized Reynolds shear stress and turbulent kinetic energy distributions. The high Reynolds shear stress regions were found to be along with the tip vortex system, the root vortex shedding path and the separation region around the turbine nacelle. The Reynolds stress plays an important role in the vertical transport of kinetic energy in the wake. As stated by Cal et al. (2010), the Reynolds stress enables kinetic energy to be entrained from the aloft into the boundary layer towards the wind turbine. Another separation region at approximately 70% span also induced a slightly high Reynolds stress and merged with the tip vortex system. It also revealed clearly that the wake flow at the downstream of the turbine nacelle would be highly turbulent (i.e., with very high turbulent kinetic energy), corresponding to the unsteady root vortex shedding and flow separations. Relatively high turbine kinetic energy regions were also found to be along the tip vortex system. The findings derived from the present study are found to agree with the observations of Chamorro and Porte-Agel (2009).

In the present study, the effects of the tip-speed-ratio of the wind turbine on the turbulent wake flow characteristics were also investigated. Fig. 9 shows the ensemble-averaged PIV measurement results at four typical tip-speed-ratios.

![Fig. 9: Ensemble-averaged flow field at different tip-speed-ratios](image-url)

Fig. 10 shows the transverse profiles of the ensemble-averaged streamwise velocity and the normalized turbulence kinetic energy in the wake of the wind turbine at the location of X/R=1.0 as a function of the wind turbine tip-speed-ratio. The mean velocity profile of the incoming atmospheric boundary layer wind was also given in the plot for comparison. It can be seen clearly that, compared with the velocity profile of the incoming
atmospheric boundary layer wind, significant velocity deficits were found to be generated in the wake flow due to the installation of the wind turbine in the atmospheric boundary layer wind. The size of the regions with significant velocity deficits was found to be much greater than that can be expected from the turbine nacelle only. It indicates that the incoming flow streams would be decelerated greatly as they pass through the rotating disk of the turbine blades. According to the momentum and energy conservation laws, while the aerodynamic drag force acting on the wind turbine are proportional to the square of the velocity deficits, the power output of the wind turbine (i.e., the wind energy harvested by the wind turbine) would be proportional to the cube of the velocity deficits. A larger velocity deficit 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 was found at the tip-speed-ratio \( \lambda \approx 3.0\text{–}3.5 \) for the present study. It would suggest that the wind turbine model used in the present study would experience the maximum wind load as well as have the best wind energy harvesting capability when operated at the tip-speed-ratio of \( \lambda \approx 3.0\text{–}3.5 \). The finding was confirmed from the independent wind load measurement results given in Fig. 6. The normalized turbulence kinetic energy profiles shown in Fig. 10(b) revealed clearly that the wake flow at the downstream of the turbine nacelle was highly turbulent (i.e., with very high turbulent kinetic energy levels), corresponding to the flow separation and unsteady wake vortex shedding from the turbine nacelle as revealed from the PIV measurement results described above. A region with quite high turbine kinetic energy levels can also be found along the shedding path of the helical tip vortices in the wake of the wind turbine model. The high turbulence level in the wake flow would indicate a highly unstable wind loads acting on the wind turbine, which would affect the mechanical strength and fatigue lifetime of the wind turbine significantly. The findings derived from the present study are found to agree well with the observations of Chamorro and Porte’-Agel (2009) based on cross-wire anemometer measurements.

3.3 Phase-locked PIV measurement results

In order to provide more information about the time evolution of the helical tip vortex in the wake of the wind turbine model, the phase-locked PIV measurements were conducted at eight different phase angles for the present study. The technique effectively produced a “frozen wake” image, from which a cross-section of the vortex structure was obtained. As mentioned before, the angle between the measurement plane and the position of a pre-marked rotor blade (i.e., named blade #1), is defined as the phase angle. The phase-locked averaged results at the phase angle ranging from 0~120deg for \( \lambda =3.0 \) are shown in Fig. 11. The “wave-shape” of the streamwise velocity contour can be observed, which indicates vortical flow characteristics emerging in the tip vortex region. Acceleration with red color contour can be observed downstream at some spots above the tip height due to the tip vortices, which was also observed by Massouh & Dobrev (2007). This acceleration was also revealed clearly from the induced velocity vector field after subtracting the oncoming flow as shown in Fig. 12. The “acceleration region” right behind the wind turbine is relatively large because of the high vortex strength there. The whole “wave-shape” distribution tends to move downstream with the increasing phase angle. One needs to keep in mind that all maps shown here are only cross-sections of the “wave-pipe-like” flow structure.

Fig. 10: Time-averaged measurement results in the wake of the wind turbine model at X/R=1.0.
Figure 12 shows the typical phase-locked PIV measurements at different phase angles of a pre-marked turbine blade in a rotation cycle (i.e., corresponding to different positions of the pre-marked turbine blade in relation to the vertical PIV measurement plane) as the wind turbine model operated at a tip-speed-ratio of $\lambda \approx 3.0$. As shown in the figure, at the phase angle of $\theta = 0$ deg, the pre-marked turbine blade would be in the most upward position (i.e., within the vertical PIV measurement plane). It can be seen clearly that a tip vortex would be induced at the tip of the pre-marked turbine blade at $\theta = 0$ deg. 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 turbine blade and move downstream, as indicated by the red dashed line shown in the figure. It was also revealed clearly that the tip vortex induced by the pre-marked blade (also named the 1st blade) would align itself nicely with the other tip vortices induced by the 2nd and 3rd turbine blade to form a moving tip vortex array in the vertical PIV measurement plane. The relative velocity vectors (i.e., after subtracting the incoming free stream velocity at the tip of the turbine blade from the measured flow velocity fields) at phase angle $\theta = 0$ deg and $\theta = 60$ deg were also shown in the figure in order to visualize the formation and evolution of the tip vortex array more clearly. It should also be noted that, in addition to the tip vortex array, the flow separation and unsteady vortex structures shedding from the turbine nacelle were also visualized clearly form the PIV measurement results. It also can be observed that the separate region,
although not as significant as the tip vortex, located inboard of the tip at approximately mid-span, moving along with the wake expansion, and merging with the tip vortex system at approximately 2.0R downstream.

The three-dimensional wake flow structures downstream the wind turbine model can be reconstructed based on the phase-locked PIV measurement results. Fig. 13 shows the reconstructed 3-D wake flow field with the Cartesian coordinate system fixed to the 1st rotor blade. The track lines of the tip vortex cores, which were generated by tracking the centers of the regions of concentrated vorticity induced by the three turbine blades at different rotation phase angles, were also added in the figure in order to clearly elucidate the helical motion of the tip vortices in the wake of the wind turbine. It can be clearly observed that the tip vortices originated from the tips of the three rotor blades would form three independent helical vortex tubes as they moved downstream. As mentioned above, the helical motion of the tip vortices has a reversed rotational direction with respect to the rotation of the turbine blades. The gap between the helical vortex tubes was found to be a function of the wind turbine tip-speed-ratio. While the helical vortex structures in the wakes of wind turbines were visualized qualitatively with smoke in the previous studies (Anderson, 1982; Vermeer, 2001; and Hand et al., 2001), the PIV measurement results given in the present study are believed to be the first attempt 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: Reconstructed 3D wake flow structures in wake of the wind turbine model
Figure 14 shows the decay profile of the peak vorticity of the helical tip vortices as a function of the downstream distance in the near wake of the wind turbine at the tip-speed-ratio of $\lambda = 3.0$. The measurement data were obtained by tracking the maximum vorticity of the tip vortex at different phase angles. As shown in the plot, a power law function was used to fit the measurements data, which indicates that the strength of the tip vortex would decay as the downstream distance increases following a power law.

Figure 15 shows the tip vortex structures in the wake of the wind turbine at different tip-speed-ratios. It can be observed that both the vorticity of the tip vortices and the gap between vortices would decrease with the increasing tip-speed ratios. Such trend is believed to be connected to the vortex formation process, i.e. the pressure difference between the pressure side and suction side induces the tip vortex. As the tip-speed ratio increases, the angle of attack with respect to the airfoil cross section would decrease as illustrated in Fig. 7. The smaller pressure difference between the pressure side and suction side of the rotor blades would result in a weaker tip vortex. However, the vorticity of the root vortices increased drastically that accounts for the severe separation near the root of the turbine blade. For $\lambda = 4.5$, the series of root vortices were mostly combining together and merging with separate region of the nacelle, and turned out to be a long band region of concentrated vorticity. The separate regions at approximately 70% span become more distinct at high tip-speed ratio, but still tends to merge with the tip vortex system at a shorter distance downstream. For example, the separate region at 70% span of the blade for $\lambda = 4.5$ merged to the tip vortex system at approximately 1.2R downstream of the wind turbine.

Fig. 16 shows the schematic of the trajectory of three helical tip vortices tubes as mentioned above and the scattering distributions of the tip vortex cores in the vertical plane based on one hundred frames of the PIV results for the same phase angle $\theta = 0$ deg. The unsteady feature of the locations of the vortex cores, mainly induced by the unsteady boundary layer flow were revealed in the scattering traces of the vortex centers. Three trajectories of helical curves emerged at wind turbine tips crossed the centers of the regions of concentrated vorticity. It was found that the vortex centers approximately distributed within a circular with a diameter ranging from 9.3mm–37.2mm for $\lambda = 3.0$, and ranging from 7mm–30mm for $\lambda = 4.0$. The centers of these circles align on a straight line for the case of $\lambda = 3.0$, but show a meandering behavior for the case of $\lambda = 4.0$, which has been discussed by Bingol et al. (2007) and Larsen et al. (2007). It seems the vortex center distributions are more stable for the high tip-speed-ratio in terms of smaller diameter of the scattering circles.
Fig. 15: The evolution of the wake vortex structures at different tip-speed-ratios

Fig. 16: The wandering of the wake vortex structures at different tip-speed-ratios
IV. Conclusion

An experimental study was carried out to characterize the dynamic wind loads and evolution of the wake vortex and turbulent flow structures in the downstream of a horizontal axis wind turbine (HAWT), placed in an atmospheric boundary layer wind tunnel. In addition to measuring dynamic wind load acting on the wind turbine model, a high-resolution Particle Image Velocimetry (PIV) system was used to make both “free-run” and phase-locked flow field measurements to quantify the transient behavior of the helical tip vortex and turbulence flow structures in the near wake of the wind turbine model. The characteristics of the turbulent wake flow including the evolution of the helical tip vortices, velocity deficits, and turbulent properties of the wake flow were found to vary significantly as a function of the tip-speed-ratio of the wind turbine. The dynamic wind loads acting on the wind turbine were analyzed in correlation with the detailed flow field measurements. The findings derived from the present study can be used to improve our understanding of the underlying physics for an accurate estimation of the dynamic aerodynamic loads required for the optimal mechanical design of wind turbines.

References