Wind Turbine Response across Scales: Simulation and Experiment

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In this short paper we discuss issues that will be brought up in the presentation surrounding the range of spatial and temporal scales that create forced nonsteady responses in wind turbine and wind farm function. All who have directly contributed to the research underlying this discussion are represented in the author list, with a high level of appreciation for the collaborations.

Impacts of Spatio-temporal Variabilities in Wind Velocity on LCOE

Utility-scale wind turbines, individually and within wind farms, operate in highly turbulent flow environments so that the loadings that generate power are highly variable, both in time and spatially across the blades and rotor disk. These variabilities have significant impacts both on the numerator and on the denominator of the Levelized Cost of Energy (LCOE) expression:

$$\mathbf{LCOE} = \frac{\text{Capital Investment} + \mathbf{20\text{-}yr\ Operating\ Costs}}{\mathbf{20\text{-}yr\ Energy\ Production}} \tag{1}$$

Given that LCOE is the primary measure used for decisions on siting, wind farm development and overall cost of wind in relationship to other forms of electricity production, there is a need for research focus on the mechanical process that significantly impact the numerator and denominator of the LCOE expression (1).

The denominator is impacted by spatio-temporal variability through the continual movements in sectional and whole blade performance around design points in blade pitch and rotor performance around design points in rotor yaw as the local and rotor-averaged wind vector changes in both magnitude and direction as turbulence eddies pass through the rotor plane. These impacts can be significant, for example, when blade sectional angles-of-attack exceed the threshold for attached blade boundary layer flow, an intermittent process that contributes to temporal rotor moment modulations that could contribute significantly to degradation of average power depending on the changing stability state of the lower troposphere during its diurnal and seasonal cycles, and depending on the level and sophistication of controls that modulate the relationships between variabilities in wind turbine parameters (blade pitch, generator torque) and spatio-temporal variabilities in wind velocity vector over the power-generating rotor disk.

More important to LCOE, perhaps, is the impact of these same spatio-temporal variabilities on the longer-term operating costs of the wind turbine and wind farm through reductions in reliability from component failures. Drivetrain bearing failures, particularly the main bearing on the low-speed-shaft and gear-box bearings, are costly to replace due to the high crane expenses to remove and replace components that reside in a nacelle ~100 m from the ground, often within challenging terrain. Temporal chaotic

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variations in shaft bending moments may be a primary cause of fatigue and premature failures of the main bearing, for example.

The Extraordinary Range of Length and Time Scales Relevant to Wind Turbine/Farm Forcing

The turbulence embedded within the air flow that passes through a wind turbine rotor can be highly variable from turbine to turbine within a wind farm and depends on whether or not the rotor experiences only the turbulence embedded within the atmospheric boundary layer flow or a mix of atmospheric boundary layer turbulence and turbulence motions from the wakes of upstream wind turbines. The "front" couple rows of wind turbines within a wind farm experience directly the spatio-temporal variabilities in the passage of atmospheric turbulence eddies through the rotor disk while the temporal responses of wind turbines further into the wind farm are strongly impacted by the highly turbulent wakes from upstream wind turbines. However, there can be strong interactions between the energy-containing turbulence eddies with the atmospheric boundary layer and the wakes behind individual wind turbines, both because the scale and nature of the modulations in wind turbulence passing through the rotor disk can modulate the development of the near-wake vortices, their stability and breakdown dynamics, and especially the spatio-temporal characteristics of the meandering of the wake of the whole, a process central to the temporal variations in wind turbine loads.

There is not a single dominant structural and statistical characteristic of the velocity fluctuations that dominates the nonsteady forcings of wind turbines within wind farms. This is partly due to the extraordinarily large range of length and time scales that are involved in determining these characteristics.

The Atmospheric Micro Scales and the Rotor Response Scales

At the atmospheric level, the three-dimensional energy-dominant coherent structure of the velocity deviations from the mean atmospheric winds vary a great deal in relationship to: (1) fundamental differences between the unstable daytime vs. stable nighttime boundary layer, (2) in the daytime the diurnal changes in both turbulence eddy size and in the convective vs. shear driven structure of the energy-dominant eddies as solar heating increases from sunup, to peak surface heat flux mid-day, to sundown, (3) the highly nonstationary collapse of the boundary layer in the transition from the daytime to nighttime stably stratified ABL with potential formation of internal coherent structures such as low-level jets, (4) other nighttime nonequilibrium transitions as turbulence is progressively suppressed by increasing stable stratification, and (5) the modulation of the mean winds and turbulence eddy structure at the "microscale" (i.e., within the ABL) during the passage of weather events at the "mesoscale" (i.e., above the ABL in the free troposphere).

Over land, the closet period of wind-turbine interaction that can be described as quasi steady occurs in the early afternoon, typically for a few hours after peak solar apogee. In this quasi-equilibrium state, the atmospheric surface layer depth is 15-20% of the boundary layer depth, which can vary between typically 1000-2000 m. The turbulence motions that contribute to the largest temporal variations in blade loadings are with energy-dominant "integral-scale" ABL turbulence eddies with characteristic transverse dimensions that scale on the distance from the ground within the surface layer up to a height, in the afternoon ABL, of 150 m - 400 m. Thus, the rotor disk of current 2-3 MW wind turbines over land with rotor diameters $\gtrsim 100$ m 100 m and hub heights ~90 m is fully within the atmospheric surface layer. Furthermore, in the early afternoon the characteristic energy-dominant eddy size is roughly 40 m - 140 m from the lower to upper margins of the rotor disk—that is, of order blade length to rotor disk diameter. The blade sectional chord lengths, however, are typically in the range 2-4 m, 1-2 orders of magnitude below the energy-dominant eddy size in the afternoon atmospheric surface layer. The dominant force that generates torque $\propto$ power at the hub is lift per unit span on a wind turbine blade section. Thus, one anticipates that the spatial gradients in sectional blade loads along the span of the blade are relatively mild and that the blade responds primarily to temporal variations in fluctuations in wind velocity associated with the passage of energy-dominant turbulence eddies. This conclusion was verified by large-eddy simulations of utility-scale wind turbine rotors embedded within a typical afternoon daytime atmospheric boundary layer over land with high resolution blade-boundary-layer-resolved CFD [Vijayakumar *et al*. (2016, 2015, 2014, 2012) , Nandi *et al*. (2017a,b, 2016), Lavely *et al*. (2014) and with high-resolution actuator line representations of the blades [Nandi, *et al.* (2017a), Lavely (2017).].

Nandi, *et al*. (2017b) analyzed data collected in the field on a GE 1.5 MW wind turbine in the afternoon summer ABL to demonstrated the existence of three time scales important to the response of wind turbine blade and rotor loadings during the passage of daytime ABL eddies. These data from a GE field campaign in Germany validated and added detail to characteristic time scales that emerged from the blade/rotor-in-daytime-ABL large-eddy-simulations of Vijayakumar, Nandi and Lavely (see reference list) The longest time scale in blade response is associated with the passage of the atmospheric energy-dominant eddies which, depending on the degree of global instability in the afternoon ABL was found to be ~30-60 s. The blade passage time scale is determined by the rotor rated RPM which varies with wind turbine but is typically ~ 8-18 RPM for utility-scale wind turbines, so blade passage time scale is typically ~ 4 - 7 s when the wind turbine is operating in region 2 of the power curve. This is the second dominant characteristic rotor response time scale. However it was found by Nandi *et al*. experimentally, and Vijayakumar with blade-boundary-layer-resolved LES/CFD, that the passage of the blades through the internal structure of the turbulence eddies create large ramp-like excursions in section angle of attach, lift and integrated blade torque at time scales below 1 second (tentatively, ~ 0.5 - 1 s). These same ramp-like events are observed in the rotor moments that pass through the drivetrain (Lavely 2017, Lavely *et al*. 2012, 2011), which may have a significant impact on bearing fatigue on the low-speed-shaft portions of the drivetrain.

So long as the wind turbine resides within the daytime surface layer, and so long as the atmospheric boundary layer is in a quasi-equilibrium state so that the entire boundary layer from surface to capping inversion is fully formed, the relevant turbulence integral scale associated with the energy-containing eddies is roughly proportional to the distance and therefore the scale of the turbulence eddies that generate the largest temporal excursions in blade and rotor loadings increase in scale over the rotor disk so long as the upper margin of the rotor is within the surface layer, roughly 15-20% of the capping inversion depth. In the transition from the early morning ABL shortly after sunup to peak solar apogee after noon, the ABL is out of equilibrium as the boundary layer grows from a couple hundred meters to peak capping inversion depth at 1000-2000 m. During this period the surface layer forms and grows from of order 50-100 m to ~ 150-400 m at peak solar apogee, suggesting that the largest scale of turbulence eddy encountering the rotor disk also increases until the surface layer folly covers the rotor disk. Thus one can expect the largest spatial and temporal scales of blade and rotor response to increase from smaller scales in the morning to larger equilibrium eddy scales roughly mid-day.

Towards the end of the day, as the sun sets, solar heating turns off and surface heat flux reverses direction from atmospheric heating to cooling, buoyancy production of turbulence rapidly changes to turbulence destruction near the surface, and a highly nonstationary collapse in the boundary layer takes place as the ABL transitions to its nighttime stability stratified stated. Not only does ABL turbulence structure rapidly change, along with the turbulence length and time scales, but this nonequilibrium collapse is often accompanied by the formation of internal flow structures some of which can impact wind turbines. For example, a not uncommon occurrence in the transition from unstable daytime to stable nighttime ABL in the plains is the formation of “low-level jets,” high-speed flow localized in z near the ground that often occurs within a couple hundred meters from the surface and can therefore impact a wind turbine rotor disk (Kelley *et al*. 2006. The relative fluctuation levels decrease during the evening due to stable stratification in turbulence destruction at the surface with a much lower internal boundary layer thickness and transition to more shear-dominated structure compared to the buoyancy-with-shear driven daytime ABL.

The Atmospheric Micro Scales and the Blade Boundary Layer Response Scales

Vijayakumar *et al*. (2015, 2016, 2014, 2012) developed a high-resolution blade-boundary-layer-resolved simulation of the 60 m blade of the 5 MW NREL wind turbine rotating within a typical daytime atmospheric boundary layer over land. Nandi *et al*. (2017) developed a corresponding simulation for the 39-m blade of the GE 1.5 MW wind turbine. To resolve the viscous layer within the highly turbulent blade boundary layer at the high sectional blade Reynolds numbers that exist towards the outer span of the NREL 5MW wind turbine blade at rated conditions in the daytime ABL, it was necessary to place the first grid level at 5 μm from the blade surface for a turbulent blade boundary layer thickness ~ 1 mm. The viscous layer determines the stresses on the blade surface; more importantly, the interaction between the highly unstable viscous layer and the energy-dominant turbulence eddies within the blade boundary layer above, with scales ~ 50 -1000 μm, determines whether or not the viscous layer will separate from the blade surface.

Lavely, *et al*. (2017, 2011) and Vijayakumar (2015), have shown with high fidelity CFD of the utility-scale wind turbine within the daytime ABL that the impact of the fluctuations in wind velocity vector on fluctuating sectional loads along wind turbine blades is dominantly through local changes in sectional angle-of-attack as the rotating blade cuts through the energy-dominant atmospheric eddies. Furthermore, the passage of atmospheric eddies have the potential to cause large changes in angle-of-attack which in the outer 50% of the blade caused large changes in sectional lift without separation when the wind turbine is operating at rated power and wind speed. Because of the large scale separation between atmospheric eddy scale and blade chord in the middle part of the day, the time changes in angle-of-attack largely determine the time changes in blade torque, and therefore power. Lavely (2017) further showed that changes in sectional blade angle-of-attack arise primarily in response to the time changes in horizontal fluctuating velocity, which can easily be 50% or more of the mean in the equilibrium daytime atmospheric boundary layer. This result was verified in the GE field studies analyzed by Nandi *et al*. (2017b) where it was found, through data from a leading edge probe on a utility-scale wind turbine blade correlated with horizontal velocity fluctuations measured on an upstream met mast in the daytime ABL, that the time changes in wind velocity vector angle relative to sectional chord was strongly correlated with the time changes in the horizontal velocity magnitude.

Blade separation is a major aerodynamic phenomenon local to blade surface at extraordinarily small scales (relative to the rotor) that can impact forces and moments globally to impact significantly nonsteady response of the drivetrain to time-varying integrated loads over the blade and rotor disk. The research above suggests that when a utility-scale turbine blade rotates at design conditions in the quasi-steady state equilibrium daytime ABL, as the blade passes through atmospheric eddies the changes in angle-of-attack are substantial enough to cause large (±50%) variations in moments at the hub, but generally not substantial enough to cause the blade boundary layer to separate over the outer 1/2 - 2/3 of the rotating blade. However the blade-boundary-layer-resolved simulations of Vijayakuamar *et al*. (2015, 2016) and others indicate that inner region of the NREL 5 MW wind turbine blade is largely separated and highly nonsteady. Because the contribution of this separated region to the integrated torque is much reduced by the small moment arm, its impact is relatively modest. However Nandi *et al*. (2016, 2017) analyzed and simulated with URANS the oscillating S809 airfoil to show that the appropriately normalized parameters derived from the nonsteady variations in angle-of-attack quantified by Vijayakumar *et al*. (2016, 2016) and Lavely *et al*. (2017, 2011) are sufficiently large to suggest that out-of-design operation could lead to dynamic stall over portions of the blade. Furthermore, deviations in atmospheric state from the canonical afternoon quasi-equilibrium and stationary ABL could cause the temporal variations in wind velocity to be much more severe than the canonical state.

The Atmospheric Micro Scales and the Wake Response Length and Time Scales

In context with the previous discussion, a potentially important source of severe temporal fluctuations in wind velocity and sectional leading edge velocity vectors that can cause greater boundary layer separation over larger portions of the turbine blade is the strongly fluctuating wind variations resulting from the passage of wakes through the turbine rotor disc from upstream wind turbines. At the scale of the rotor disk several diameters downstream of the upstream wind turbine, the large variances in the wake of the upstream wind turbine pass over the downstream rotor disk at the wake-meandering frequency.

Whereas it is known observationally that wake meandering is very different in the presence of atmospheric turbulence, and is correspondingly very different in the daytime vs. nighttime ABL, very little research has been done to characterize and understand the additional time responses of blade and rotor forces and moments to the passage of wake turbulence through the rotor disk in addition to the influences of atmospheric turbulence in the absence of wake turbulence (and vice versa).

It is clear, however, that in addition to the turbulence eddies within the wake, the lateral spatio-temporal motions of the wake as a whole (meandering) is an important element to these additional temporal loads, and it is clear that wake meandering is strongly affected by daytime atmospheric turbulence where atmospheric eddies have lateral scales of order the wake scale. The relationship between wake and atmospheric eddies in the stable nighttime ABL, however, is very different, making "wake steering" control strategies more effective in the nighttime ABL.

Consequences of Nonsteady Loadings on the Drivetrain

In his PhD thesis, Adam Lavely (2017) developed analysis using an actuator line model of the NREL 5 MW wind turbine embedded within the same daytime atmospheric boundary layer used by Vijayakumar e *et al*. (2015, 2016) to study the mechanisms by which the largest nonsteady moments are created on the low-speed-shaft (LSS) with the potential to impact premature fatigue failures of the drivetrain bearings. Interestingly it was discovered that the nonsteady changes in-plane bending moments on the LSS—those responsible for torque and power—result from a fundamentally different mechanism from in out-of-plane bending moments—those that create off-axis motions of the LSS that impact the main bearing and entrance to teh gearbox. Lavely also found that nonsteady axial motions of the LSS (also potentially involved in bearing fatigue failures) respond with the same mechanism as does torque. In essence, Lavely found that torque and axial load fluctuations result primarily from microscale fluctuations in the horizontal velocity vector of wind fluctuations averaged over the rotor disk, the fluctuations embedded within the energy-dominant eddies of the (daytime) ABL at the rotor scale. Cause and effect occurs through the impact of fluctuations in sectional angle-of-attack which has been found to be driven primarily by microscale fluctuations in the horizontal wind velocity (see discussions above). We found that out-of-plane bending moments, on the other hand, are driven not by the temporal fluctuations in the wind velocity, but by the temporal fluctuations in the *asymmetries* of the fluctuating wind vector over the wind turbine rotor disk. This result is potentially important also for considerations of nonsteady response due to wake-turbine interactions.

As described in Lavely's thesis (2017), we worked with Jon Keller (NREL National Wind Technology Center) analyze 3 months of data collected through the "Gearbox Research Collaborative" (GRC) about 10 years ago from an instrumented gearbox from a wind turbine in the field in northern Colorado near Wyoming. The measurements taken included strain, displacements and accelerations on various shafts, gearbox housing attachments and gearbox components. Although not directly applicable to main bearing fatigue failures, the analysis of out-of-plane bending moment from the gearbox data obtained in the field is strongly consistent with the computational analysis that points to asymmetry as the driver of these potentially deleterious bending moments.

Influences from Atmospheric Meso Scales and related Weather Events

We have already pointed out the importance to nonsteady response of wind turbine aerodynamics and integrated forces and moments on the low-speed-shaft to dynamics and motions from the scale of the atmospheric boundary layer, ~1000 - 2000 m, to the scale of the eddies and wind turbine rotor, ~ 40 - 140 m, to the blade chord scale, ~2-4 m, to the scale of the internal viscous layer within the blade boundary layers, ~ 5 μm. As described above, all of these scales of motion are important to the nonsteady response of the wind turbine, and therefore wind farms, to that nonsteady turbulence contend of the atmospheric boundary layer. This represents over ***eight orders of magnitude in spatial scale separation*** between the largest and smallest scales that are relevant to wind turbine function (and LCOE as described above)! (This compares with two orders of magnitude in response time scale from the eddy passage time (~ 60 s) to the ramp-like response of the blade as it passed through internal eddy turbulence structure (~ 0.5 s)—unless one includes the smallest response scale within the high Reynolds number blade boundary layer which then increases to eight orders of magnitude disparity in time scale as with length scale.)

However there are an additional three orders of magnitude relevant separation in spatial scale when one also considers potential significant roles of flow patterns at the mesoscale, largely horizontal flow patterns with scales of motion from the hundreds of kilometers to tens of kilometers. The impacts of these large-scale weather patterns, largely horizontal and within the free troposphere, on the evolution of the atmospheric boundary layer below, within which are embedded wind turbines and wind farms, are two-fold: (1) the role of the passage of weather events on the modulation of the mean and fluctuating wind coherent structure in the ABL that interacts with wind turbines/farms, and (2) the role of mesoscale motions on the generation of power over the scale of large wind farms and the interactions among wind farms. In context with (1), Jayaraman *et al*. (2016) studied the impacts of the forcing of the ABL out of equilibrium by the passage of typical frontal weather patterns on the ABL mean flow and turbulence coherent structure in the Midwest (Kansas-Oklahoma) by forcing large-eddy simulation of the daytime atmospheric boundary layer with frontal variations in mesoscale wind and surface head flux obtained from the NCAR "Weather Research and Forecasting Model" (WRF). They find that nonsteady changes in mean horizontal pressure force at the mesoscale in the free troposphere drives the ABL at the microscale to force time changes in the direction and magnitude of the mean velocity field that impacts wind turbines/farms and deviations in turbulence structure associated with nonequilibrium dynamics. The implication is that weather events can alter both the mean velocity field and the effective stability state of the ABL with consequences to the details of the nonsteady forcing of wind turbines.

In addition to mesoscale-forced nonequilibrium effects on the ABL wind and wind-turbine-scale turbulence structure, mesoscale wind patterns can impact groupings of wind turbine within very large wind farms, those approaching O(100 km) in the horizontal, directly at the meso scale. The impacts of Coriolis acceleration turning the flow through the wind farm, for example, has an impact on control of wind turbine orientation within the wind farm as well as on the interaction between the wake of a wind farm on a downstream wind farm.

Concluding Discussion

In conclusion, the mechanical responses in forces and moments to mean and nonsteady wind loadings that drive both wind turbine power generation—the denominator in LCOE formula—and the nonsteady variations in in-plane and out-of-plane bending moments that can drive premature bearing failure, reduce reliability and increase operation costs—the numerator in LCOE—result from the interactions among a very large range of scales. For individual wind turbines and wind turbines within smaller and sparsely-spaced wind farms the dominant wind forcings that create load responses significant to wind turbine function and LCOE are embedded within the "microscale" motions of the atmospheric boundary layer and cover the following ranges of scales:

- Microscale largest: The energy-dominant "integral scale" eddies of fully-developed "microscale" ABL turbulence within the daytime atmospheric surface layer, 40-140 m, of order the wind turbine blade length and wind turbine rotor diameter;
- Largest: The interaction of turbine rotor wakes of upstream wind turbine (of order the rotor diameter, ~100 m) with downstream wind turbines within wind farms;
- Largest: Internal flow structures developed in the nonequilibrium collapse of the unstable daytime ABL into the stable nighttime ABL (e.g., low-level jets of order rotor diameter in depth);
- Mid: The blade chord scale, 2-4 m, over which sectional lift and drag are produced as the dominant forces involved in the generation of torque and power and that create nonsteady moments at the hub that pass through the drivetrain;

Mid: The internal structure of the daytime integral-scale eddies (those that contain the largest variances in wind velocity vector magnitude and direction), through which the rotating wind turbine blades pass and as a result of which wind turbine load responses at three ranges of characteristics time are generated: integral scale eddy passage time (~minute), blade passage time (~ 4 - 7 s, depending on rotor RPM), and a short important "ramp" time scale associated with the passage of eddies through the internal structure of the integral-scale turbulence eddies;

Mid: The internal structure of rotor wakes presumable create smaller-spatial-scale responses on downstream wind turbine blades and rotors (largely unexplored); furthermore, wake instabilities, and the impact of ABL microscale eddy structure on wake instabilities, create spatio-temporal oscillations in the wake ("meandering") that likely generate ranges of spatial and temporal force and moment time scales (also largely unexplored);

Smallest: The viscous layers within the blade boundary layers, ~5 - 20 μm, in which the viscous stresses are produces on the blade surface and, more importantly, that interact with turbulence motions within the blade boundary layer above to either maintain attached blade boundary layers or that allow the boundary layer to separate and dramatically lower sectional lift and increase sectional drag.

This represents 8 orders of magnitude (!) in the range of important spatial scales that interact in the functions of wind turbines, both on and off design. However at the wind farm level, and potentially even at the wind turbine level, mesoscale (non-extreme) weather events create responses in function at scales up to 3 orders of magnitude larger than the relevant ABL turbulence scales:

Mesoscale largest: Direct impact of mesoscale motions and weather events on large wind farm function as a unit at the "mean" flow scale for wind turbine function, including Coriolis effects on mean wind direction;

Impacts of Mesoscale Weather on Largest Microscale Motions: The time changes in the "mean" (from the wind turbine perspective) mesoscale wind vector create deviations from equilibrium in the evolution of the ABL microscale motions that can impact the scale and structure of the energy-dominant turbulence motions that force the wind turbine to create nonsteady load variations.

If one includes the mesoscale as relevant in addition to the microscale at the atmospheric level, then the response of both individual wind turbines within wind farms and the wind farm as a whole involves 11 orders of magnitude in the relevant spatial scales in the winds that impact wind turbine and wind farm function. Even if one discounts mesoscale effects as secondary, 8 orders of magnitude in the range of dynamically important spatial scales of motion for evaluating and improving Levelized Cost of Energy in wind turbine and wind farm function is very large and points to the severe computational and experimental challenges in the evolution of the science of wind turbines and wind farms as needed to advance technology for ever more efficient production of energy from the wind.

References

Jayaraman, B. Brasseur, J.G., Haupt, S., Lee, J. 2016 Deviations from Equilibrium in Daytime Atmospheric Boundary Layer Turbulence arising from Nonstationary Mesoscale Forcing. (abstract) Bull. Amer. Phys. Soc.: http://meetings.aps.org/Meeting/DFD16/Session/M13.3

Kelley, N.D., Jonkman, B.J., Scott, G.N. 2006, The Great Plains Turbulence Environment: Its Origins, Impact, and Simulation. Presented at AWEA's 2006 WindPower Conference, Pittsburgh, Pennsylvania,June 4–7, 2006, NREL/CP-500-40176.

Lavely, Adam, 2017 *Effects of Daytime Atmospheric Boundary Layer Turbulence on The Generation of Nonsteady Wind Turbine Loadings and Predictive Accuracy of Lower Order Models*, PhD Thesis, Pennsylvania State University. August 2017.

Lavely, A., Vijayakumar, G., Craven, B., Jayaraman, B., Jha, P., Nandi, T., Paterson, E.G., Brasseur. J.G. 2014. Toward a Blade-Resolved Hybrid URANS-LES of the NREL 5-MW Wind Turbine Rotor within Large Eddy Simulation of the Atmospheric Boundary Layer, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0869.

Lavely, A.W., Vijayakumar, G., Brasseur, J.G., Paterson, E.G., Kinzel, M.P. 2012 Comparing Unsteady Loadings on Wind Turbines using TurbSim and LES Flow Fields, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0818.

Lavely, A. W., Vijayakumar, G., Kinzel, M.P., Brasseur, J.G., Paterson, E.G. 2011 Space-Time Loadings on Wind Turbine Blades Driven by Atmospheric Boundary Layer Turbulence. *Proc. 49th AIAA Aerospace Sciences Meeting*, 4-7 Jan 2011, Orlando, FL, AIAA Paper 2011-635.

Nandi, Tarak. 2017 *Effects of Blade Boundary Layer Transition with Daytime Atmospheric Turbulence on Wind Turbine Performance Analyzed with Blade-Resolved Simulation and Field Data*. PhD Thesis, Pennsylvania State University, May 2017.

Nandi, T.N., Herrig, A., Brasseur, J.G. 2017 Nonsteady wind turbine response to daytime atmospheric turbulence. *Phil. Trans. R. Soc. A* 375: 20160103.. http://dx.doi.org/10.1098/rsta.2016.0103

Nandi, T., Brasseur, J.G., Vijayakumar, G. 2016 Prediction and Analysis of the Nonsteady Transition and Separation Processes on an Oscillating Wind Turbine Airfoil using the γ-Re_θ Transition Model. AIAA SciTech, 4-6 Jan 2016, San Diego, CA, AIAA2016-0520.

Vijayakumar, Ganesh. 2015 *Non-steady Dynamics of Atmospheric Turbulence Interaction with Wind Turbine Loadings through Blade Boundary Layer Resolved HPC*. PhD Thesis, Department of Mechanical Engineering, Pennsylvania State University, University Park, PA, May 2015.

Vijayakumar, G., Brasseur, J.G., Lavely, A., Jayaraman, B., Craven, B.C. 2016 Interaction of Atmospheric Turbulence with Blade Boundary Layer Dynamics on a 5MW Wind Turbine using Blade-Boundary-Layer-Resolved CFD with hybrid URANS-LES. AIAA SciTech, 4-6 Jan 2016, San Diego, CA, AIAA2016-0521.

Vijayakumar, G., Lavely, A., Jayaraman, B., Craven, B., Brasseur. J.G. 2014, Blade Boundary Layer Response to Atmospheric Boundary Layer Turbulence on a NREL 5MW Wind Turbine Blade with Hybrid URANS-LES, 32nd ASME Wind Energy Symposium, 13-17 January 2014, National Harbor, MD, AIAA 2014-0867.

Vijayakumar, G., Brasseur, J.G., Lavely, A.W., Kinzel, M.P., Paterson, E.G., Churchfield, M.J., Moriarty, P.J. 2012 Considerations in coupling LES of the atmosphere to CFD around wind turbines, *Proc. 50th AIAA Aerospace Sciences Meeting*, 9-12 Jan 2012, Nashville, TN, AIAA Paper 2012-0817.

Wharton, S. and J. K. Lundquist, 2011 Assessing Atmospheric Stability and its impacts on rotor-disk Wind Characteristics at an Onshore Wind farm, Wind Energy **15**: 525–546