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SHORT PAPER

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Visualization of the tip vortices in a wind turbine wake

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Abstract In the present study, an experimental study was conducted to characterize the formation and the evolution of the helical tip vortices and turbulent flow structures in the wake of a horizontal axis wind turbine model placed in an atmospheric boundary layer wind. A high-resolution particle image velocimetry system was used to make detailed flow field measurements to quantify the time evolution of the helical tip vortices in relation to the position of the rotating turbine blades in order to elucidate the underlying physics associated with turbine power generation and fatigue loads acting on the wind turbines.

Keywords Tip vortex · Turbine wake aerodynamics · HAWT · PIV measurements

1 Introduction

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. 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 et al. 2003). 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 flows downstream of wind turbines significantly. The tip vortices are also recognized as an important source of noise generation and blade vibration (Massouh and Dobrev 2007).

A good physical understanding is essential in order to provide an accurate estimation of the dynamic wind loads required for the optimal mechanical design to improve the performance and fatigue lifetime of wind turbines. This requires a detailed knowledge about transient behavior of the turbulent wake flows downstream of wind turbines and the evolution of the helical tip vortices induced by the rotating turbine blades. While a number of studies have been conducted in the recent years to investigate wind turbine wake aerodynamics, very few experimental investigations can be found in literature to provide detailed field measurements to quantify the transient behavior of the helical tip vortices in the near wakes of wind turbines. Furthermore, most of the previous researches were conducted with the wind turbine models placed in flows with uniform incoming flow velocity and relatively low turbulence intensity. However, in reality, wind turbines always operate in atmospheric boundary-layer winds with significant wind shear and turbulence intensity along the elevation direction.

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In the present study, an experimental study was conducted to characterize the formation and the evolution of the helical tip vortices and turbulent flow structures in the wake of a horizontal axis wind turbine (HAWT) model placed in an atmospheric boundary layer wind. A high-resolution particle image velocimetry (PIV) system was used to make detailed flow field measurements to quantify the time evolution of the helical tip vortices in relation to the position of the rotating turbine blades in order to elucidate the underlying physics associated with turbine power generation and fatigue loads acting on the wind turbines.

2 Experimental setup

The experimental study was conducted in an aerodynamic/atmospheric boundary layer (AABL) wind tunnel located at Iowa State University. As shown in Fig. 1, arrays of wood blocks were used as the roughness elements at the upstream of the wind turbine model to generate an atmospheric boundary-layer flow. A three-blade HAWT model with a scale ratio of 1:350 was used for the experimental study. The rotor blades of the wind turbine model 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 rotor radius of the wind turbine model is 127 mm (i.e., $D = 254$ mm) and the height of the turbine nacelle is 225 mm, which would represent a wind turbine with the rotor radius of about 45 m and tower height of 80 m in a wind farm. A small electricity generator was installed inside the nacelle of the wind turbine model, which could produce electricity as driven by the rotating turbine blades. During the experiments, the wind speed at the hub height was set to be 4.0 m/s (i.e., $U_0 = 4.0$ 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) would be about 6,000, which is significantly lower than those of real wind turbines. 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. However, as suggested by Medici and 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 blades was adjusted by applying different

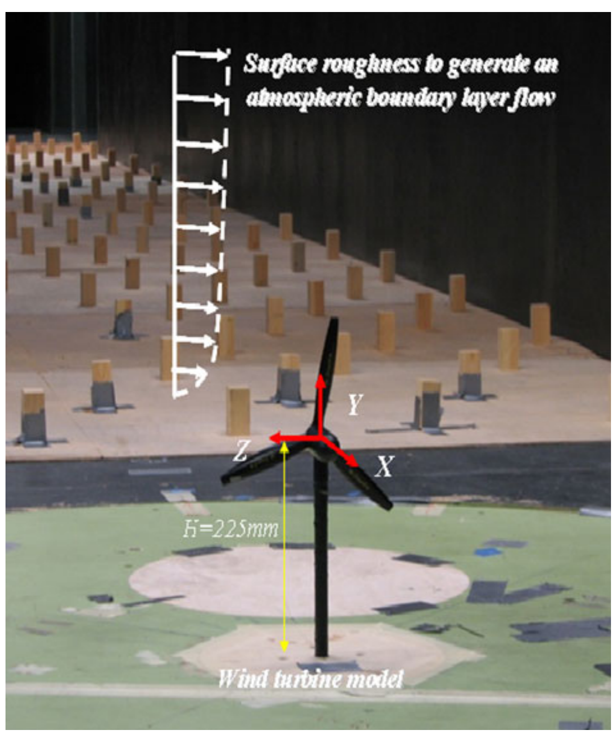

Fig. 1 The test wind turbine

electric loads to the small electricity generator 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 (i.e., $\lambda =$ blade tip rotation speed/wind speed) was found to vary from 0 to $\sim$4.5. A high-resolution digital PIV system was used in the present study to conduct detailed flow field measurements in a vertical plane (laser sheet thickness $\sim$1.5 mm) passing the rotation axis of the wind turbine model to quantify the characteristics of the turbulent wake flow downstream of the wind turbine model. In addition to 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, phased-locked PIV measurements were also conducted in order to elucidate more details about the time evolution of the helical tip vortices in relation to the position of the rotating turbine blades. Further information about the experimental setup, shapes of the turbine blades, tower and nacelle designs, digital PIV system and image processing procedures, temporal and spatial resolution of the PIV measurements and the estimation of the measurement uncertainty is available in Yang (2009).

3 Results and discussions

Figure 2 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, the pre-marked turbine blade would be in the most upward position (i.e., the middle plane of the rotor blade is within the vertical PIV measurement plane) at the phase angle of $\theta = 0°$. It can be seen clearly that a tip vortex would be induced at the tip of the pre-marked turbine blade at $\theta = 0°$. 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 $\theta = 0°$ and $\theta = 60°$ 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 blade roots and turbine nacelle were also visualized clearly form the PIV measurement results.

The 3-D wake flow structures at the downstream of the wind turbine model can be reconstructed based on the phase-locked PIV measurement results. Figure 3 shows the reconstructed 3-D wake flow field with

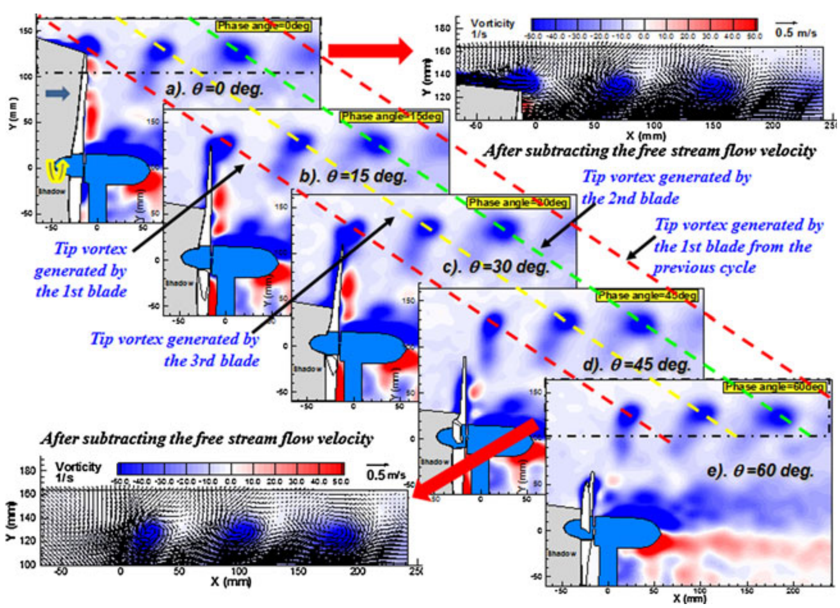

Fig. 2 The phase-locked PIV measurements at tip-speed-ratio, $\lambda = 3.0$

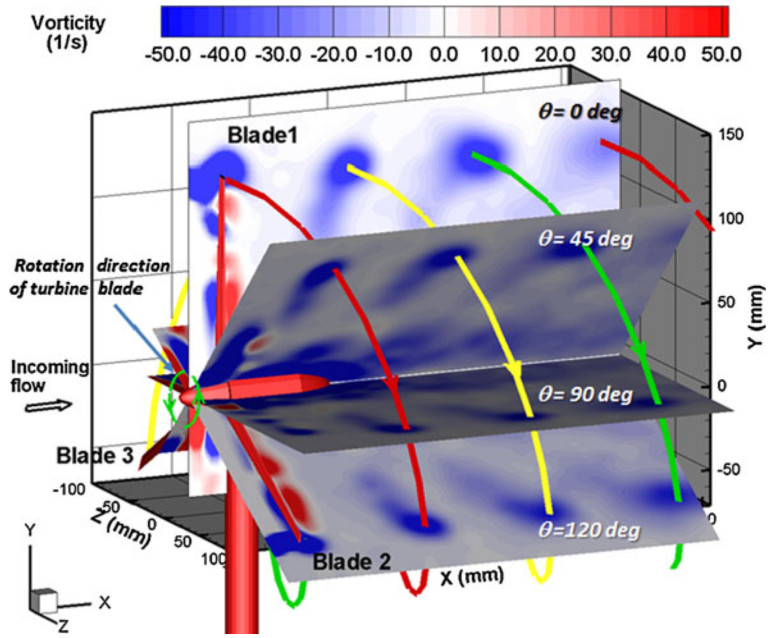

Fig. 3 Reconstructed 3D wake vortex structures at $\lambda = 3.0$

the Cartesian coordinate system fixed to the pre-marked rotor blade. The path lines of the tip vortices, which were generated by tracking the positions of the tip vortex cores revealed from the phased-locked PIV measurements at different phase angles, were also plotted in the figure. It can be seen clearly that the tip vortices originated from the tips of the three turbine blades would form three helical vortex tubes as they travel downstream. The helical motion of the tip vortices was found to have a reversed rotation direction in relation to the rotation 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. While the helical tip vortex structures in the wakes of wind turbines were visualized qualitatively with smoke in the previous studies (Grant and Parkin 2000; Vermeer et al. 2003), the present study is believed to be the first to provide the quantitative measurements to elucidate the formation and evolution of the helical tip vortex structures clearly and quantitatively.

Figure 4 shows the transverse profiles of the time-averaged flow velocity and the normalized turbulence kinetic energy (T.K.E. $= 0.5(\overline{u'}^2 + \overline{v'}^2)/U_\infty^2$) in the wake of the wind turbine model at the downstream location of $X/D = 0.5$ as a function of the turbine tip-speed-ratio. The velocity profile of the incoming atmospheric boundary layer wind was also given in the plot as the baseline 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 a stronger aerodynamic drag force 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. 4, the largest velocity deficit was found at the tip-speed-ratio $\lambda \approx 3.0$–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 $\lambda \approx 3.0$–3.5. The finding was confirmed from the independent wind load and power generation measurement results, which are not reported here. The normalized turbulence kinetic energy profiles shown in Fig. 4 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 blade roots and turbine nacelle as revealed from the PIV measurement results shown in Fig. 2. A region with quite high turbine

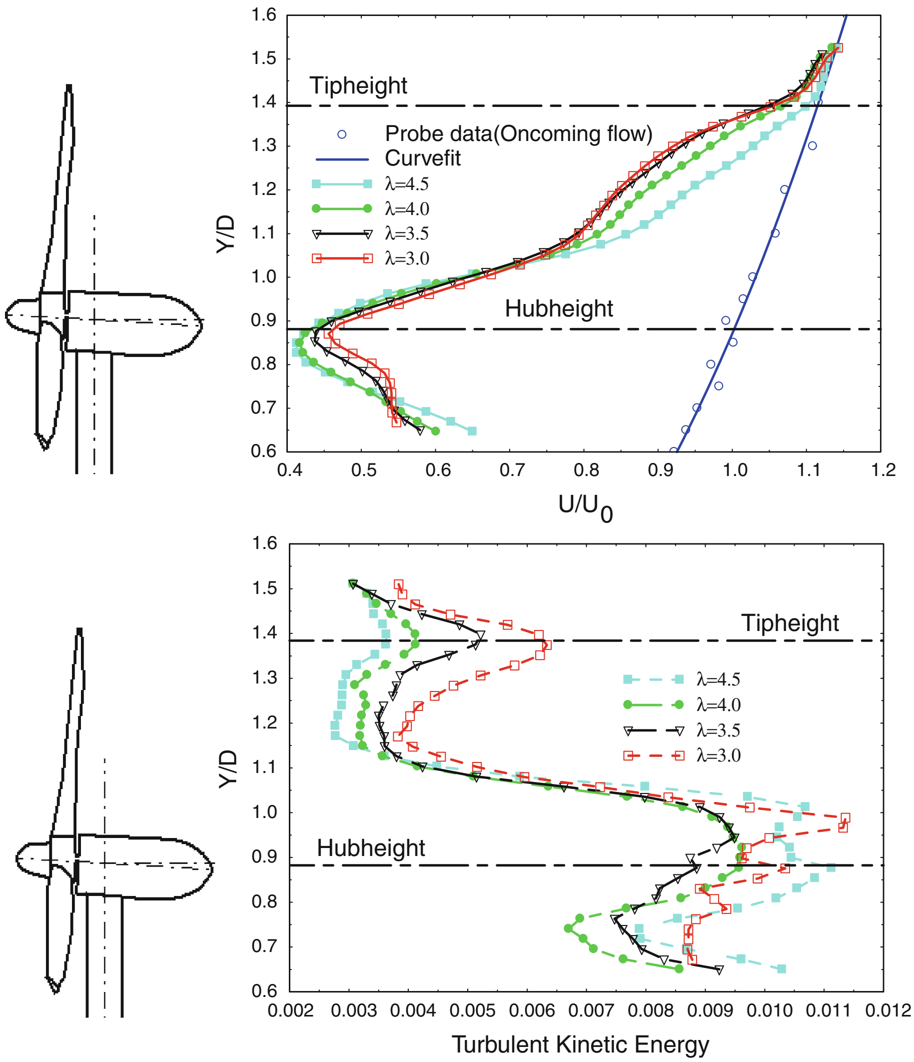

Fig. 4 The transverse profiles of the mean velocity and turbulent kinetic energy at $X/D = 0.5$

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 Porté-Agel (2009) based on cross-wire anemometer measurements.

In summary, an experimental study was conducted to visualize the formation and evolution of the helical tip vortices in the wake of a HAWT model placed in an atmospheric boundary layer wind. A high-resolution digital PIV system was used to make detailed flow field measurements to quantify the transient behavior of the helical tip vortices and turbulence flow structures in the wake of the wind turbine model. The findings derived from the present study can be used to improve our understanding of the underlying physics associated with turbine power generation and fatigue loads acting on the wind turbines.

References

Alfredsson PH, Dahlberg JA, Vermeulen PEJ (1982) A comparison between predicted and measured data from wind turbine wakes. Wind Eng 6:149–155

Chamorro LP, Porté-Agel F (2009) A wind-tunnel investigation of wind-turbine wakes: Boundary-layer turbulence effects. Bound-Layer Meteorol 132:129–149

Grant I, Parkin PA (2000) DPIV study of the trailing vortex elements from the blades of a horizontal axis wind turbine in yaw. Exp Fluids 28:368–376

Massouh H, Dobrev I (2007) Exploration of the vortex behind of wind turbine rotor. J Phys Conf Ser 75:012036

Medici D, Alfredsson PH (2006) Measurements on a wind turbine wake: 3D Effects and bluff body vortex shedding. Wing Energy 9:219–236

Vermeer LJ, Sorensen JN, Crespo A (2003) Wind turbine wake aerodynamics. Prog Aerosp Sci 39:467–510

Yang ZF (2009) Experimental investigations on complex vortex flows using advanced flow diagnostic techniques. Ph.D. Dissertation, Iowa State University