On the multi-scale turbulent structure interactions within wind farms

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Abstract. The quantification of the scale-by-scale interaction of multi-wakes and background flow is required to estimate turbines behaviour within wind farms. The paper provides insight on the evolution of multi-scale turbulence of a model wind farm operating in turbulent boundary layer. The wind farm configured with aligned turbines set at streamwise spacing between units of 5 diameters by spanwise spacing of 2.5 diameters, corresponding to an array of 8×3 turbines. Hotwire anemometry was used to acquire high-resolution measurements of streamwise velocity fluctuations at various locations. Experimental results suggest that the contribution of multi-scale turbulence structures to the kinetic energy of the wake is highly dependent on the location inside the wind farm, the evolution is significantly modulated by turbine rotation, wake interactions and outer flow, large scale motions mainly dominate outer and far wakes, while small scales are popular in inner and near wakes.

Keywords: Wind farm, wakes, turbulent boundary layer, spectra, large scale motions

1. Introduction

Wind energy is developing rapidly and plays a constructive and vital role in energy supply, environmental protection and climate change. Installed power capacity from wind energy has been experiencing an explosive growth last decade, annual installations for onshore and offshore of more than 50GW each year have topped, despite ups and downs in some markets [1]. Wind turbines operate under various and complex flow conditions characterized by multi-scale and energetic turbulent motions. Understanding the aerodynamic field characteristics of wind farm in turbulent atmospheric boundary is vital and essential for wind farm micro-siting, wind turbines layout optimization and
operation stability [2,3]. In particular, the quantification of the scale-by-scale interaction of the multi-wakes and outer flow is required to estimate turbines behavior within wind farms [4].

Fully developed turbulent possesses tremendously many degrees of freedom, a wise strategy to discern the dynamics is to describe the dominant spatiotemporal scales and discard the inessential ones [3,5]. Based on proper orthogonal decomposition, VerHulst & Meneveau found that streamwise rotating rolls as dominant coherent structures creating strong ejection and sweep regions in flow, while streamwise varying structures and modes varying in vertical direction [6]. Dominant length scales responsible for the kinetic energy entrainment stay strong further inside wind farm although confined by layout spacing [7]. Field experimental data were analyzed with wavelet transform and structure function to study the scale-dependent correlations under neutrally stratified conditions [8]. Wake meandering, a large-scale coherent motion exists in the turbine wake under different inflow and operating conditions [9], has considerable effects on the development of wake, the similarity of wake meandering at near-wake and far-wake locations has been characterized via actuator models [10,11] and geometry-resolving simulations [9]. Jin et al. [12] analyzed the distribution of the large-scale motions and integral length scale ($A_u$) in the wake of a wind turbine within a uniform flow under very low and high turbulence levels. They showed the distinctive effects of background turbulence on $A_u$ in the intermediate and far field wake; however, its growth rate was approximately linear regardless of the background turbulence. Singh et al. [13] pointed out that more homogenized velocity structure in the wake is produced by the impact of turbine rotation on break and deflect the large-scale flow structures, accompanying with strongly attenuated non-local transfer between large and small scales. Recently, Liu et al. [14] revealed the strong modulation of wind farm layout on the evolution of integral time scale, the downwind turbines impinged with reduced scales with respect to those of incoming flow as a result of the dampening of the very large-scale motions.

The main goal of this paper is to provide more insight on the evolution of multi-scale turbulent flow within wind farms, quantify the scale-by-scale interaction of imposed wakes and background flow. Section 2 describes the methodology; Section 3 presents the results and discussion. The main conclusions are summarized in section 4.

2. Methodology

Model wind farms operating in turbulent boundary layer were setup in the Effiel-type boundary layer wind tunnel of the University of Illinois at Urbana-Champaign. The boundary-layer wind tunnel test section is 6.1 m long, 0.914 m wide and 0.45 m high. More detailed information on the facility could be found in Adrian et al [15].

The model farm was operated in high turbulence settings by placing an active turbulence generator at the entrance of the test section to produce shear flow with an inertial subrange spanning two decades [12]. The incoming velocity and turbulence intensity at hub height is 9.33 m/s and 10.5% respectively, resulting in a Reynolds number $Re \approx 7.0 \times 10^4$ and tip speed ratio roughly 4.9. The rough surface was designed with roughness elements consisting of 5 mm chains laid in spanwise direction with a streamwise spacing of 20 mm in the test section [16]. A friction velocity of $u_* \approx 0.55 \text{ m/s}$ and an aerodynamic roughness length of $z_0 \approx 0.12 \text{ mm}$ was obtained by fitting a logarithmic curve on the mean velocity profile near the wall. The boundary layer thickness is roughly 2.2 times turbine hub height (see Figure 1).

The blades of the turbines were 3D-printed by Objet Vero material at University of Illinois rapid-prototyping laboratory. The blade geometry is based on a reference model turbine designed at Sandia National Laboratory [17]. The model has a diameter $d_f = 120 \text{ mm}$, nacelle length $d_n = 10 \text{ mm}$ and hub height $z_{\text{hub}} = 125 \text{ mm}$. Further information about the geometry of the model turbine is provided in Tobin et al [18].

The model wind farm consisted of aligned units with crosswise separation 2.5 times rotor diameters by streamwise distance with $5d_f$ were considered to study the multi-wake interactions, resulted in an
array of 8×3 horizontal-axis turbines. A dummy row was placed downwind of the last row to avoid potential edge effects.

High resolution velocity measurements were obtained at various locations at the vertical plane (via and parallel to turbine axis) of the central column turbines with a DANTEC boundary layer type hotwire anemometer sampled at 10 kHz for periods of 120 s and moved with a traversing system controlled by Arduino Code. Throughout the calibration and experiments, the temperature was kept within 23±0.5 °C with air conditioner to avoid thermal drift of the voltage.

3. Results and Discussion

3.1. Mean Velocity and Turbulence Intensity

Selected time-averaged mean velocity and turbulence intensity vertical profiles are shown in Figure 2, respectively, at $x / d_f = 1$, 4 behind the first, fifth and seventh row. As expected, the recovery at a given $x / d_f$ location behind a turbine is greater for an upwind turbine as compared with a downwind one at first several rows; however, the mean velocity profile quickly adjusts to an equilibrium state after first 3 to 4 rows, so that there is no further difference in recovery as we move to downwind turbines inside a wind farm. The turbulence intensity profiles show two peaks in the near wake ($x / d_f = 1$) around top and bottom tip heights, which is due to the turbine tip vortex shedding [19]; there is an additional peak at the hub height only for the first turbine, indicating the effect of vortex...
shedding from turbine nacelle (motor), while this effect is clearly diminished in the downwind turbines operating under higher turbulence induced by upwind turbines rotation.

3.2. Integral Time Scale

The integral time scale is computed via the integral of the correlation function of the streamwise velocity [14]. Figure 3 shows the vertical profile of integral time scale for the wake of the first row and seventh row as function of vertical height at various streamwise locations. It is noted that the integral time scale in the wake is substantially reduced by the turbines rotation, suggesting that the inertial sub-range for the wake is smaller compared to base flow [13]. The deficit of integral time scale is largest around the axis of unit in the very near wake and recovery with the increase of vertical offset and streamwise distance due to more energy containing eddies from outer enter into the wake region. Accompanying with the recovery in the turbine shadow region (between top and bottom tip heights), the integral time scale beyond the top tip height slightly decrease with downwind distance as energy transfer to wakes, while those below the bottom tip heights increase with downwind distance, this phenomenon is owing to that the large scale motions dominate the flow mixing most over the top of turbine, while the low mean velocity and narrow space restrict the kinetic flux at lower height.

Compared with the first row circumstance, the recovery rate of the integral time of the turbine far inside the wind farm is faster in the turbine shadow region due to the enhanced turbulent level induced by upwind turbines. It’s noted that far inside wind farm, the spatial distributions of integral time scale are more homogeneous than the first row, which suggests that large scale motions attenuated while small scale motions enhanced during the multi-wake interactions. The normalized scale around the top tip height is around 0.8 regardless of streamwise locations, corresponding to the scale at the order of rotor diameter.

![Figure 3. Distribution of integral time scale of the a) first and b) seventh row](image)

3.3. Velocity Spectra

To highlight the differences between various locations within wind farm across scales, selected pre-multiplied velocity spectra \( f_\Phi \) at hub height \( a1 \), bottom tip height \( b1 \) and top tip height \( c1 \) across the near and far wake \( (x/d_T = 0.5, 2.5 \text{ and } 4.5) \) of the first row are shown in Figure 4, while Figure 4a2-c2) corresponds to their counterparts of the seventh row. Obviously, the contribution of the turbulent kinetic energy is quite different across wind farm. Due to the strong effect of boundary layer shear, the turbulent kinetic of incoming flow decrease as the height increase. The frequencies corresponding to the peaks at bottom tips are smallest, though the dominant frequencies of incoming
flow are within the frequency region $f_{d_{T}}/U_{hub} \sim [10^{-2}, 10^{0}]$ across heights, indicates the existence of large scale motions.

Due to the active filter effect of wind turbine rotation, the large scale motions are dampened in the wake while the small ones are amplified [20]. In the near wake, small scale turbulent structures exhibit highly enhancement due to the turbine rotating and blades vortex shedding process. Especially near the blades tips in Figure 4b1-c1), the peaks correspond to the rotor rotating frequency $f_{r}$ and its harmonics $3f_{r}$. However, far inside the wind farm, the characterized dominant frequencies are attenuated and disappeared due to the instability of the tip vortex shedding and significantly modulation of the enhanced turbulence inducing from upwind turbines. With the increase of downwind distance of individual turbine, the energy containing in large scale motions increase while that of small scale motions decrease during the wake evolution, owing to the interactions between large scales of wakes and the ambient flow become more intense. Within the wind farm, the dominant frequency in the far wake is around $f_{d_{T}}/U_{hub} \sim 0.2$, which is close to the characterized Strouhal number of bluff body, indicating the presence of unsteady wake meandering phenomenon [11].

![Figure 4. Velocity spectra at various locations. a1) hub height, b1) bottom tip height and c1) top tip height of the first row; a2-c2) represent the counterparts of the seventh row.](image)

To better reveal the multi-scale structure evolutions within wind farm, the pre-multiplied spectra difference $\Delta (f \Phi_{w}) = f \Phi_{wake} - f \Phi_{incoming}$ between wakes and incoming flow are illustrated to further highlight these differences across scales in Figure 5a1)-c1) for the first row and Figure 5a2)-c2) for the seventh row. The distribution of fluctuation energy within wakes across heights is quite different from that of incoming flow. At hub height, the turbulent kinetic energy content mainly increase within the frequency domain $f_{d_{T}}/U_{hub} \sim [10^{-1}, 10^{0}]$ and decrease in relatively larger scales in the near wake, while slightly increase of large scales energy is expected in the far wake. Note, due to the narrow
space restriction and low mean shear effect on momentum transfer, the fluctuation energy is less at bottom tip height except the region in the vicinity of the turbine, where the enhancement of small scales kinetic is mostly due to vortex shedding of blades and tower. In contrast, the energy highly increases across scales at top tip heights in both near and far wake, especially within the frequency domain \( f d_T / U_{hub} \sim [10^{-4}, 10^0] \). Compared to the first row, wakes far inside wind farm are shown to contain more kinetic energy regardless of heights.

Figure 5. Pre-multiplied spectral difference of the velocity fluctuations at various locations a1) hub height, b1) bottom tip height and c1) top tip height of the first row; a2-c2) represent the counterparts of the seventh row.

4. Conclusion
The variation rule of the fluctuation energy of the turbulence structure within the wind farm is revealed. At different heights, the contribution of the multi-scale turbulence structure to the kinetic energy of the wake is different with the variation of the downstream distance of the wind turbine. Under the filtering modulation of the wind turbine, the large scale turbulent structure is destroyed and the small scale structure is promoted in the near wake at hub height and lower tip height. While at the height of the upper tip, the fluctuation energy of each scale turbulent structure in the wake is more energetic than that of the incoming flow, and the increase is mainly occurred within the region \( f d_T / U_{hub} \sim [10^{-4}, 10^0] \). Owing to the modulation of wind turbine rotation on the flow, the characterized turbulent structure, corresponding to the rotor rotating frequency and its harmonics, dominate the near wake fluctuation of the first row in the vicinity of the upper and lower blade tips. Whereas in the seventh row, affected by enhanced turbulence level and momentum mixing of upwind wakes, the influence of these unstable rotating-related frequencies are weaken. However, compared with the incoming flow and the first row, the overall turbulent kinetic across scales is considered to be more energetic far inside wind farm.

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