Space-Time Loadings on Wind Turbine Blades Driven by Atmospheric Boundary Layer Turbulence

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We quantified the interactions between the spatio-temporal loadings on wind turbine blade blades and the turbulence structure of the neutral and moderately convective atmospheric surface layer by combining the Blade Element Method incorporated in the FAST/AeroDyn codes from NREL with a dynamic stall model with large-eddy simulation (LES) of the atmospheric boundary layer (ABL). The inflow conditions were obtained from high-resolution LES interpolated to the turbine blade. The central aim of our analysis is to search for and quantify direct causal relationships between specific space-time variabilities in the turbulent inflow velocity field and the spatio-temporal variability of forces on the turbine blades, and the integrations along the blade span that produce time variations in bending moment at the hub and shaft torque. A related interest is the impact of an accurate versus inaccurate predictions of shear rate by the LES. We find that atmospheric turbulence is a major contributor to blade loadings and that the distribution of force fluctuations is sensitive to the specific structure of ABL turbulence. A well designed, accurate LES model has significant advantages for quantifying the role of atmospheric turbulence on wind turbine performance.

Nomenclature

ω  Frequency
V∞  Characteristic Velocity

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I. Introduction and Motivation

Wind turbine downtime has been consistently higher than anticipated, in large part because of a lack of quantitative knowledge of the true space-time loadings along the span of the rotor blades that arise from the interactions between the rotor and the fluctuating wind field. The surface layer of the atmospheric boundary layer (ABL) contains strong coherent turbulence structure that generates high variability in space-time wind vector orientation and magnitude relative to the rapidly rotating blades. Like the mean velocity, the coherent turbulence structure is strongly influenced by the ground and changes most dramatically in the atmospheric surface layer (ASL). The result is highly unsteady highly spatially-varying blade loadings that are correlated to the specific structure of atmospheric turbulence. The variability is worsened by the strong dependence of the turbulence structure on the state of the atmosphere, itself highly variable. The unsteady forces along the rotor blades respond directly to the span-dependent transients in boundary layer separation and dynamic stall. These, in turn, affect dynamic blade deformations, trailing vortex and wake formation and noise, and integrate to produce blade bending moments and fluctuating torques on the drive shaft that are transferred directly to the gearbox, a particular hot point for failure.

Field experiments and simulations have been limited in their quantifications of wind-turbine interactions. Field data cannot provide the in full space-time information needed for complete understanding of the flow field and, to date, simulations have been limited by resolution, accuracy, specificity and the lack of true space-time atmospheric wind inputs. Wind turbines interact with the wind through a wide range of characteristic length and time scales. Three scale ranges relevant to wind turbine aerodynamics are investigated: the rotor airfoil scale (smallest), the scale of the ABL turbulence structures (of order the rotor disk and larger), and mesoscale modulations to the geostrophic wind and surface heating. These are summarized in Table I. In the current study we analyze the interactions between wind turbine rotor aerodynamics and the energy-containing turbulence eddies of the atmospheric surface layer associated with shear and buoyancy-driven turbulence production. The atmospheric eddies are accurately simulated with well-resolved large-eddy simulations (LES) of the ABL. Wind turbine aerodynamic loadings are modeled using the blade element model (BEM) and dynamic stall models embedded with the AeroDyn/FAST design code developed at the National Renewable Energy Laboratory (NREL). Our focus is the interactions between ABL turbulence structure of order the rotor disk in scale and wind turbine aerodynamics at a time scale relevant to the unsteady blade aerodynamics over the 10-minute
averaging period typically used in wind turbine yaw control algorithms. In this study we address, in particular, space-time variability in aerodynamic loadings associated with (1) small scale atmospheric turbulence at the blade and rotor disk scales, (2) with changes in ABL turbulence structure between the neutral vs. buoyancy driven stability states of the daytime boundary layer, and (3) with longer time changes associated with the spatial relationship between the wind turbine and the highly coherent thermals in the moderately convective boundary layer (MCBL).

<table>
<thead>
<tr>
<th></th>
<th>Time Scales</th>
<th>Length Scales</th>
<th>Modeling Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Turbine</td>
<td>(\mathcal{O}) (revolution period) a few seconds</td>
<td>(\mathcal{O}(1-100 \text{ m})) Blade chord and wind turbine height</td>
<td>BEM with dynamic stall model in FAST/AeroDyn</td>
</tr>
<tr>
<td>Energy-containing ABL turbulence structure</td>
<td>(\mathcal{O}(10-1000 \text{ s})), depending on ABL stability state</td>
<td>(\mathcal{O}(10-1000 \text{ m})), depending on ABL stability state</td>
<td>LES of the ABL at prescribed stability state</td>
</tr>
<tr>
<td>Mesoscale modulations</td>
<td>(\mathcal{O}) (multiple days)</td>
<td>(\mathcal{O}) (tens of km)</td>
<td>Prescribed geostrophic wind &amp; surface heating</td>
</tr>
</tbody>
</table>

Table 1. Length and Time scales in the atmosphere relevant to wind turbines.

The current study is a step in the direction of our ultimate aim: to develop the highest possible fidelity computational experiments of wind turbine - atmosphere interactions with modern numerical methods and the latest in high-performance computing to create wind data that are well-resolved in both space and time and to predict the unsteady loadings on turbine blades and integrated moments and torques at the hub. To raise the fidelity of ABL-wind turbine simulations and predict true ABL-turbine interactions, care must be taken in the details of the numerical algorithms in context with the resolution and structure of the grid. We take advantage of recent advances in methodology that correct a well-known over-prediction of mean shear-rate in large eddy simulation (LES) of the atmospheric surface layer since its introduction.

In the current study we apply space-time atmospheric velocity fields from improved LES of the ABL to estimate spatio-temporal blade loadings using the BEM computational models of wind turbine loading within the FAST\(^1\) and AeroDyn\(^2\) design software developed at NREL, with a rigid wind turbine model. This is a preliminary study with BEM with LES inflow fields that will, in the future, be extended to full LES of the ABL coupled with unsteady hybrid URANS/LES over wind turbine blades. Like the full simulations under development, the current study includes models for boundary layer separation and dynamic stall incorporated within the FAST/AeroDyn software. The BEM methodology is a computationally efficient software tool for preliminary aerodynamic analysis. Results must be interpreted with the recognition that BEM is a relatively simple model, fully dependent on empirical data, applied to the complex 4-dimensional environment of wind turbine aerodynamics. Future comparisons with well-resolved LES/CFD will be applied to improvement of the BEM
modeling strategy for wind turbine technology.

In the next section we describe the LES and FAST/AeroDyn methodology (which henceforth shall be referred to as “FAST”). The following section summarizes the LES of the ABL coupled with the aerodynamics models at the different boundary layer states and describes the development of inflow conditions for FAST. We also summarize a fundamental problem with LES predictions of the mean winds that has been recently corrected. The following section summarizes analysis of wind turbine loadings from coupled ABL-FAST simulations with emphasis of effects of ABL turbulence on space-time variability.

II. Methods and Models

A. Large Eddy Simulation of the Atmospheric Boundary Layer

The largest wind turbines span a large percentage of the ASL, which itself covers roughly the lower 15-20% of the boundary layer depth \( z_i \). Surface layer turbulence statistics and structure depend strongly on the stability state of the atmosphere and experience strong mean shear and inhomogeneity. In this study we contrast the space-time loadings on wind turbine blades from the turbulence structure of neutral and moderately convective atmospheric boundary layers. Specifically, as quantified by the ratio of the Monin-Obukhov length scale \( L \) \( (L < 0 \) in the unstable ABL) and the depth to the capping inversion of the atmospheric boundary layer \( z_i \), we contrast the two states \(-z_i/L = 0\) and \(-z_i \approx 10\). We consider a flat surface with uniform roughness of 16 cm. In the neutral boundary layer, turbulence is dominated by wind shear; buoyancy forces are negligible and do not contribute to boundary layer turbulence. In the moderately convective boundary layer, turbulence production by buoyancy and shear interact to create coherent thermals in the surface layer that originate in the streamwise elongates ”steaks” of low streamwise velocity fluctuations created by shear near the surface. This interaction creates boundary layer scale rolls that can extend for many kilometers. The largest wind turbines span the atmospheric surface layer and experiences strong inhomogeneities as the coherent turbulence structures transitions from horizontal to vertical-dominated deviations from the mean.

In addition to the changes in turbulence structure, mean wind shear is also strongest in the surface and varies significantly across the rotor disk. Furthermore, in the mid-latitudes the rotation of the earth creates a Coriolis force that twists the mean wind direction significantly from bottom to top of the rotor disk. Coupling the shear, convection and Coriolis effects creates a complicated inhomogeneous highly unsteady flowfield that is difficult to measure experimentally. In the current study, LESs of the ABL are carried out to capture the complex structure of the surface layer typically experienced by wind farms in Texas and the Midwest United States in terrain with long fetch. Our ABL code is pseudo-spectral in the horizontal and finite difference in the vertical, thus minimizing numerical dissipation and retaining the highest possible accuracy at the smallest resolved scales.\(^3\),\(^4\)

The LES predictions of the ASL were applied as input to the BEM models within the AeroDyn\(^2\) software developed at the National Renewable Energy Laboratory (NREL) and integrated with the aero-elasticity model within FAST (Fatigue, Aerodynamics, Structures and Turbulence).\(^1\) We applied the combined AeroDyn/FAST code only to predict the aerodynamic loadings on a rigid turbine blades in response to the unsteady wind inputs from the ABL large-eddy simulations.
B. BEM and stall models for Aerodynamic Loadings on Wind Turbine Blades

We apply the BEM model within the AeroDyn model developed at the NREL National Wind Technology Center (NWTC) to analyze the aerodynamic response of wind turbines to different situations. The model is contained within FAST, a code in which AeroDyn is combined with an aeroelasticity model. We refer to this combined code as the “FAST” code.

The FAST code is capable of handling a variety of different types of inflow wind velocity fields from simple models based purely on the mean wind velocity at the hub height to 4-dimensional flow fields such as the results of LES simulations. The modular design of FAST allows different turbine components and control systems to be exchanged supporting the testing of new turbine configurations. The control systems can be used to create off-design situations, such as improper yaw angle or rotational speeds. The most current version of FAST, 7.00.01a, includes the additional capability of modeling offshore wind turbines.

The FAST code has been modified to show additional information for each of the radial locations along the blade. This allows for local dynamics due to unsteady wind fields to be further analyzed in addition to what is currently programmed into FAST. In particular space-time changes in local loadings of interest in our study will be compared with the temporal changes in integrated quantities such as torque on the shaft and bending moments at the root of the blade. Of particular interest are the correlations among the spatio-temporal and temporal variations and the corresponding spatio-temporal variations in the atmospheric winds that drive the loadings, as predicted by our LES of the ABL.

The semi-empirical dynamic stall model developed by Leishman and Beddoes is included in AeroDyn. The model assumes unsteady aerodynamics with arbitrary time history at each spanwise aerofoil segment. The unsteady aerodynamics is modified with dynamic-stall features from an empirical model of the induced-vortex lift and lags in reattaching a separated flow. In this way the model predicts dynamic stall and associated hysteresis.

The Leishman-Beddoes model used in FAST has two major limitations. Firstly, the model assumes that the flow travels chord-wise along a given radial station on the wind-turbine blade, so it is unable to predict cross flow. It has been shown that cross flow is important to accurately capture loading on model-scale wind-turbine blades. The second limitation is associated with the fidelity of the computation. The FAST methodology, including the models, has been validated well with existing data sets. However, as dynamic stall locations can be limited in extent along the blade, a more detailed model of the turbine blade should be used in order to accurately glean loading information from FAST calculations.

Unsteady aerodynamics on blade sections becomes important when the reduced frequency, shown in Equation 1, exceeds roughly 0.1. $V_\infty$ has components associated with the both the incoming wind and the rotational velocity of the wind turbine blade. The higher rotational velocity towards the blade tip tends reduce unsteady effects as compared to root velocity. The FAST model utilizes 17 different locations along the blade, a fairly low resolution that limits the accuracy of unsteady stall predictions.

$$k = \frac{\omega c}{2V_\infty}$$  \hspace{1cm} (1)

Thus, the model for dynamic stall within FAST limits the extent to which the effects of dynamic stall on wind turbine loadings can be ascertained, and the limitations in the FAST model must be kept in mind when interpreting results. Although temporal and spatial characteristics of wind events causing dynamic stall can be identified with FAST, the loadings...
associated with dynamic stall are not as well correlated to the characteristics of unsteady wind events as would happen in reality.

C. Turbine Model

The wind turbine analyzed in this study is a model developed by NREL of a 5-MW wind turbine for use by the wind turbine community as a baseline large wind turbine. The model was created as a composite based on the Multibrid M5000, the RE power 5M as well as conceptual models used in the WindPACT, RECOFF and DOWEC projects. There are several versions of this wind turbine model created for FAST including different offshore configurations. The results shown below are using the “On-shore-Baseline” model.

The NREL 5-MW model is designed with 17 radial analysis locations along each blade. This gives an approximate resolution of one analysis point every 3.5 meters. FAST applies space-time interpolation to couple input wind velocities (e.g., from our LES) to the aerodynamic loading predictions the AeroDyn subroutines. The current simulations are carried out with time-resolved wind data at the plane of the wind turbine rotor. The temporal resolution of the LES is 0.5 seconds which, combined with the spatial accuracy, is comparable to similar computational experiments.

FAST is capable of handling a variety of structural degrees of freedom for the blades, hub and tower. In order to focus on the aerodynamic loading associated with wind turbulence interactions, we modeled a fully rigid wind turbine. The coning angle, typically -2.5 degrees (2.5 degrees in the upwind direction), was adjusted so that the tip of the blade resides at the same location as if the blade were being bent by the wind. The shaft-tilt angle, 5 degrees above the horizontal, was not changed from the original model.

III. Space Time Structure of the ABL relevant to Wind Turbine Aerodynamics

A. Accuracy Issues with Large-eddy Simulations

Large-eddy-simulations of the high Reynolds number boundary layer are known to produce poor results in near-wall regions as the horizontal length scales of the vertical velocity fluctuations reduce roughly proportional to the distance from the surface. The error is evident both in the mean velocity and in the turbulence structure. A methodology for correcting this deficiency has recently been developed that allows for the near wall regions to be properly modeled. Brasseur & Wei defined three criteria that must be satisfied for any LES of the high Reynolds number boundary layer to properly predict law-of-the-wall (LOTW) in the surface layer. These criteria were framed in terms of three non-dimensional variables that define a parameter space in which systematic adjustments can be made to the simulation in order to achieve LOTW scaling. This occurs when the three parameters exceed critical values that can be estimated from basic scaling arguments, a region of the parameter space referred to as the high accuracy zone (HAZ).
The existence of an overshoot leads to incorrect turbulence structures near the ground as a result of incorrect prediction of turbulence Reynolds stress production. The turbulence structures enter into the temporal changes in the forces experienced by the wind turbine rotors so accurate prediction of ASL turbulence is potentially important in an accurate prediction of wind turbine blade loadings.

In the current study we analyze the effect of this overshoot by producing two LES of the ABL, one with the overshoot removed and the other with the overshoot present.

B. LES of ABL performed for this study

The Large Eddy Simulations of the Atmospheric Boundary Layer performed for this study are tabulated in Table 2.

<table>
<thead>
<tr>
<th>Stability state</th>
<th>Location in $\mathcal{R} - Re_{LES}$ parameter space</th>
<th>Domain</th>
<th>Grid</th>
<th>Smagorinsky constant</th>
<th>Surface Temperature flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBL</td>
<td>HAZ Overshoot</td>
<td>3x3x1 km</td>
<td>172x172x108</td>
<td>0.1 0.18</td>
<td>0.0</td>
</tr>
<tr>
<td>MCBL</td>
<td>HAZ Overshoot</td>
<td>5x5x2 km</td>
<td>172x172x176</td>
<td>0.1 0.18</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 2. Table of LES simulations performed for this study.

We performed LES of ABL at two different stability states to demonstrate its effect on the space time loadings of the wind turbine. To test the effect of the deviations from LOTW in LES of ABL, we perform two simulations at each stability state, one containing a well resolved shear layer and the other containing an under-resolved shear layer. The four simulations in are plotted in the $\mathcal{R} - Re_{LES}$ parameter space shown in Figure B.

Figure 2 shows the profiles of $\phi_m = \frac{\partial}{\partial z} \frac{\partial u}{\partial z}$ for each simulation. Figure 2a and 2c correspond to simulations in the HAZ while Figure 2b and 2d correspond to a simulation with an under-resolved shear layer.

C. Structure of the Moderately Convective Boundary Layer

Figure 3a shows a contour plot of the fluctuations of the stream-wise velocity from the horizontal mean at the hub height ($z = 90$ m) of the NREL 5MW wind turbine. The blue regions correspond to the low speed streaks present in high Re boundary layers close to the surface. Also shown in Figure 3a are two outlines of the NREL 5MW turbine, drawn to scale, at different locations in the simulation domain. One of the locations is within the low speed streaks.

Khanna and Brasseur show that scalars, such as temperature, tend to concentrate in these low speed streaks. These concentrations of temperature are the source of thermals/updrafts. However these updrafts are weak in the neutral boundary layer because they are reduced by the corresponding downdrafts. Figure 3b shows iso-surfaces of vertical velocity ($w = 2$ m/s) superimposed on the contour plot of Figure 3a. Comparing Figure 3a and Figure 3b show that the updrafts are strongly correlated with the low speed streaks.
Figure 1. All LES of ABL in $R - Re_{LES}$ parameter space.

Figure 2. Profiles of $\phi_m$ for each LES of ABL showing the overshoot.
We now analyze the local flow structure around the two wind turbines shown in Figure 3. A plane of data is extracted at each wind turbine location in Figure 3a as a function of time. Figures 4 - 6 show the difference in the structure of the incoming wind experienced by the wind turbine when it is in and out of the updraft structure. Figure 4 shows contours of vertical velocity in and out of the updrafts. In the MCBL, the vertical velocity fluctuations near the surface are suppressed by the ground and pick up strength at higher elevations. The bulk of this change occurs across the height of the wind turbine disk. A point on a wind turbine blade will see these structures as a rapid succession of alternating velocities. A kinematic simulation of input turbulence does not take this spatial correlation into account. Figure 5 shows contours of fluctuations in stream-wise velocity across the height of the wind turbine. The wind turbine sees a difference of from the true statistical mean at the hub height over extended periods of time. A kinematic simulation of turbulence does not take this into account and introduces random fluctuations in the stream-wise velocity to achieve the required variance. Figure 6 shows the same contours as in Figure 5 but with the mean super imposed to illustrate the difference between the velocity profiles in and out of the updraft structures.

D. Comparison of structure of the MCBL with the NBL

The wind turbine sees a different structure of the incoming wind when operating in a NBL and a MCBL. The updrafts associated with the low speed streaks are weak in the NBL and do not grow in size away from the ground. Thus the low speed streaks seen by a turbine are weak, small size structures that have a small time scale associated with them as shown in Figure 7c. Over a 10 minute period, the turbine sees many of such weak structures pass by and hence their effect will not be visible in the corresponding 10 minute averages of wind turbine loading. However the corresponding updrafts in the MCBL are stronger, more coherent and consistent over a 10 minute period. Thus the 10 minute averages of the wind turbine loads in a MCBL may not be representative of the true statistical average load for a wind turbine sitting in an MCBL for a long period of time.
E. Effect of ABL turbulence structure on mean velocity profiles across the wind turbine disk

As discussed in Section I, a wind turbine interacts with the wind through a wide range of time scales. Due to the changes apparent in time and length scales much larger than than the wind turbine, the wind turbine operates in an “unsteady” state continuously. Different
Figure 6. Contours of streamwise velocity $u$ at 3 different planes when the wind turbine is (a) In the updraft and (b) Out of the updraft. Also shown is the path followed by a point on the tip of a blade over 6 revolutions.

statistical means can be utilized when attempting to describe the interaction between the wind and the loading on the wind turbine. A popular average used in the wind turbine community is a 10 minute average. Figure 8 shows the mean velocity profiles across the height of the turbine at 2 different stability states of the atmosphere. As discussed in Section I, the wind turbine sees a different velocity profile in the updrafts and the downdrafts. To quantify this effect, a mean velocity profile conditioned on the vertical velocity is found. The curve corresponding to “MCBL updraft” in Figure 8 represents the mean velocity profile when the vertical velocity is positive ($w > 0$). The curve corresponding to “MCBL downdraft” in 8 represents the mean velocity profile when the vertical velocity is negative ($w < 0$). Thus the loads on the wind turbine in a MCBL are likely to oscillate about different local means when it is in and out of an updraft structure.

Table E shows the mean stream-wise velocity at hub height when different averages are employed. The LES simulations were designed such that the ensemble mean velocity at hub height in all cases is between 12.3 and 12.8 m/s which are slightly higher than the rated speed of the wind turbine (11.4m/s). However, the local 10 minute averages are found to be different from the true (full domain) mean velocity at the corresponding stability state of the atmosphere. The 10 minute averages in the updrafts are close to the mean conditioned on the vertical velocity showing that the conditional mean represents the true nature of the ABL within turbulence streaks.

IV. Response of Wind Turbine Loadings to ABL Turbulence

A portion of the LES result was chosen to be the inflow wind used in FAST. There was a plane of data slightly larger than the wind turbine disc area and was taken at every LES time step for 600 seconds. The plane of data is given by all three velocity components at each
Figure 7. Contours of $u'$ at 2 different planes when the wind turbine is (a) In the updraft of MCBL, (b) Out of the updraft of MCBL and (c) In a NBL.

<table>
<thead>
<tr>
<th></th>
<th>Horizontal Average</th>
<th>Conditional Mean</th>
<th>10 min avg. at WT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Updraft</td>
<td>Downdraft</td>
</tr>
<tr>
<td>NBL HAZ</td>
<td>12.72</td>
<td>12.36</td>
<td>13.2</td>
</tr>
<tr>
<td>NBL Overshoot</td>
<td>12.8</td>
<td>12.6</td>
<td>13.45</td>
</tr>
<tr>
<td>MCBL HAZ</td>
<td>12.3</td>
<td>11.74</td>
<td>12.72</td>
</tr>
<tr>
<td>MCBL Overshoot</td>
<td>12.8</td>
<td>12.3</td>
<td>13.33</td>
</tr>
</tbody>
</table>

Table 3. Mean stream-wise velocity at hub height calculated using various methods.
Figure 8. Mean velocity profiles across the height of the rotor disk in various stability states of the atmosphere and their corresponding power law fit.

LES grid location. FAST interpolated in time and space to find the velocities at the analysis points. The mean velocity profiles, as given by the hub height mean velocity and power variable, given in Table E and Figure 8 and Equation 2, are used as FAST inflow conditions to represent the neutral boundary layer and moderately convective boundary layers in and out of updraft structures without any of the turbulence structures evident in the LES. Both the LES and shear profiles are analyzed using FAST to isolate the effect of the turbulence in each of these atmospheric cases.

\[ V_z = V_{hub} \left( \frac{z}{z_{hub}} \right)^{V_{SHR}} \]  

(2)

The simulations were done for a 10 minute interval similar to other wind turbine statistics. The 10 minute interval began following an introductory time used to steady the transients due to computational processing within FAST. The computed time represents 121 full rotations of the blade and is used to obtain all of the statistical results shown below at the particular spots chosen in the LES domains. A particular difficulty in designing an LES model for a given wind-turbine condition is that the 10 minute interval used to gather statistics is not long enough to capture the changes in the mesoscale modulations. Thus, both the location in and out of the updraft in the moderately convective boundary layer are presented.

For this study, we examine the local and integrated loading characteristics. Local variables include force coefficients, the forces per unit span and separation characteristics extracted from BEM nodes (on a single rotor blade) at \( r/R = 0.324, 0.591, 0.724 \) and 0.957.
The integrated in-plane and out-of-plane forces and moments were computed at the root of this blade and on the low speed shaft. Due to time and space limitations, only a portion of the results are shown.

**A. Observed Effects of Turbulence**

The observed effects of turbulence can be shown through comparisons in the FAST loading predictions utilizing both pure shear and temporally varying LES inflow conditions. The shear cases, which are conditional mean profiles taken from the entire LES domain, represent the statistical average over a long period of time that the wind turbine would see. The LES inflow conditions, however, have turbulence structures and have a local mean which can be different from the global conditioned means.

Figure 9 shows the lift per unit span at a blade location at 32% and 72% of the blade span for the neutral boundary layer. The shear (no turbulence) case is shown in red, and the LES data used as an unsteady FAST input in blue. It is evident that the loading, which is a simple sine wave in the shear case, changes dramatically when the turbulence is introduced. The change is in both the mean, due to the averaging process, and in the unsteady turbulence features. The peaks become much more pronounced and the standard deviation of the plots also increases. The statistics for the lift per unit span at both a station at 32% span, and station at 72% span are shown in Tables A and A, respectively.

The effect of adding turbulence is to increase the standard deviation of the lift per unit span and increase the maximum loadings. Also, longer time variations are visible within the ABL data showing fluctuations in the mean atmosphere. Note that the increase in lift in the 72% case from the 32% case is due to the increased velocity from rotation moving outboard on the blade. This also causes the inner location to see more effects of the turbulence structures as the flow field is not as dominated by the rotational velocity. This effect is also visible as the differences between the lift values between the shear and turbulent cases are more similar at the 72% span location.

![Figure 9. Lift per unit span, in N/m, in the neutral boundary layer at r/R of (a) 32.4% and (b) 72.4% span. The LES result is shown in blue and the shear (without turbulence) in red.](image)
The same comparison can be made of the integrated forces felt by the root of one of the wind turbine blades. The integrated root force corresponding to out-of-plane motion are shown with and without turbulence in Figure 10a for the neutral boundary layer. Again, the plot suggests that the effect of turbulence is large in both changing the magnitude of the oscillations and the low-frequency content. Figure 10b shows the frequency spectra for the out-of-plane root forces. While the higher frequencies corresponding to 1/rev and higher harmonics are evident in both the shear and turbulent cases, there is slight added content at low frequencies even in the neutral boundary layer.

Figure 11 show the same spectra for the moderately convective boundary layer out of and in the turbulence structures. The spectra corresponding to the MCBL out of the updraft structure looks similar to the neutral boundary layer case in that the low frequency energy has a slight increase over the shear case. This effect is more pronounced in the energy spectra corresponding to the MCBL in the updraft structures. This low frequency energy represents the large scale variations due to the updraft structures sweeping through the wind turbine disc.

Figure 12 shows the energy spectra for the torque on the low speed shaft due to the rotational power of the three wind turbine blades. The low speed shaft connects the blades to the gearbox and eventually to the generator to produce power. The loadings on this shaft due to the turbulence are different than those found using the shear only inflow conditions. The loading varies throughout a much wider range as forces integrated from the blades leads
Figure 10. Integrated force in the out-of plane direction for a single blade. (a) Shows the force, in kN and (b) shows the energy spectra. The LES result is shown in blue and the shear (without turbulence) in red.

Figure 11. Energy spectra for the integrated force in the out-of plane direction for a single blade. (a) Inside the turbulence structure. (b) Outside the turbulence structure. The LES result is shown in blue and the shear (without turbulence) in red.

to unsteady loadings. The low frequency energy visible in the out-of-plane force in Figure 11 is visible in both of the MCBL locations. The PDF plots for the turbulence cases, shown in Figure 13, show that the distribution of torques follows a fairly smooth function that is different depending on the location of the wind turbine within the MCBL. The same plots for the cases with shear only, found in Figure 14, show that the shear only cases are almost even in nature as the three blades, each being in a different portion of the rotor disc, work to nearly equalize each other out in total integrated torque.
Figure 12. Energy spectra for the low speed shaft torque. (a) Inside the turbulence structure. (b) Outside the turbulence structure. The LES result is shown in blue and the shear (without turbulence) in red.

Figure 13. Probability density functions for the low speed shaft torque. (a) Inside the turbulence structure. (b) Outside the turbulence structure. The means are shown as black lines.

B. The Boundary Layer State

Neutral boundary layers, as discussed previously, are characterized by a multitude of small scale turbulence structures with little overall coherence. The mean velocities throughout the LES domain are similar. The moderately convective boundary layer has larger scale turbulence structures that are coherent. The local mean velocity in the moderately convective boundary layer can vary. These characteristics are evident in the hub height wind velocity, shown in Figure 15a. The NBL, shown in black, has many more jumps and stays closer to the 10 minute mean. The moderately convective cases, shown in blue for the updraft region and in red outside of the updrafts show larger variations in time.

The characteristics presented above can also be viewed elsewhere on the rotor disc. Figures 15b and 16 show the velocities at the top and bottom of the rotor disc for the neutral
Figure 14. Probability density functions for the low speed shaft torque. (a) Shear case corresponding to inside the turbulence structure. (b) Shear case corresponding to outside the turbulence structure. The means are shown as black lines.

Figure 15. Wind velocity over the 10 minute interval. (a) At the hub for the neutral boundary layer (in black), the moderately convective boundary layer in updraft structures (blue) and in the moderately convective boundary layer outside of the updraft structures (in red.) (b) The velocity for the neutral boundary layer at the top and bottom (top in the higher plot) of the rotor disk. All velocities in m/s.

and moderately convective boundary layers, respectively, in the colors used in Figure 15a. The updraft regions in the moderately convective boundary layer cause a significant drop in the mean velocity while the regions between the turbulence structures often have accelerated stream-wise flow which is illustrated in the lower mean value in Figure 16. The two locations in the moderately convective case only have 10 minutes of data presented here. If the results were presented for a time scale on the order of the mesoscale fluctuations, the differences in the mean between the two cases would be non-existent, though the local mean for any short period of time might be different, such as presented here.

Figures 17, 18 and 19 display the coefficient of lift, the dynamic pressure and the lift
per unit span at a radial location of $r/R = 72\%$. The lift per unit span is the product of the coefficient of lift, the dynamic pressure, and the chord length. The three sets of three pictures here illustrate that the lift per unit span of the blade location which varies in each 10 minute interval and between atmospheric stability states. This can be shown to come from both the changes in $C_l$ and in dynamic pressure for both the neutral and moderately convective cases. The large scale turbulence structures are evident in the dynamic pressure for the moderately convective updraft case. The lift coefficient is a function of the airfoil design, which is constant through the three cases, and the angle of attack. The angle of attack variations are visibly different between the three cases. The change in the mean from the shear only profile in each case signifies that the mean velocity for the location and duration of the test is not the same as the conditional mean found.

Figure 17. Coefficient of lift for the (a) neutral boundary layer, (b) moderately convective boundary layer in the updraft structure and (c) the moderately convective boundary layer outside of updraft structures. The LES results are shown in blue and the shear (without turbulence) in red.
Figure 18. Dynamic pressure for the (a) neutral boundary layer, (b) moderately convective boundary layer in the updraft structure and (c) the moderately convective boundary layer outside of updraft structures, in N/m². The LES results are shown in blue and the shear (without turbulence) in red.

Figure 19. Lift per unit span for the (a) neutral boundary layer, (b) moderately convective boundary layer in the updraft structure and (c) the moderately convective boundary layer outside of updraft structures, in N/m. The LES results are shown in blue and the shear (without turbulence) in red.

The figure also displays the increased lift-per unit span for the moderately convective boundary layer outside the structure, as compared to within the structure. As discussed above, the updraft coherent streaks come in regions of lower stream-wise velocity. Wind turbines, operating by extracting energy primarily from the horizontal streamwise velocity, are affected by this change in mean velocity. This is seen by the loadings going up on the simulations in which the turbine is out of the updraft structures.

The differences between the moderately convective boundary layers is also evident in the low frequency portion of the torque-energy spectra shown in Figure 12. It is apparent that large-scale turbulence structures are much more prevalent when the turbine is positioned sitting inside the low-speed streak. Again, it should be noted that if the turbine in either location were to be analyzed for an extended period of time within a moderately convective boundary layer, it would see both the effects of both moderately convective boundary layer cases shown as the updraft structures will propagate through the boundary layer.

The convection of turbulence structures through the moderately convective boundary layer is also evident in the statistical properties of the FAST outputs. Table B and B are the statistical properties of the low speed shaft torque and the force in the windward direction.
integrated across the rotor plane and down the tower, respectively. The first thing to note is how much the mean changes based on the atmospheric state. The mean wind velocity in the entire domain is constant between the neutral and the moderately convective LES. However, the local mean speeds, a function of the location and the amount of time simulated within FAST, are different. This leads to variations in the mean results for all variables and is visible in both the shaft torque and total stream-wise force. The updraft regions of the MCBL, due to their lower velocity, have a decreased mean on the integrated quantities as compared to either the NBL or the MCBL (when out of the updraft regions) values.

A second observation from these statistics is the change in the standard deviation. The updraft structures, while low in mean velocity, have much more variability in the flow variables due to the large-scale structures present. This leads to much higher standard deviations in the integrated quantities. The location out of the updraft region gives much lower standard deviations than both the updraft regions and the neutral boundary layer. This is because the turbulence structures that give rise to the fluctuations in the flow field are suppressed and thus, while the mean is higher, the fluctuations are lower.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBL</td>
<td>6070.2009</td>
<td>158.2980</td>
<td>0.6996</td>
<td>-0.4238</td>
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<tr>
<td>MCBL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in updraft</td>
<td>2524.4370</td>
<td>180.4417</td>
<td>0.1301</td>
<td>-0.6846</td>
</tr>
<tr>
<td>outside</td>
<td>8114.7712</td>
<td>147.9284</td>
<td>-0.0987</td>
<td>-0.9374</td>
</tr>
</tbody>
</table>

Table 6. The statistical data for the torque on the low speed shaft. Mean and standard deviation in Nm.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
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<td>11.3297</td>
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<td></td>
<td></td>
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<td>in updraft</td>
<td>570.9591</td>
<td>16.2257</td>
<td>0.1617</td>
<td>-0.7205</td>
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<tr>
<td>outside</td>
<td>990.6993</td>
<td>8.2325</td>
<td>-0.2843</td>
<td>-0.6145</td>
</tr>
</tbody>
</table>

Table 7. The statistical data for the total integrated force in the streamwise direction. Mean and standard deviation in kN.

C. The Impact of a Common Inaccuracy in LES of the Atmospheric Surface Layer

As discussed in Section A, LES of ABL are known to produce poor results in near-wall regions. The LES simulations for this study have been designed in the parameter space shown in Figure B. It is possible to compare FAST results utilizing LES inputs that were within the HAZ and those containing an overshoot in order to gain insight into the importance of this with respect to wind turbine aerodynamics. Figures 20 and 21 compare the probability density function of the torque on the low speed shaft of the wind turbine when the simulation is in the HAZ and contains an overshoot for the neutral boundary layer and the moderately convective boundary layer inside an updraft. The PDFs look visibly different between the HAZ and overshoot cases and have a higher skewness in the overshoot cases. The existence of
an overshoot leads to incorrect turbulence structures near the ground as a result of incorrect prediction of turbulence Reynolds stress production. The overshoot causes the low speed streaks in near the surface to become more coherent. This causes updrafts to be stronger both in the NBL and the MCBL. The increased coherence in the updrafts is reflected in the pdf profiles shown below.

![Figure 20](image1.png)

**Figure 20.** Probability density functions for the low speed shaft torque in a neutral boundary layer. (a) LES parameters within the HAZ. (b) LES parameters leading to an overshoot. The means are shown as black lines.

![Figure 21](image2.png)

**Figure 21.** Probability density functions for the low speed shaft torque in a moderately convective boundary layer within the updraft structures. (a) LES parameters within the HAZ. (b) LES parameters leading to an overshoot. The means are shown as black lines.

The vertical location of the overshoot in $\phi_m$, shown in Figure 2, is below the lowest point on the wind turbine rotor disk (37m). The effect of the overshoot visible in the wind turbine statistics present may have been reduced as the change in mean, and not in the shear, is the only feature in the flow being analyzed. The vertical location of the overshoot has been known to go up when the vertical resolution is reduced and vice-versa. Thus the effect of
the overshoot may be more pronounced a) when the wind turbine is smaller and directly interacts with the overshoot or b) the simulation uses a coarser grid resolution in the vertical causing the vertical location of the overshoot in the simulation to go up.

V. Discussion: Importance of Accurate Atmospheric Turbulence on Wind Turbine Loadings

We have shown that turbulence has a large impact the load predictions of a utility scale wind turbine. The turbulence has two effects: 1) it changes the unsteady loading to be more chaotic in nature and 2) amplifies the peak loadings; both of these can decrease the life of wind turbine components due to fatigue loading. The stability of the atmosphere is shown to be important as the neutral and moderately convective boundary layers give rise to different loading characteristics. Two different wind turbine locations within a single moderately convective boundary layer were found to have different flow fields due to the nature of the turbulence structures. The regions with coherent turbulence structures, where updrafts are occurring, have a lower mean velocity and thus have lower mean loadings on the wind turbine blades but higher fluctuations. This also illustrates the importance of sampling time for wind turbine design including times at which the turbine is both in and out of turbulence structures as the global mean shear profile does not adequately cover the loadings that will be experienced by wind turbines at a local time-scale within a moderately convective boundary layer. The importance of utilizing LES that accurately captures the LOTW is shown to be important due to the mean velocity magnitude changing and thus causing a change in the wind turbine loading.

VI. Acknowledgments

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References


