Detection of tip-vortex signatures behind a 2.5 MW wind turbine

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ABSTRACT

The near-field signature of the vortical structures shed from the blade tips behind a 2.5 MW horizontal axis wind turbine in a stably-stratified atmospheric boundary layer (ABL) was quantified for the first time. This study utilizes wind velocity measurements from sonic anemometers installed on a meteorological tower, which offers continuous characterization of wind conditions in the field, at elevations coinciding with the bottom, hub and top tip heights of the turbine. Using the stringent criteria on wind speed, direction and steadiness, we are able to subsample the dataset in which the sonic anemometers are positioned near the edge of the turbine wake. The spectral analysis of this dataset shows a distinct peak at the turbine rotational frequency (f_T) for hub and top tip height measurements. Based on recent literature, we infer that this peak is the signature of tip-vortices, and the shift of this signature from blade-passing frequency ($3f_T$) to f_T is likely to be caused by vortex grouping phenomena. Slight changes of mean wind direction in other data samples result in the absence of the spectral peak, suggesting the very local extent of tip vortices.

Key words: Wind turbine; Field measurement; Turbine wake; Tip vortex; Vortex grouping; Spectral analysis.

1. INTRODUCTION

Understanding the dynamics of transport processes that modulate the spatial distribution and evolution of large-scale turbulence and momentum recovery in the wake of axial-flow turbines is essential for optimizing turbine arrays since most of such devices operate under multiple-wake

conditions (Chamorro *et al.* 2013). Therefore, a significant amount of work has been focused on overall wake and wake vortical structures (e.g. Bingöl *et al.* 2010, Trujillo *et al.* 2011 and Okulov and Sorensen 2007). Wind turbine wakes contain helical vortex structures that play an important role in the development of the near wake and consequently the resultant far wake, which impacts the power generation and structural integrity of downstream turbines in wind farms (Sherry *et al.* 2013). To characterize these wake vortical structures, several recent investigations have examined the propagation and behavior (e.g. diffusion and rollup) of tip vortices shed by axial-flow turbines and propellers, which can provide insights for constructing physical-based wake models. For example, water-tunnel experiments of Felli *et al.* (2011) on model propellers investigated the interaction between tip and hub vortices. Their study outlined the dependence of wake instability transition on the spiral-to-spiral distance between vortices and the evolution of the tip vortex filaments as a multi-step grouping mechanism, whose characteristics depends on the blade number. Using phase-locked particle image velocimetry (PIV) measurements, Sherry *et al.* (2013) investigated the evolution and breakdown of the helical vortex structures measured behind a model wind turbine in a water channel. Their results showed a breaking of the helical symmetry and merging of the vortices in the wake. Using 3D visualizations in the wake of a miniature axial-flow turbine, Chamorro *et al.* (2012a) observed the propagation, stability and interaction between consecutive tip vortices. They noted that instability can be triggered by vortex-to-vortex interactions. Zhang *et al.* (2012) performed a wind tunnel experiment to study tip-vortex structures behind a standalone wind turbine model using PIV and hot-wire anemometry (HWA). The 2D vorticity as well as swirling strength contours calculated from PIV measurements revealed stronger tip-vortex signatures near the top tip compared to those at the bottom tip. Their spectral analysis on HWA data indicated that these signatures exist up to about 2–3 rotor diameters downwind of the turbine under the conditions investigated. Numerical simulations by Ivanell *et al.* (2010) focused on the stability of tip vortices under harmonic perturbations. Their results showed that the instability is dispersive and that growth arises only for some specific frequencies and modes. Flow visualization in a 10 m rotor diameter wind turbine under controlled flow conditions at the NASA-AMES wind tunnel revealed long lasting tip vortices forming a helical trajectory (Hand *et al.* 2001). In addition, field experiments using a similar turbine evidenced the effect of the inflow irregularities in disrupting the turbine flow field and distorting the wake vortex helices (Schreck 2002). In spite of all of

these efforts, the behavior and dynamics are largely unclear for the tip vortices shed by a full-scale wind turbine operating under atmospheric turbulent flows. Very few studies have quantified or even qualitatively characterized such structures under in situ conditions, partly due to the technical challenges associated with the measurements.

In this research, we use ultrasonic anemometers in the near field behind a 2.5 MW wind turbine to detect the signature of tip vortices with the goal of understanding their general characteristics in the turbulence energy spectra of the turbine wake. The paper is organized as follows. First, we describe our experimental setup and field conditions in Section 2. Second, in Section 3 we provide the spectral analysis of tip vortex signatures using wind velocity measurements at multiple heights under slightly different wind directions. We end with remarks in Section 4.

2. EXPERIMENTAL SETUP

The field experiments were performed at the University of Minnesota EOLOS Wind Energy Research Field Station. The facility consists of a Clipper Liberty 2.5 MW horizontal-axis wind turbine and a 130 m meteorological tower. The 3-blade wind turbine has a rotor diameter of $d_T = 96$ m, and its hub height is $z_{hub} = 80$ m. The meteorological tower (hereon referred as met tower) is located 160 m south of the wind turbine, which is the upwind side of the turbine under the prevailing wind direction at this location. A series of 1 Hz sensors provides detailed characterization of mean velocity, temperature and humidity in the atmospheric boundary layer at six elevations from near ground (10 m) to that of turbine top tip height (130 m). The met tower is also equipped with four Campbell Scientific CSAT3 sonic anemometers of 20 Hz sampling rate, which are placed at 10 m, 30 m, 80 m, and 129 m, respectively. The top three heights match the top and bottom tip of the rotor as well as the turbine hub height. The anemometer at the lowest elevation measures the near-ground wind. More details on the field experimental setup can be found in Chamorro *et al.* (2014).

In the current investigation, we intend to detect the signatures of tip vortices located at the lateral edge of the turbine wake by taking advantage of the available sonic anemometers mounted on the met tower. To enable this challenging measurement, the wind turbine is required to operate under specific wind direction such that the tip vortices generated from turbine blades pass through the sample volume of the anemometers. Since the met tower is located in the

proximity of the wind turbine (~ 1.6 rotor diameters south of the turbine tower), we assume that the radial propagation of the tip vortices is not significant, $< 4^\circ$ according to estimations based on wake expansion models (e.g. Katic *et al.* 1986). Consequently, based on the geometric relation illustrated in Figure 1, it can be shown that 16.7° West from the North is the ideal wind direction for our intended measurements using the hub height anemometer. Under this configuration and the assumption of negligible wake expansion, the tip vortices are expected to pass through the sample volume of the sensor at 133.3° from its forward axis, which is within the measurable range of a CSAT3 sonic anemometer, i.e. azimuth angles between $\pm 170^\circ$ (Campbell SI. Instruction manual 2012; Revision 9/12). Additionally, in favor of quantifying the signature of tip vortices using spectral analysis, the wind is required to be steady in both speed and direction. To sub-sample the candidate time series for our purpose, we restrict the wind direction to be within $\pm 5^\circ$ of the defined ideal direction and maximum fluctuations in speed less than 10% of the mean value. The sampling is performed over a database containing roughly 14 months of continuous acquisition.

The time series of wind speed and direction satisfying the above conditions are presented in Figure 2. The selected dataset lasts 800 s with mean wind velocity 5.4 m s^{-1} . In this period, the turbine is operated between its cut-in and rated wind speeds. The mean direction is only -0.6° from the ideal direction. As illustrated in Figure 2, the instantaneous streamwise velocity fluctuations stay under 0.5 m s^{-1} and the direction changes are within 4° from the mean. Overall, this basic flow setting provides us an opportunity to investigate the periodic signatures of the tip vortices using the available sonic anemometers installed on the met tower. For the selected time series, the time-averaged vertical profiles of flow conditions measured at the met tower are presented in Figure 3. The mean velocity profile displays positive and monotonic mean velocity gradient within the elevation span of the turbine blades without appreciable signature of velocity deficit, indicating that the sonic anemometers are located at the lateral edge of the wake or outside the wake (Figure 3a). The turbulence intensity distribution (Figure 3b) reaches a minimum at the hub height, related possibly to the damping effect of turbine on the energetic large-scale structures in the ambient turbulence (Chamorro *et al.* 2012b). The temperature is -10°C near ground, and increases 2°C within the first 50 m above the ground, and stays almost constant at the heights corresponding to the turbine blade span (Figure 3c) where the relative humidity exhibits lower gradient than that closer to the ground (Figure 3d). To assess the

atmospheric condition during the measurements, we employ the bulk Richardson number, i.e. $Ri = g\Delta T\Delta z/(T_0\Delta U^2)$, calculated using measurements from the met-tower. In this expression, g is the gravitational acceleration, ΔT and ΔU are the temperature and velocity difference between near ground ($z_1=10$ m) and at the turbine top tip ($z_4=129$ m), and T_0 is a reference temperature taken as the average of the measurements at six elevations shown in Figure 3c. The bulk Richardson number represents the relative importance of buoyancy and shear in producing turbulence, which is a dimensionless indicator of ABL stability close to the ground (Kaimal and Finnigan 1994). The above analysis is consistent with the prior study, i.e. Chamorro *et al.* (2014), conducted in the same field site. As a result, the estimated bulk Richardson number is approximately 0.3. We acknowledge that the data at edge of the turbine wake may not provide an accurate estimate of the Richardson number for characterizing the atmospheric conditions in our experiments. However, the presence of the turbine promotes the mixing of the flow structures in the wake which results in a lower estimate of Richardson number compared with those based on the information outside the wake. Therefore, the Richardson number of 0.3 would suggest a stably-stratified atmospheric boundary layer during the time period of our measurements. To further justify the above assessment, we perform analysis using ambient flow (i.e. the flow outside of the wake) in close vicinity of the time period used for Figure 2 and 3 (referred to as tip-vortex dataset). Specifically, a 41-min long dataset (referred to as ambient-flow dataset) sampled 61 min before tip-vortex dataset. The mean wind direction for ambient flow dataset is 24.3° west from the North, which is 7.6° away from mean wind direction of tip-vortex dataset (located at the edge of the wake according to our sampling criteria). Based on the Jensen's model (Katic *et al.* 1986), this angle difference would position ambient-flow dataset outside of the wake. The comparison of the mean velocity and temperature profiles from both datasets (the tip-vortex and ambient-flow datasets) shows a clear similarity of both profiles (not shown for brevity). As we expected, the bulk Richardson number of the ambient-flow dataset was calculated to be ~ 0.4 , which is indeed slightly larger than that obtained from the tip-vortex dataset. Therefore, we infer that the time-averaged vertical profiles of flow conditions obtained from the tip-vortex dataset (located at the edge of the wake) can still provide valuable characteristics of the atmospheric boundary layer even though it is weakly influenced by the turbine wake.

3. TIP VORTICES SIGNATURE IN THE SPECTRAL DOMAIN

To identify the energetic vortical structures shed from turbine blade tips, we compute the turbulent energy spectra (Φ) and their pre-multiplied counterparts ($f\Phi$) for the velocity time series from the sonic measurements at the different heights on the met tower. In particular, the pre-multiplied spectrum involves considerations of power per unit volume (Jimenez 1998), which is a more effective tool for highlighting the relative significance of coherent motions compared with a regular spectrum. Based on the helical trajectory of the tip vortices advected from the turbine, the tip vortices will induce velocity fluctuations primarily in the radial direction. Therefore, according to the relative position between wind turbine and the met tower (Figure 1), it is expected that the tip vortices are more likely to yield consistent signature on the turbulent energy spectrum for spanwise component compared with those of vertical and streamwise components. This postulate has been confirmed by comparing the spectra of each velocity component for the selected time series. For brevity, the comparison is not shown and only spanwise spectra are presented for discussion throughout the entire paper.

Figure 4 shows the spectral characterization of the spanwise velocity at the hub height. In the regular energy spectrum (Figure 4a), the classic $-5/3$ law ($\Phi \propto f^{-5/3}$) for the inertial subrange is observed in one decade frequency range [0.1, 1] Hz. It shows that the selected time series has approximately sufficient timespan to resolve established energy cascading process in the atmospheric boundary layer. More remarkably, within this range, a distinct peak appears at frequency $f \approx 0.177$ Hz. This peak is substantially accentuated in the corresponding pre-multiplied spectrum (Figure 4b), indicating clearly the presence of an energetic vortical structure at this frequency. To demonstrate its linkage with turbine performance, the rotational frequency of the turbine (f_T), obtained from the supervisory control and data acquisition (SCADA) data of the turbine, is presented in Figure 4c. As is evident, the turbine rotates steadily within a narrow band 0.177 ± 0.001 Hz. This frequency band encloses precisely the distinct energy peak in the turbulent spectrum, suggesting that the spectral peak is a direct consequence of the helical trajectory of tip vortices periodically crossing the sample volume of the anemometer.

Although the tip-vortex signature is dependent on wake position and other operational variables like tip speed ratio, spectral peaks at blade-passing frequency, i.e. $3f_T$, are generally reported for near wake measurements in many prior studies (e.g. Chamorro *et al.* 2011 and Zhang *et al.* 2012). As shown in Figure 4, our field measurement reveals a shift of spectral peaks

from blade-passing frequency to turbine rotational frequency (f_T). This spectral shift can be also observed in a couple of recent studies on a wind turbine wake (Chamorro *et al.* 2012c) and a wake flow of a propeller (Felli *et al.* 2011). In particular, using flow visualization techniques in water tunnel experiments, Felli *et al.* (2011) discovered that the spectral-peak shift from $3f_T$ to f_T is caused by a ‘multi-step’ grouping of tip-vortex filaments whose characteristics depends on the blade number. They found that for the three-bladed propeller, the grouping mechanism occurs through a two-step process. In the first step, starting from the transition field ($x/D \approx 4$), an alternative grouping with one single and one pair of vortex filaments occurs. More downstream ($x/D \approx 6$), the single filament tends to be rolled up by the inductance effect of the filaments pair, progressing into a group with three filaments. Correspondingly, the tip-vortex signature in velocity power spectrum becomes stronger at f_T and weaker at $3f_T$ as the sampling location moved further downstream. In the field of wind turbine aerodynamics also, the tip vortex pairing phenomenon has been observed both experimentally (e.g. Alfredsson and Dahlberg 1979) and numerically (e.g. Ivanell *et al.* 2010). For example, though not directly linked with spectral signatures, Sherry *et al.* (2013) has reported the three-vortex interaction phenomena in a phase-locked planar PIV measurement of vortical structure signatures in the wake behind a model wind turbine in a water tunnel experiment. Their results showed that with an increase in tip speed ratio the vortex merging due to mutual inductance between the vortical filaments occur closer to the rotor plane, and the remaining third filament merges further downstream, resulting in a single vortex structure. In addition to tip-speed ratio, vortex grouping phenomena and related tip vortex signatures have also been related to several other factors such as Reynolds number, turbine geometry and aeroelasticity, unsteadiness presented in the turbine operation and ambience flows (e.g. Felli *et al.* 2011, Nemes *et al.* 2012, Delbende and Rossi 2013, and Hong *et al.* 2014).

To illustrate the effect of Reynolds number on the tip-vortex signature, Figure 5 compiles the power spectra from Chamorro *et al.* (2012c) and our field experiment. In Chamorro *et al.* (2012c), HWA was implemented in the wake of a model wind turbine under several different Reynolds numbers (Re), with Re defined based on the rotor diameter and hub height velocity. As it shows, the spectral peak at turbine rotational frequency is clearly visible in the power spectra of wind tunnel experiments for $Re \geq 9.3 \times 10^4$. Notably, the examined Reynolds numbers in this study (Chamorro *et al.* 2012c) are relatively higher than the other wind tunnel experiments (e.g. Zhang *et al.* 2012) where this frequency shift is absent. In general, the spectral peak becomes

stronger at f_T while dampens at $3f_T$ with increasing Reynolds number, and the spectral peak diminishes completely at $3f_T$ in our field measurements at $Re = 5.6 \times 10^6$. In addition, the shift of spectral peak to f_T in our field measurements (under the conditions provided in Section 2) appears at $x/D \leq 1.6$ compared to $x/D \approx 6$ and $x/D > 2$ in Felli *et al.* (2011) and Chamorro *et al.* (2012c), respectively, where the Reynolds numbers are significantly lower. It is worthwhile noting that the recent super-large-scale PIV measurements around the same full-scale turbine has also observed two and three tip-vortex merging to occur within half of rotor diameter behind the wind turbine (Hong *et al.* 2014). This is likely to be a result of higher ambient turbulence which amplifies the flow perturbations and consequently promotes interaction/merging of neighboring tip vortices through reducing their separation distances (Delbende and Rossi 2013 and Delbende *et al.* 2014). A recent numerical study by Delbende and Rossi (2013) focusing on the dynamics of three helical vortices revealed that flow perturbation and shifting the initial vortex position leads to a rapid destabilization of the vortex system as well as the grouping and merging events. They have suggested the potential relevance of their work with real turbine wakes which are generally associated with very small non-dimensional helical vortex pitch and large perturbations due to incoming flow and rotor geometry. Nemes *et al.* (2012) claimed that the source of perturbation relating to the filaments that undergo pairing are also likely to be introduced through small inhomogeneities in the blade construction leading to variations in blade loading and hence vortex strength. Based on the trends suggested in abovementioned studies, the unsteadiness presented in the full-scale flow-turbine interaction in the atmospheric boundary layer promotes the tip vortex interaction in the wake and consequently merging of three consecutive tip-vortices. This results in the shift of spectral peak from $3f_T$ to f_T , as an indication of passage of one single vortex, at $x/D \approx 1.6$ as we observe here. This finding reveals the limitation of current laboratory studies in replicating full-scale wind turbine operating in the ABL, in terms of e.g. Reynolds numbers and atmospheric unsteadiness. Consequently, this limitation causes uncertainties in the prediction of the dynamics of vortex evolution and merging phenomenon in utility-scale turbine wake, which is significant for understanding momentum transport and mixing induced by the turbine.

Under the extant instrumentation and flow conditions, similar analysis is performed for wind measurements at the turbine bottom and top tip heights, and the results are shown in Figure 6. The energy spectra at these elevations also illustrate a resolved inertial subrange in the similar frequency range to that of at the hub height. However, for the bottom tip height, no distinct peak

is observed from neither the regular (Figure 6a) or the pre-multiplied spectra (Figure 6b), while at the top tip height, the spectral peak appears in the same narrow band corresponding to the turbine rotational frequency. Compared with the hub height results, this peak is more distinguishable and energetic. The deviation of the spectral signatures of tip vortices between bottom and top tip heights can be associated with the change of wind speed, mean shear and turbulence levels with height. The variation of wind speed can lead to difference of tip speed ratio, and thus a change of tip-vortex strength between top-tip and bottom-tip heights. Under the condition of our experiments, the vortex strength at the top-tip height is estimated to be about twice of that at bottom-tip height, which could be an important factor affecting the tip-vortex signatures observed at different heights. In addition, closer to the ground, the relatively higher mean shear and turbulence levels are more likely to trigger instabilities of the vortical structures, and enhance the interaction between adjacent vortices and therefore dampen their signature. Conversely, relatively low mean shear above the hub height facilitates the tip vortex formation and roll-up, and contributes to evolution of tip vortices, and consequently, a stronger spectral signature is observed there. This mechanism is consistent with the observations from wind-tunnel experiments under controlled flow conditions (Chamorro and Porté-Agel 2009). It is also worthwhile noting that some large-scale wake phenomena such as the meandering of the wake, resulting from large scale structures in the ambient turbulent field (Troldborg 2008 and Larsen *et al.* 2007) could eventually modify the tip-vortex signature captured by the sonic anemometers on the met tower. This phenomenon is, however, not expected to occur in the very near wake region of the current measurements.

To further investigate the locality of tip vortices, we perform spectral analysis on another two datasets with mean wind direction slightly deviated from that of the first selected time series. As illustrated in Figure 7 and 8, both datasets contain approximately 700 s, providing similar span of time scales as the first dataset. The wind conditions for both datasets are considered steady with the fluctuations of streamwise velocity staying within 0.5 m s^{-1} and direction less than 4° . One dataset has time-averaged wind direction 17.4° from the North, i.e. 0.7° west of the ideal direction. The other one yields a direction of 15.6° from the North, which deviates east of the ideal direction by 1.1° . These two sample datasets are also obtained under stably-stratified conditions with similar Richardson number as that of the first dataset (results not presented). Although the energy spectra of both datasets show the inertial subrange, no distinct energy peak

is observed at turbine rotational frequency for measurements at all three elevations. For brevity, only hub and top tip height results are presented for both datasets in Figures 7 and 8 to demonstrate this point. Compared with the first dataset, the slight changes of the time-averaged wind direction of these two samples correspond to spanwise displacements of 2-3 m at the met tower according to the geometric relation. These spanwise displacements are sufficient for the tip vortices to miss out the sample volume of anemometers, as inferred from the absence of their signatures in the energy spectra. In general, if we consider the scale of tip vortices to be on the order of the chord length of the blade tip, i.e. approximately 1 m for the EOLOS turbine, the results suggest the highly-localized characteristics of these vortical structures. In other words, the tip vortices do not show significant diffusion or expansion in the near-wake region of our full-scale turbine.

4. FINAL REMARKS

Using stringent sample criteria, the wind velocity measured by the sonic anemometers on a met-tower near a full-scale wind turbine was used to probe the signature of tip vortices. Based on recent publications (Chamorro *et al.* 2012c and Felli *et al.* 2011), we associate the precise matching of the spectral peak observed at the turbine rotational frequency f_T with the tip-vortex signatures although such signatures are commonly observed at blade-passing frequency $3f_T$. As shown in the water tunnel experiment behind a propeller by Felli *et al.* (2011), this shift of tip-vortex signature from $3f_T$ to f_T initiates at $x/D \approx 4$, and after $x/D \approx 6$ there is no presence of blade passing frequency in the spectra caused by the grouping of neighboring tip vortex filaments. This grouping phenomenon has also been largely reported for wind turbines in laboratory (e.g. Alfredsson and Dahlberg 1979, and Chamorro *et al.* 2012c). Compared to the reported laboratory experiments in this paper, both our experimental studies (the current paper and Hong *et al.* 2014) performed within the wake of the same 2.5-MW wind turbine revealed that vortex merging/grouping occur much closer to the turbine (i.e. less than two rotor diameter) under the conditions investigated. This enhanced vortex interaction compared those in the wind tunnel experiments is likely to be related to the characteristics of full-scale studies such as (1) the small dimensionless pitch of helix and large perturbations due to incoming flow and rotor geometry (Delbende and Rossi 2013); (2) the inhomogeneities in the blade construction leading to

variations in blade loading and hence vortex strengths (Nemes *et al.* 2012). A combined effort of detailed data analysis and comprehensive literature survey allows us to infer with substantial confidence that the spectral peak observed at f_T is indeed a signature of tip vortices.

Needless to say, due to the stringent requirements on the experimental setup, the datasets available for current analysis are limited. More datasets need to be collected to substantiate our research findings and obtain a complete picture of tip vortex behaviors. In addition, as shown by a number of prior studies, the propagation and stability of tip vortices can be very complex and modulated by a number of factors including atmospheric boundary layer conditions and structural properties of the turbine blades. It is also not totally clear that the signature of these vortices can serve as a direct indicator of disturbed wake region behind the turbine. Specially-design experiments, in particular, whole-field flow measurements behind a utility-scale turbine are needed to obtain a thorough understanding of the characteristics and dynamics of tip vortices under various flow conditions including thermal stability, mean shear across the rotor, and the background turbulence levels.

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Figure 1. (a) 3D schematic of the Eolos wind turbine and the instrumented met-tower, (b) 2D plan view showing the ideal wind direction for capturing tip vortices using the available anemometer at the hub height of the met tower.

Figure 2. The time series of (a) streamwise velocity and (b) relative direction ($\Delta\theta$ illustrated in Figure 1) of the selected dataset with the time-averaged relative direction ($\overline{\Delta\theta} = -0.6^\circ$).

Figure 3. Vertical profiles of (a) mean wind velocity, (b) turbulence intensity, (c) mean temperature and (d) mean relative humidity. The velocity and turbulence intensity are obtained from the measurements of 20 Hz sonic anemometers, while the temperature and relative humidity are acquired using 1 Hz sensors. The solid and dashed lines represent tip-vortex and ambient flow data sets, respectively.

Figure 4. (a) Turbulent energy spectrum and (b) pre-multiplied spectrum of the spanwise velocity component at hub height. (c) The rotational frequency of the turbine for the selected time duration.

Figure 5. The shift of the tip-vortex signature from blade-passing frequency ($3f_T$) to turbine rotational frequency f_T promoted by increasing the Reynolds number. The turbulent energy spectra of spanwise velocity component measured at top-tip height behind (a), (b) and (c) a model wind turbine (adapted from Chamorro *et al.* 2012c), and (d) at hub height behind a full-scale 2.5 MW wind turbine.

Figure 6. (a,c) Turbulent energy spectra and (b,d) pre-multiplied spectra of the spanwise velocity component measured at the bottom and top tip heights, respectively.

Figure 7. The time series of (a) streamwise velocity and (b) relative direction, and the turbulent energy spectra of spanwise velocity component measured at (c) hub height and (d) top tip height for the selected dataset with $(\overline{\Delta\theta}) = 0.7^\circ$.

Figure 8. The time series of (a) streamwise velocity and (b) relative direction, and the turbulent energy spectra of spanwise velocity component measured at (c) hub height and (d) top tip height for the selected dataset with $(\overline{\Delta\theta}) = -1.1^\circ$.

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