Probing wind-turbine/atmosphere interactions at utility scale: Novel insights from the EOLOS wind energy research station

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Abstract. Despite major research efforts, the interaction of the atmospheric boundary layer with turbines and multi-turbine arrays at utility scale remains poorly understood today. This lack of knowledge stems from the limited number of utility-scale research facilities and a number of technical challenges associated with obtaining high-resolution measurements at field scale. We review recent results obtained at the University of Minnesota utility-scale wind energy research station (the EOLOS facility), which is comprised of a 130 m tall meteorological tower and a fully instrumented 2.5MW Clipper Liberty C96 wind turbine. The results address three major areas: 1) The detailed characterization of the wake structures at a scale of 36×36 m² using a novel super-large-scale particle image velocimetry based on natural snowflakes, including the rich tip vortex dynamics and their correlation with turbine operations, control, and performance; 2) The use of a WindCube Lidar profiler to investigate how wind at various elevations influences turbine power fluctuation and elucidate the role of wind gusts on individual blade loading; and 3) The systematic quantification of the interaction between the turbine instantaneous power output and tower foundation strain with the incoming flow turbulence, which is measured from the meteorological tower.

1. Background

Wind energy has emerged as one of the fastest-growing renewable energy resources, partially due to the accessibility and abundance of the resource, as well as its comparatively mature technology and low cost. Among different aspects of wind energy development, one of major remaining opportunities to effectively reduce the levelized energy cost relies on substantial gains in understanding the interaction of wind turbines and wind farms with atmospheric boundary layer (ABL). With exponential increase in size, the state-of-the-art utility-scale turbines have a rotor diameter above 100 m. The aerodynamics around such gigantic structures imposes significant challenges for the research community to implement the knowledge from prior laboratory studies to industrial applications due to: 1) the substantially high Reynolds number; 2) variable atmospheric conditions and terrain effects; 3) the unique dynamic response of turbine tower and blades; 4) the proprietary strategies involved in the turbine and wind farm controls.

Despite past vigorous field research efforts (e.g., [1-3]), the interaction of ABL with turbines and multi-turbine arrayed at utility scales remains poorly understood, which contributes to sub-optimal
performance at the plant scale and an average power loss of 10-20% [4]. In addition, the lack of knowledge of upstream flow conditions drives premature component failure, results in expensive over-design criteria and limits turbine and wind farm innovation potential [5-6]. To gain such knowledge, a synchronized quantification of turbine operational conditions and the in situ turbulent flow fields around the turbine is needed. The former is constrained partially by the lack of utility-scale wind turbine research facilities where turbine SCADA, control parameters and structural information such as blade deformation can be acquired simultaneously. The latter can be obtained by a number of existing field flow measurements techniques including meteorological tower instrumentation, Sodar and Lidar which have laid the foundation for wind energy assessment. For instance, the point measurement data from the meteorological tower instrumentation has indicated that wind turbine performance is affected by the thermal stability [3]. Sodar has been utilized for determining wind speed profiles offshore and for providing the first offshore wake measurements with varying distance from a wind turbine [1]. Lidar mounted on a full-size turbine nacelle employed in [2] allowed both one-dimensional and two-dimensional scanning of the instantaneous ‘longitudinal’ wake velocity. The produced data facilitated the resolution of the wake expansion and wake meandering dynamics, verifying the basic assumption that the wake deficit is advected passively by the larger-than-rotor-size eddies in the inflow. Nevertheless, these techniques can only provide point velocity characterization or velocity profiles at a coarse spatio-temporal resolution, which is not sufficient to allow the examination of direct flow-turbine interactions. Particle image velocimetry (PIV) based on tracking the displacement of tracers in an illuminated flow field, is the only non-intrusive measurement technique capable of obtaining planar velocity distributions with the spatio-temporal resolution required to study highly unsteady flow-structure interactions. However, PIV has only been applied, so far, to small scale turbine models, from 0.1 m to a few meters in wind tunnel experiments (e.g., [7-8]). Due to the significant technical obstacles, PIV has yet to be applied to areas larger than a few square meters (e.g. [9-10]), which is at least one order of magnitude smaller than that is needed for making an impact on wind energy field research.

To address the aforementioned challenges, the University of Minnesota EOLOS Wind Energy Research Field Station was established in 2010 with funding from the US Department of Energy EERE office. Since then, a series of studies have been conducted utilizing various field measurement techniques including super-large-scale PIV, Lidar wind profiling and sonic anemometry measurements from the meteorological tower. This paper aims at reviewing some of the most important insights that have been gained to date by performing field scale experiments at this facility.

2. Experimental Facility

As illustrated in figure 1, the field station consists of a heavily instrumented 2.5 MW Clipper Liberty C96 wind turbine (hereafter referred to as the EOLOS turbine) and a 130 meter meteorological tower (hereafter referred to as the met tower). The EOLOS turbine is a 3-bladed, horizontal-axis, pitch-regulated machine with a rotor diameter \( D \) of 96 m and a supporting tower 80 m in height, capable of operating at variable speed. The met tower, located 160 m (corresponding to \( \sim 1.7D \)) south of the turbine (as south is the predominant wind origin), is designed to characterize the local ABL. The field station is equipped primarily with five synchronized sensor systems: 1) standard turbine operational instrumentation; 2) rotor instrumentation including 9 tri-axial accelerometers and 10 strain gauges installed on each blade for characterizing blade deformations; 3) turbine tower instrumentation including 20 strain gauges mounted at the tower base for quantifying structural response; 4) foundation instrumentation including three tri-axial accelerometers bolted to the cement foundation; 5) met tower instrumentation including a number of wind velocity (sonic, cup and vane anemometers), temperature and humidity sensors installed at elevations ranging from 7 m to the highest point of the rotor, 129 m. Four of these elevations (129 m, 80 m, 30 m, and 10 m) are instrumented with high-resolution, Campbell Scientific CSAT3 3D sonic anemometers with sampling rate of 20 Hz. These four heights were specially selected to match the rotor top, rotor hub, rotor bottom and standard 10 m height. To ensure accurate measurements, all CSAT3 anemometers are mounted on 18-foot-long
booms that were custom designed to be rigid and limit sway. In addition, all CSAT3’s are paired with a tri-axial accelerometer capable of measuring tower and boom arm movement. Three meters below each of the CSAT3’s (elevations of 126 m, 77 m, 27 m, and 7 m) and at points representing elevations at the midpoint between the edge of the rotor and hub height (105 m and 55 m) are standard cup-and-vane anemometers. Temperature and relative humidity sensors are mounted directly on the tower adjacent to the cup-and-vane anemometer booms. The measurements from the five systems are sampled continuously 24 hours a day and stored on backed up servers.

Figure 1. A schematic of EOLOS wind energy research station.

3. Results Section

3.1 Characterize flow structures using super-large-scale PIV (SLPIV)

3.1.1 Experimental approach.
SLPIV experiments are performed using natural snowflakes as flow tracers. Compared with conventional tracers used for laboratory PIV measurements, the tracers provided from natural snowfall has the following characteristics that are particularly suitable for PIV measurements in super-large-scale field of views, which, combined, eliminates almost any possible artificial seeding mechanisms:  
1) **Economic and environmentally benign**: Natural snowfall involves no economic cost and comes completely from the environment.
2) **High uniformity**: Natural snowfall covers a significantly larger region than the entire field station, and can thus ensure a relatively uniform particle seeding in our sample region for an extended period of time compared with many artificial seeding mechanisms in the field.
3) **Strong light scattering**: Snowflakes have strong light scattering capability (especially side scattering) owing to their multi-facet crystal structure, which lowers the illumination power required for PIV.
4) **Non-intrusiveness**: Using natural snowfall does not involve additional seeding apparatus (jets, flying objects, tower, etc.) to artificially introduce tracers into the sampling area, which can perturb the original flow field.

A major concern of seeding with snow particles is the limited traceability due to their inertia and gravitational effect. Evidently, not any natural snowfall is suitable for implementing SLPIV. As discussed in [11], the morphology and density of snow particles differs substantially according to various factors such as relative humidity and temperature. For PIV tracers, it is preferable that the snow particles yield large surface area and well-defined dendrite structures for strong light scattering and yet remain porous and light-weight for good traceability. In general, to trace a flow with time scale $\tau_f$, the traceability of snow particles can be characterized by the Stokes number, $St = \tau_p/\tau_f$, where
τ_p is the particle response time. For good traceability, the Stokes number should be much smaller than 1. An estimate of St for our preliminary experiments is presented, showing reasonably good traceability of snowflakes for the large-scale turbulent motions of interest. Nevertheless, due to the complex and variable structure of snowflakes, we mainly rely on prior research and our validation experiment (section 3.1.2) to make the judgment. It is noteworthy that artificially generated snow particles have been used for PIV measurements on the scale of a few square meters [12].

Our SLPIV setup is composed of an optical assembly for illumination, a high-resolution imaging device and a data acquisition system. The optical assembly includes a 5KW highly collimated search light (a divergence < 0.3° and initial beam size of 300 mm in diameter) and a curved reflecting mirror for projecting a horizontal cylindrical beam into a vertical light sheet. The sheet expansion angle is controlled by adjusting the mirror curvature. The illumination system is affixed to a trailer, providing good mobility for aligning the light sheet with the predominant wind direction as required for planar PIV measurement. The imaging device consists of a CMOS camera and an attached 50 mm f/1.2 Nikon macro imaging lens. The camera has a 5K×5K pixels sensor with 4.5 µm/pixel and runs up to 30 frames/s at full sensor size. In our experiments, the imaging device is tilted at an angle with respect to the ground. Thus, a Scheimpflug adjustment adapter is employed for creating a slight angle between the lens plane and the camera sensor plane in order to achieve in-focus imaging of the entire sampling area. To calibrate our current setup, we first ensure that the tripod-mounted camera is leveled about its optical axis and that the optical axis is aligned perpendicular to the light sheet, and then we measure the tilt angle of the camera and its horizontal distance from the light sheet. Based on this information and the focal length of the imaging lens, we can correct the distortion resulting from the tilt imaging and determine the physical scale and location of the sampling area.

3.1.2 Validation experiment.

Figure 2. (a) A schematic of the setup for the validation experiment. (b) Time-averaged streamwise velocity profile U and (c) In-plane TKE at the centerline of the light sheet obtained from SLPIV as compared to the sonic measurements from the met tower. Note that the average time for the mean velocity profile and in-plane TKE is ~170 s limited by the variable wind and snow conditions in the field.

The experiment to validate snow-based SLPIV was conducted in the early morning hours of March 5th, 2013. The details of this experiment are provided in [13]. As illustrated in figure 2a, in this experiment, the illumination system was deployed adjacent to the met tower, where the local meteorological conditions and wind velocity can be determined with the sonic anemometers on the tower. The topography upstream of the sampling area was a nearly flat field on the scale of 2 km, with
a few very sparse roughness elements such as scattered 1-2 story buildings and tree patches, and the
snow coverage provided additional modulation of the terrain roughness. The camera located 116 m
from the light sheet was operated with a 2K×5K pixel sensor size at 15 frames/s. The sampling area of
~22 m × 55 m covered an elevation span up to ~56 m above the ground. The upper bound of the
sampling area was constrained by the illumination power and camera sensitivity of the current optical
setup. By cross correlating time-consecutive images using an adaptive multi-pass algorithm, the wind
velocity distribution in the illumination plane was obtained at a resolution of 34 cm/vector. Very near
the illumination light source (i.e. z < ~ 4 m), the particle images contain highly saturated spots and
large particle voids associated with vortical flow structures generated from the illumination system.
Therefore, to ensure valid vector calculations, the PIV cross correlation was only implemented in the
range of z = 4 m to z = 56 m. Figure 2b and c presents a comparison between SLPIV and the sonic
measurements for the mean velocity and turbulent kinetic energy (TKE) profiles, respectively. In the
measurable range of SLPIV, the maximum difference between the measurements from the two
techniques is <3% for the mean velocity and <14% for TKE.

3.1.3 Flow structure measurements behind the turbine.

![Figure 3](image)

**Figure 3.** (a) A schematic of the SLPIV setup behind the EOLOS turbine. (b) The frontal view and (c)
the side view of the illumination light sheet during the deployment. Note that Figure 3b and 3c were
taken using a Canon EOS T1i camera with wide angle lens and subjected to image distortion.

The deployment was carried out during a snowstorm in the early morning hours of Feb 22nd, 2013. The
meteorological conditions offered an optimal concentration of snowflakes with good traceability and
light scattering capability, enabling flow visualization of coherent motions in the near-wake of the
EOLOS turbine. The details of this experiment are described in [14]. As illustrated in figure 3, the
SLPIV measurement was performed in a sampling area of 36×36 m², ranging from 3 m to 39 m above
the ground, in the lower portion of the rotor wake behind the turbine. During this period, the wind
speed ranged from 3–7.5 m/s, and the turbine was operating a transitional region from Region 1 to
Region 2, namely, Region 1½. The camera was operated with a full sensor of 5K×5K pixels at 30
frames/s, the wind velocity distribution in the illumination plane was obtained at a resolution of 44
cm/vector following standard PIV calculation procedure. From a vertical velocity distribution
averaged using ~1500 vector fields acquired in 20 minutes, the settling velocity of snow particles \( W_s \)
was estimated to be about 0.65 m/s, leading to the particle response time \( \tau_p \approx 0.07 \) s. After subtracting
Figure 4. (a) Sample of $x$-$y$ plane instantaneous velocity vector fields from the SLPIV measurements superimposed on the contours of the velocity magnitude. Nondimensionalized velocity and locations are provided using the mean wind speed at the hub height $U_{hub} = 5.67$ m/s and rotor diameter $D = 96$ m. (b) The time-averaged streamwise velocity profile $U$ at $x = 26$ m (along the centerline of the light sheet). The black dashed line is a canonical log-layer profile that fits the SLPIV mean velocity profile in the range of $0.15 < z/D < 0.3$ to illustrate the velocity deficit and acceleration zone in the wake. (c) A close-up view of velocity field around tip-vortices. As illustrated in figure 3, the origin of $x$ is at the center of turbine tower and that of $y$ is at the ground. Galilean translated vector field ($u - 0.9U_{hub}$, $v - 0.1U_{hub}$) is shown to visualize the counterclockwise rotational motion of the vortices. The velocity vectors are skipped in 1:4 (a) and 1:2 (b) in both $x$ and $y$ directions for clarity.

$W_s$ from the original velocity, a sample velocity field (figure 4a) illustrates some wake-flow features, such as the traveling tip vortex cores shown as void regions, momentum entrainment between vortices, and the shear layer delineating the lower boundary of the turbine wake and incoming flow. The time-averaged streamwise velocity profile (figure 4b) yields a maximum located below the lower tip. Above the velocity maximum in figure 4b ($z/D > 0.3$), a sudden drop of velocity occurs, which
is associated with the momentum deficit in the wake region. Near the ground \((z/D < 0.15)\), the velocity distribution shows an increase in velocity over the canonical log-layer profile, suggesting a region of flow acceleration induced by the rotor-imposed blockage. In the close-up view of the instantaneous flow field (figure 4c), the counter-clockwise rotating patterns of the fluctuating velocity vectors, marking each tip vortex core, surround regions of low snow particle concentration (no PIV vectors available). Considering a length scale \(l=2.5 \text{ m}\) and velocity fluctuation \(u_f \sim 1 \text{ m/s}\) associated with an individual vortex core, a representative time scale is given by \(\tau_f = l/u_f \approx 2.5 \text{ s}\). The corresponding St is about 0.03, suggesting that snow particles are deemed acceptable tracers for these large-scale motions in our sampling area. During this experiment, the circulation around each tip vortex core were measured and synchronized with turbine operational data (power output, blade pitch and blade strains) to study turbine’s dynamic control for power maximization and its structural response to unsteady wind conditions (more details in [14]).

3.2 Probe the impact of inflow conditions using on site Lidar profiler
During the summer months in 2012, 2013, a WindCube V1 wind profiling Lidar from LeoSphere, were employed at the EOLOS site to provide an instantaneous description of the flow impinging the turbine rotor. We briefly summarize here the work described in [15]. The Lidar operates along four lines of sight (LOS) at an angle of 27.8 degrees from the vertical direction, acquiring velocity data at different distance along each LOS (see e.g. [16]). These raw velocity data are then spatially averaged and projected on a Cartesian reference system aligned with the vertical direction to reconstruct the three velocity components of the flow at various elevations. While non-locality effects due to spatial averaging increases with height due to the divergence of the LOS, the sampling volume along each LOS remains constant [16] as well as the temporal resolution, the latter fixed at 1 Hz.

The Lidar measurements presented here are used for two specific purposes, both aiming at identifying the best strategy to measure the incoming wind for turbine control: 1) assess the upwind effect that the turbine manifests on the incoming flow as compared to the undisturbed mean velocity profile, 2) study at which height the wind velocity, sensed in the proximity of the rotor, is mostly correlated to the instantaneous power. In this study, two different WindCube alignments are tested: 1) the Lidar is pointed due north (defined here as global alignment and requiring four beams along the cardinal directions); 2) the Lidar is aligned with the wind, directing the nominal north-south LOS plane to be perpendicular to the turbine (defined here as local alignment). In the latter configuration, the estimate of the streamwise velocity only requires a projection of the measured velocities along the two beams (LOS velocities) on the horizontal plane, which involves little contamination from the mean vertical velocity profiles. Hence, the local alignment is chosen to provide a better representation of the blockage effect exerted by the turbine on the mean velocity profile at the center plane, and the divergence of the streamlines due to lockage can be quantified in our measurements by the reduction of the streamwise velocity at different elevations. Measurements are shown in figure 5 (more details in [15]), where the Lidar mean velocity profile 0.8 \(D\) upwind of the turbine is compared with the undisturbed mean velocity profile obtained from the met tower instrumentation (sonic, cup and vane anemometers). A different concavity which clearly represents the signature of the turbine on the incoming flow near the rotor is observed, with a maximum reduction by 5% of the incoming streamwise velocity, 0.8 \(D\) upwind of the nacelle (in good agreement with [17]).

The second effort discussed here is to correlate the Lidar instantaneous velocity measurements at different elevations with the synchronized turbine operational SCADA data including instantaneous power, tip speed ratio, generator torque, etc. The major question is to statistically define at which height the wind velocity provides the most representative velocity time history, with respect to power fluctuations (see also the effect on blade deformation in [15]). Experiments were performed at the EOLOS site under both thermally weakly stable and unstable conditions \((-0.63 < z/L < 0.31, \text{ where } L \text{ is the Monin Obukhov length and } z \text{ is the height of the sonic anemometers nearest to the surface})\). The mean upward velocity profiles are averaged over continuous periods of time (extending from 1 to
2.5hrs, depending on the mean wind and temperature conditions) when the turbine nacelle direction was within $15^\circ$ of the Lidar location.

![Figure 5. Mean velocity profile 0.8 $D$ upwind of the turbine along the wind direction, inside the turbines induction zone (Lidar), as compared to the undisturbed mean velocity profile (CSATs and wind Cups), located 1.7 $D$ upwind of the rotor along the north-south direction.](image)

The simultaneously sampled time histories of the instantaneous power $P(t)$ and streamwise flow velocity $u(z,t)$ estimated by the Lidar are used to calculate the temporal cross correlation coefficients $\rho(z, \tau)$ ranging from 0 to 1 when normalized by the product of the respective standard deviations. The $\rho(z, \tau)$ curves have a peak location in the time lag axis, which depends on the delay between wind gusts and the turbine response, and a peak magnitude which accounts for the similarity between the two time series. The identified peak values in the time lag phase space, are then plotted as a function of the measurement height, leading to the curve $\rho_{max}(z)$ shown in figure 6b. This provides a clear indication of where the velocity is predominantly correlated to the turbine power and thus where an instrument sensing the flow would be optimally positioned to serve as an input for the turbine control. From a physical perspective, it is reasonable that the peak occurs in the upper half of the rotor (where the wind is stronger), away from the tip (where the blade have a very small residence time) and away from the hub height (where no lift is produced).

![Figure 6. (a) Temporal cross correlation function between the incoming velocity measured by the Lidar and the turbine power for different heights with values provided in panel (b); (b) Peak values of the cross correlation coefficients shown in panel (a), i.e. $\rho_{P_U(\max)}$, as a function of the elevation at which the velocity is measured. Vertical line represents the correlation coefficient between power $P$ and the vertically (from bottom to top tip) averaged velocity $U_{ave}$. The higher correlation observed with $U_{ave}$ indicates that the turbine responds more effectively to wind variations averaged in the whole rotor area.](image)

3.3 **Quantify unsteady turbine behavior using sonic measurements from the met tower.**

The instantaneous power output and strain at the tower foundation of the EOLOS turbine is investigated and linked to the incoming flow turbulence measured from a sonic anemometer placed in
the met-tower at the height coincident with the turbine hub. Mean velocity and temperature across the rotor were steady during the one-hour period selected (see figure 7). The results indicate that both the turbine power and strain at the tower foundation are modulated by atmospheric turbulence in a complex manner. As illustrated in figure 8, the spectral content of both quantities exhibits three distinctive regions. Within the first region, defined by approximately subrotor length scales, the turbine power appears to be insensitive to the flow turbulence. In the intermediate region, with length scales up to those on the order of the atmospheric boundary layer thickness, the spectral contents of the power fluctuations, $\Phi_P$, and flow, $\Phi_U$, exhibit a non-linear relationship of the form $\Phi_P = G(f)\Phi_U$, where $G(f) \sim f^{-2}$ is a transfer/damping function that accounts for the turbine structure effects, including the rotor inertia, blade aerodynamics, discrete changes in the blades pitch (not important in this case), and the mechanical components of the turbine. In the third region, dominated by the very large scales of motions, the power fluctuations are found to be directly influenced by the flow turbulence. More details can be found in [18]. As shown in figure 9, the spectral distribution of the strain also showed three characteristic regions, similar to those of the power fluctuations. However, in the region containing subrotor scales, the strain follows the structure of the inertial subrange of the turbulence.

Figure 7. Characteristics of the atmospheric boundary layer at the met tower location. (a) Mean temperature. (b) Mean velocity. (c) Wind direction. (Adapted from [18])

Figure 8. (a) Spectrum of the approach velocity at various heights (turbine bottom, hub and top tip) measured in the met tower. (b) Spectrum of the turbine power. (Adapted from [18])

4. Final Remarks
In this paper, we have reviewed a number of new physical insights into the dynamics of turbine/atmosphere interactions obtained at the University of Minnesota EOLOS wind energy research facility. These insights were obtained using three flow measurement techniques, including a novel SLPIV, Lidar wind profiling and met-tower sonic anemometry. For all cases, the turbulent flow measurements are correlated with the turbine operational data enabling us to directly probe the
interaction of atmospheric turbulence with the turbine response and performance. Our results underscore the complexity of turbine/atmosphere interactions at field scale and reveal insights that would have been difficult, if not impossible, to obtain from small scale wind tunnel experiments.

![Figure 9. Spectrum of the strain at the turbine foundation at the locations of maximum compression (0°) and tension (180°). (Adapted from [18])](image)

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