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Decades of Wind Turbine Load Simulation

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A high-performance computer was used to simulate ninety-six years of operation of a five megawatt wind turbine. Over five million aero-elastic simulations were performed, with each simulation consisting of wind turbine operation for a ten minute period in turbulent wind conditions. These simulations have produced a large database of wind turbine loads, including ten minute extreme loads as well as fatigue cycles on various turbine components. In this paper, the extreme load probability distributions are presented. The long total simulation time has enabled good estimation of the tails of the distributions down to probabilities associated with twenty-year (and longer) return events. The database can serve in the future as a truth model against which design-oriented load extrapolation techniques can be tested. The simulations also allow for detailed examination of the simulations leading to the largest loads, as demonstrated for two representative cases.

I. Introduction

A wind turbine operates within an inherently random wind field, resulting in stochastic loadings that must be resisted by various components of the turbine to some desired level of reliability. Aero-elastic simulation is an essential part of the wind turbine design process, in which stochastic loadings are assessed through a number of simulations of the turbine under normal operating conditions within a prescribed turbulent wind field. Typically, some limited number of simulations is performed, each with a duration of ten minutes and with a mean wind speed sampled from a given probability distribution. The loads from these simulations are then post-processed, employing various statistical assumptions and extrapolation, to arrive at system response quantities such as component fatigue damage or extreme loads. For example, IEC Design Load Case (DLC) 1.1[1] requires extrapolation of simulation results for 10-minute extreme blade loads and tip deflections to 50-year return values.

Uncertainties in design load assessment are present due to (among other factors) lack of sufficient information about infrequent loads. This uncertainty requires the use of load safety factors applied to characteristic extreme loads. Load uncertainties may be reduced using more simulation, but this has, to date, not been possible due to the inability to simulate long periods of wind turbine operation in reasonable analysis times. Moriarty[2] performed five years of wind turbine load simulations over a period of five weeks using a desktop network, creating a useful database for assessment of load extrapolation techniques. Nonetheless, significant uncertainty remains in the tails of the load distributions below probability levels associated with a one-year return event.

High-performance computing (HPC) machines have now reached capacities that allow for simulation of decades of wind turbine operation in reasonable simulation times. This level of simulation is not yet practical for routine wind turbine design exercises. However, the capability to perform such large numbers of simulations on a few reference turbine designs can be very useful for evaluating and improving load extrapolation techniques, and for improving our basic understanding of wind turbine loads. This paper describes the application of HPC resources to wind turbine load simulation, with the overall goal of reducing the uncertainty associated with extreme and fatigue load extrapolation, thereby improving the overall wind turbine design process.

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II.   Simulation Setup

An aero-elastic model for the onshore version of the 5 MW NREL reference turbine[3] is used in the present work. The 5 MW reference turbine has a three-bladed, upwind rotor with a diameter of 126 meters, and a hub height of 90 meters. The turbine control scheme includes variable speed operation in Region 2, and variable collective blade pitch in Region 3. The cut-in, rated, and cut-out wind speeds are 3 m/s, 11.4 m/s, and 25 m/s, respectively. There is no active yaw control. The model assumes the commanded yaw position is held constant at zero relative to the nominal wind direction, while allowing for small yaw deflections subject to flexibility and damping in the yaw drive.

The aero-elastic simulations are performed using the FAST code,[5,6] version 7.00.01a-bjj, obtained from the NREL design codes website. The equilibrium inflow model is used, which is a steady-state blade element momentum model. This is required in order to maintain numerical stability of the simulations over all wind speeds and the wide range of turbulent wind fields considered. However, this model is expected to be less accurate than other model choices in predicting dynamic loads. The effect of the wake model is explored in a later section. Turbulent wind fields are generated using the NREL TurbSim code, version 1.50.[7] The average wind speed and turbulence intensity are specified according to an IEC wind turbine class of IIB.[1] This corresponds to a site average hub-height 10-minute wind speed of 8.5 m/s. A Rayleigh distribution is specified, from which the mean 10 minute wind speed is sampled for each simulation. Mean wind speeds below cut-in or above cut-out were ignored, and the total number of samples was correspondingly increased in order to give the desired number of simulations between cut-in and cut-out. The turbulence intensity is specified deterministically as a function of mean wind speed according to the IEC normal turbulence model.[1] The mean wind profile is specified as a power law with shear exponent of 0.2, and the turbulence spectrum is the Kaimal spectrum.

Two random seeds are specified for generating the turbulent wind field. These random seeds are both sampled from a uniform continuous distribution ranging from -2147483648 to +2147483647, and truncated to integer values. A total of 660 seconds of turbine operation is simulated for each run, with the initial 60 seconds discarded to avoid contamination of the results by initial transients. The inflow turbulence is generated on a 20x20 square grid with width of 137 meters, centered at the turbine hub.

The DAKOTA software framework[8] is used for management of random sampling and simulation execution. The Latin hypercube sampling (LHS) option within DAKOTA is utilized, which offers efficiencies over the simpler Monte Carlo sampling method.[9] LHS is a stratified sampling method that divides the range of each sampled variable into intervals of equal probability, and one value is randomly selected from each interval with respect to the probability distribution within the interval. Compared with Monte Carlo sampling, LHS guarantees a more even sampling, and generally leads to better estimation of the output distribution with fewer samples.

It was not possible to perform the simulations on the high-performance computer in one pass, due to system policies limiting the wall clock time available for a single job, as well as memory limitations encountered for LHS with such a large sample size. For this reason, the simulations were divided into six batches, each with a total simulation duration of sixteen years. The sampling algorithm was provided with a different seed value for each batch resulting in unique sample sets for each ten-minute simulation. The simulation results from all six batches were then concatenated into a single distribution. The resulting distributions are not expected to be as precise as those calculated with a single LHS run, but should still be more precise than the result using a simple Monte Carlo method.

DAKOTA spawns a number of concurrent simulations on the available CPU cores, automatically creating a temporary work space and executing a user-defined job script. The job script populates the TurbSim input file with the random seeds and wind speed, executes TurbSim, and then executes FAST. The load time series from FAST are then post-processed to generate blade load roses, compile load cycle counts for fatigue analysis, and calculate concurrent related loads associated with any individual extreme load. The FAST output is also post-processed to extract extreme load values, which are then passed back to the DAKOTA process. Rainflow cycle count data for each simulation are saved to a data directory for later post-processing. DAKOTA saves the extreme load values and calculates the empirical probability of exceedance (also referred to as the complementary cumulative distribution function) for any load variable. DAKOTA also saves the wind field random seeds and the wind speed for each simulation, which is useful should certain simulations require closer examination of the time series results at a later time.

III.   Computing Environment

The aero-elastic simulations are run on the Sandia Red Sky computing cluster, a 450 teraflop Linux computing cluster. Red Sky has 5305 nodes, each with 8 CPU cores, giving a total of 42,440 available cores. The present results were obtained using 1024 cores. This allows for simulation of 16 years of turbine operation in approximately 18

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wall-clock hours. Use of a greater fraction of the cluster would result in faster simulation times. However, Red Sky is a shared resource with a large number of users, so execution time must be balanced by queue wait time for jobs that request a relatively large number of cores. The 1024 core job size was found to allow for efficient job throughput on Red Sky.

The TurbSim and FAST codes were compiled within the Linux environment using the Intel Fortran90 compiler. The resulting executables were then successfully tested against the verification test cases provided with the code distributions.

A total of 96 years of simulations were performed, resulting in a total wall-clock time of approximately 4.5 days. Rainflow-counted cycles for 35 output channels were stored in binary format, resulting in a database of approximately three terabytes. A parallel code has been written to process this data and calculate fatigue spectra and loads, but results from these calculations are not presented here. The remainder of this paper focuses on extreme load behavior as assessed from the simulations.

IV.   Load Distributions

In this section the statistical extreme load distributions are presented as probabilities of exceedance in a ten minute period. The probability of exceedance, or the complementary cumulative distribution function, is the probability that a load level will be exceeded in any ten minute period. The probability of exceedance in ten minutes that is associated with a fifty year return period is $\frac{1}{365.25 \times 24 \times 60/10 \times 50} = 3.9 \times 10^{-7}$; such fifty-year return period loads are of interest in design load case (DLC) 1.1 as specified in the IEC 61400-1 design standard.[1] The current simulations allow for estimation of probability of exceedance levels down to 2.0×10^{-7}.

Probability of exceedance plots for various wind turbine loads are shown in Figures 1 through 4. There is some uncertainty in the extreme tails of the distributions, but, in general, the distributions are well-defined down to a probability level of 10^{-6}, corresponding approximately to a twenty year return load. The tails of the distributions are also all well-behaved, in the sense that there are no large changes in slope or other unexpected behavior beyond the "knee" in the distribution. This provides additional confidence in extrapolation approaches, where limited simulation data are used to extrapolate to long-term return loads. For example, suppose one week's worth of simulations were performed (approximately 1000 simulations), such that the lowest probability of exceedance computed was approximately 10^{-3}. Examining Figure 1, extrapolation of a distribution defined even down to 10^{-2} would yield good estimates of a fifty year return period load. However, the tails of the distributions do follow different shapes, depending on the load. For example, Figure 3 shows that the tail of the tower base side-to-side moment is convex, whereas the tail of the tower fore-aft moment distribution is concave. The generated database should prove useful in assessing and calibrating different load extrapolation strategies.

Presentation of maximum loads for each simulation as a function of mean wind speed is also illustrative; this allows us to identify the mean wind speed or speeds for which load extremes occur. Figure 5 shows the maximum tip deflections versus mean wind speed. The largest out-of-plane deflections occur between the rated wind speed and approximately 20 m/s, although there is one rather large deflection that occurs at around 22.5 m/s. The extreme in-plane tip deflections increase monotonically with wind speed. For both out-of-plane and in-plane tip deflections, the distribution widens as the mean wind speed increases. Figure 6 shows similar distributions for flap-wise and edge-wise blade root bending moments. The flap-wise moment distribution variation with mean wind speed is similar to that of the out-of-plane tip deflection. The edge-wise tip deflection extremes increase up to rated wind speed, then dip down as wind speed increases to 20 m/s, and finally increase again towards cut-out. The rather clean lower bounds on these distributions make physical sense: a baseline oscillation of blade flap moment is expected due to mean wind shear, while cyclical gravity loadings establish a baseline for the edgewise moment.
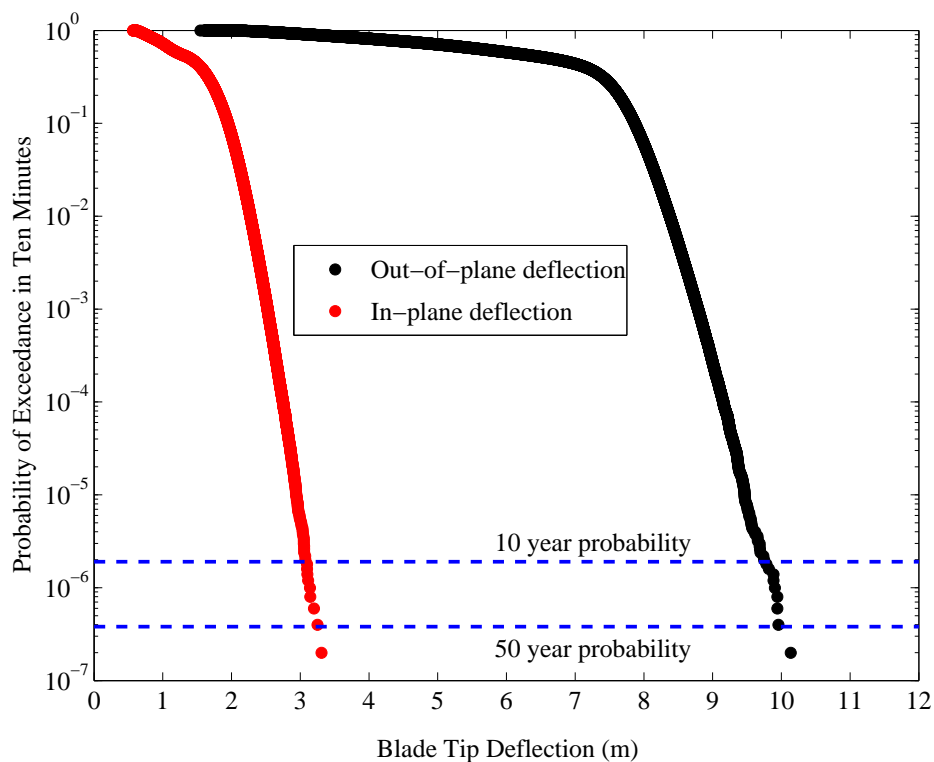
Figure 1. Probability of exceedance for blade tip deflections, derived from 96 years of simulation.
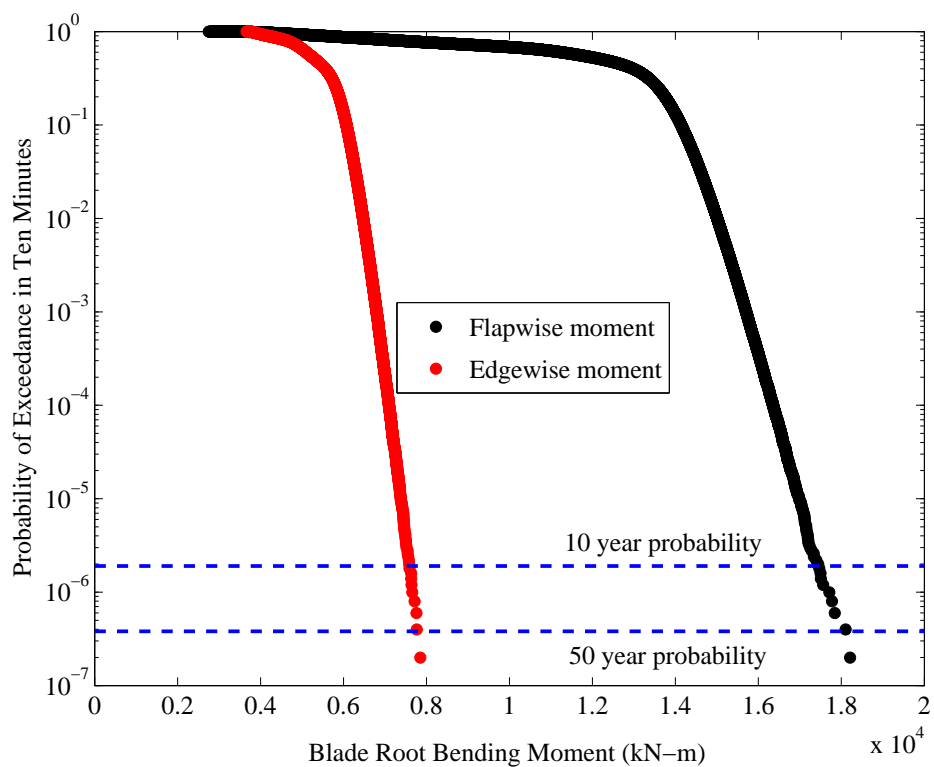

Figure 2. Probability of exceedance for blade root bending moments, derived from 96 years of simulation.

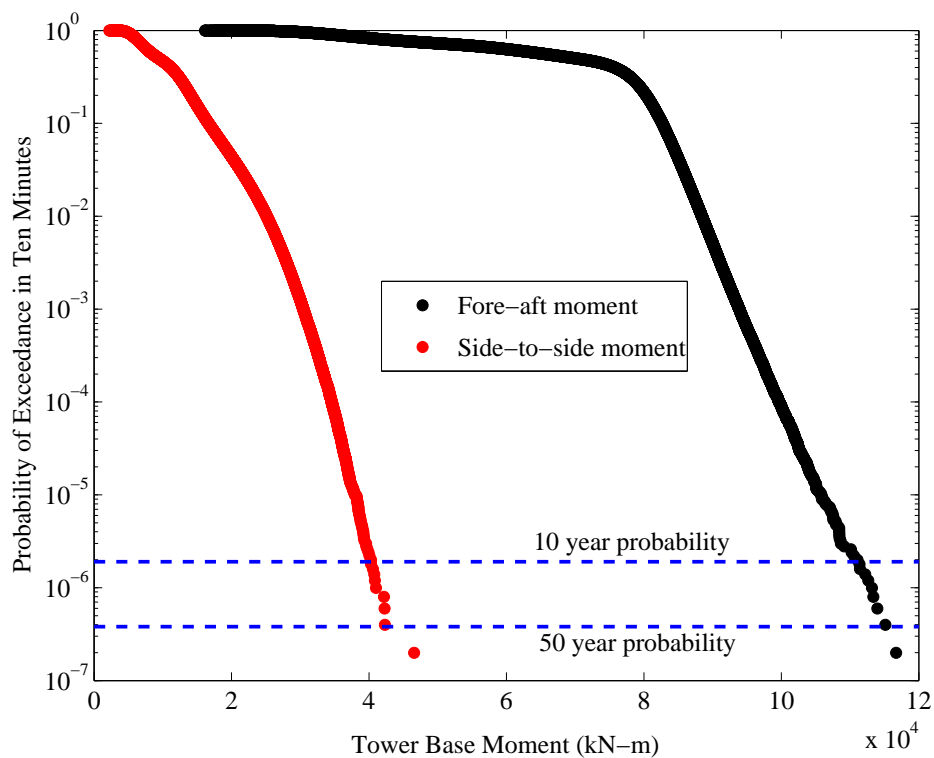American Institute of Aeronautics and Astronautics

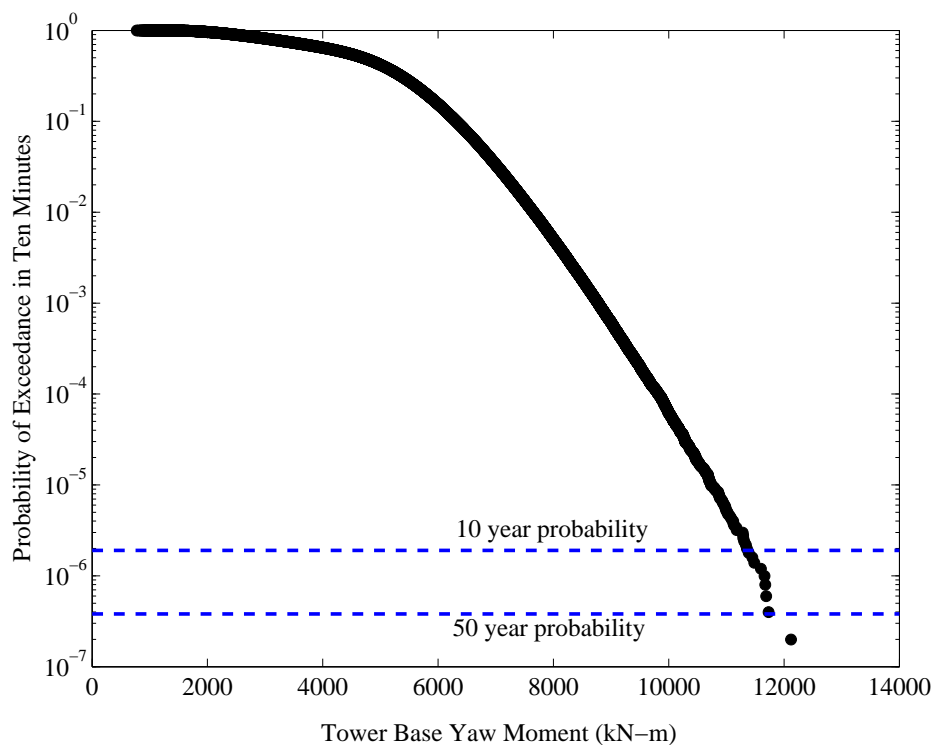**Figure 3. Probability of exceedance for tower base bending moments, derived from 96 years of simulation.**

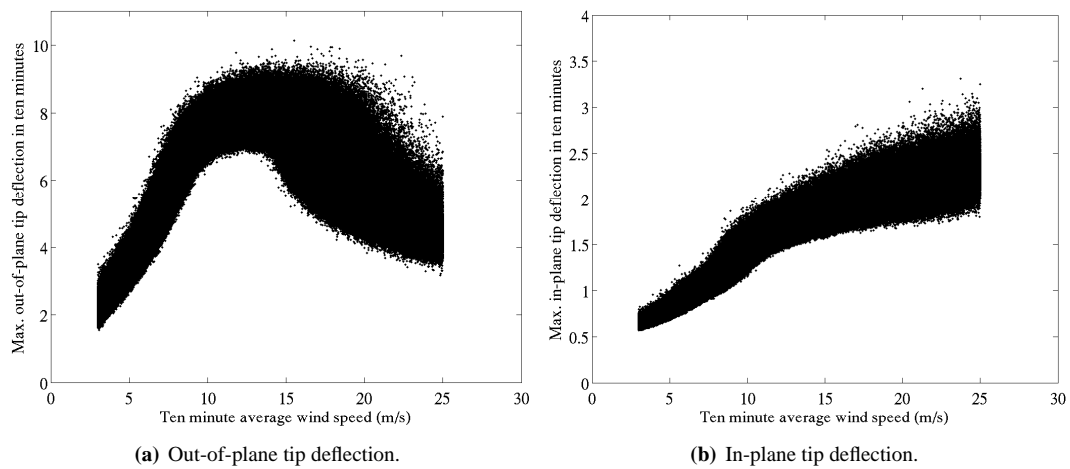**Figure 4. Probability of exceedance for tower yaw moments, derived from 96 years of simulation.**

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(a) Out-of-plane tip deflection.

(b) In-plane tip deflection.

Figure 5. Maximum tip deflection versus mean wind speed, derived from 96 years of simulation.

(a) Flap-wise blade root bending moment.

(b) Edge-wise blade root bending moment.
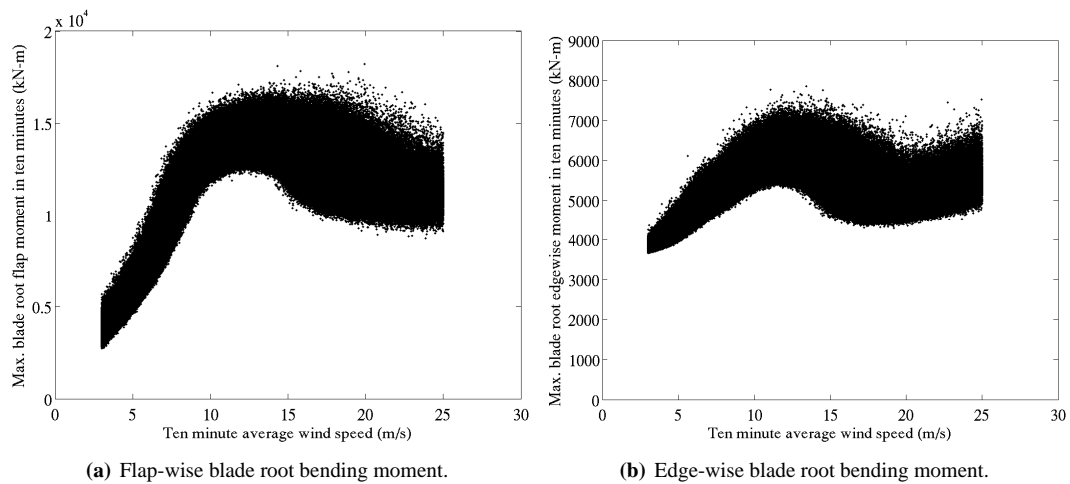
Figure 6. Maximum blade bending moments versus mean wind speed, derived from 96 years of simulation.

(a) Tower base fore-aft moment.

(b) Tower base yaw moment.
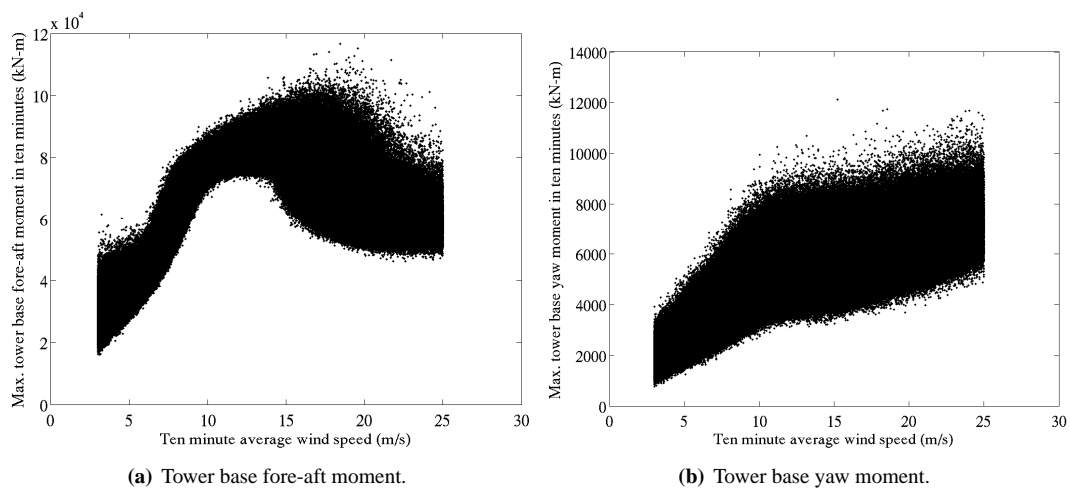
Figure 7. Maximum tower moments versus mean wind speed, derived from 96 years of simulation.

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The tower fore-aft and yaw moment extremes are plotted versus mean wind speed in Figure 7. The fore-aft moment distribution is relatively narrow up to the rated wind speed, then widens substantially beyond 15 m/s with the largest extremes occurring between 15 and 22 m/s. The tower yaw moment increases more or less monotonicaly with mean wind speed, increasing less rapidly above the rated wind speed. The largest extremes occur between 15 and 20 m/s although significant extremes occur near the cut-out wind speed as well.

V.   Extreme Load Cases

The random seed and mean wind speed used to generate the turbulent wind field were saved for each simulation, allowing any particularly interesting simulations to be reproduced later and studied in detail, if desired. The largest extreme load cases were re-run for several loads of interest in order to gain insight into the relationship between the incident wind field and resulting extreme loads.

Figure 8 shows time histories for the simulation that led to the maximum out-of-plane blade tip deflection. The mean hub height wind speed for this simulation was 15.51 m/s. The wind speed decreases to almost 6 m/s, then ramps up to about 14 m/s over a period of about ten seconds. During this ramp up, the horizontal wind direction fluctuates around a value of approximately ten degrees. Meanwhile, prior to the ramp up in wind speed, the blade pitch angle has reduced to its minimum value due to the initial decrease in wind speed. The blade pitch is unable to respond quickly enough to avoid the large extremum in tip deflection associated with the ramp-up in wind speed. Note that time histories of hub-height wind speed and direction may only partially explain the causes of extreme loads. The spatial structure of the turbulent wind field may also play an important role and is worth examining in greater detail in the future. The details of how a wind field effectively excites wind turbine structural motions of interest are also important.

Figure 9 shows time histories for the simulation resulting in the maximum observed blade root flap moment. The mean wind speed for this case was 19.94 m/s. Similar to the maximum tip deflection case, the wind speed ramps down from above the rated wind speed to below the rated wind speed, then ramps up fairly rapidly ahead of the extreme loads, with the blade pitch system unable to respond quickly enough. In this case, the vertical wind direction changes suddenly, increasing from about -10 degrees to +2 degrees within two seconds. The blade flap moment, which had previously been oscillating at a once-per-rev frequency, jumps up to the extreme value simultaneously with the ramp in vertical wind direction.

VI.   Aerodynamic Model Uncertainty

As mentioned previously, the aero-elastic loads simulations were performed using the 'equilibrium' wake model within AeroDyn, the program that provides aerodynamic loads to FAST. The equilibrium wake model, based on blade element momentum theory, assumes that the rotor wake responds immediately to the applied blade loads, such that the wake response, induced flow from the wake, and blade loads always remain in equilibrium. The other available model within AeroDyn is the generalized dynamic wake (GDW) model.[10] The GDW model solves a set of ordinary differential equations for the induced flow from the wake. This set of equations introduces a time lag between the blade loadings and the response of the wake, resulting in a more physically realistic description of the induced flow.

Simulations were initially run with the GDW model; however, a significant portion of these simulations resulted in unstable aero-elastic responses. The instabilities occurred within a range of mean wind speeds from 8 m/s to 10.5 m/s. The GDW model within AeroDyn is hard-coded to switch to the equilibrium wake model below 8 m/s, due to known problems with instabilities at low wind speeds.

As a second alternative, the ECN wake model[11] was implemented within AeroDyn. This model, also based on a solution to an ordinary differential equation, is significantly simpler than the GDW model but accounts for wake time lag effects. The ECN model also produced instabilities, although considerably fewer runs went unstable for the ECN model than for the GDW model. Figure 10 compares the maximum tip deflection versus wind speed for the equilibrium and ECN wake models. Several unstable results using the ECN model that resulted in a high-amplitude, unphysical limit cycle are visible, while several additional simulations went completely unstable and "blew up." While the obvious unstable results may be filtered out from the data set, it becomes difficult to differentiate unphysical instabilities and real, large-amplitude extreme events. For this reason, the equilibrium wake model was used to generate the loads database. Figure 10 indicates that the equilibrium model provides a conservative estimate of tip deflections relative to a dynamic wake model. Future work should focus on improvement of the stability of dynamic wake models to enable their use in the context of massive numbers of loads simulations.

VII.   Summary

This paper has described the use of high-performance computing resources to simulate wind turbine loads over multiple turbine lifetimes. This capability allows for direct estimation of extreme loads, generation of databases for direct testing of load extrapolation techniques, and identification of important loading mechanisms present in stochastic wind fields. We anticipate that large-scale load simulations using high-performance computing can play an integral role in developing future wind turbine design standards. A key challenge to the approach, identified in the present study, is the robustness of dynamic wake aerodynamic models over a large range of inflow conditions. Dynamic wake effects have important impacts on wind turbine loads, and it is desirable to incorporate these effects into comprehensive loads studies.

There are potentially many other ways that high-performance computing can impact the study of wind turbine loads. Other input parameters, such as turbulence intensity and mean wind shear, can be treated as uncertain or random, following assumed probability distributions. The simulations can also be used to characterize concurrent loads; for example, it is useful to define the probability of achieving a certain edge-wise blade bending moment when the flap-wise bending moment concurrently exceeds some threshold. Fatigue calculations using a massive loads database would allow for testing of assumptions made during a wind turbine fatigue analysis. Finally, high-performance computing resources are anticipated to be even more valuable when considering the more complicated case of an offshore wind turbine, where combined wind and wave loadings must be considered.

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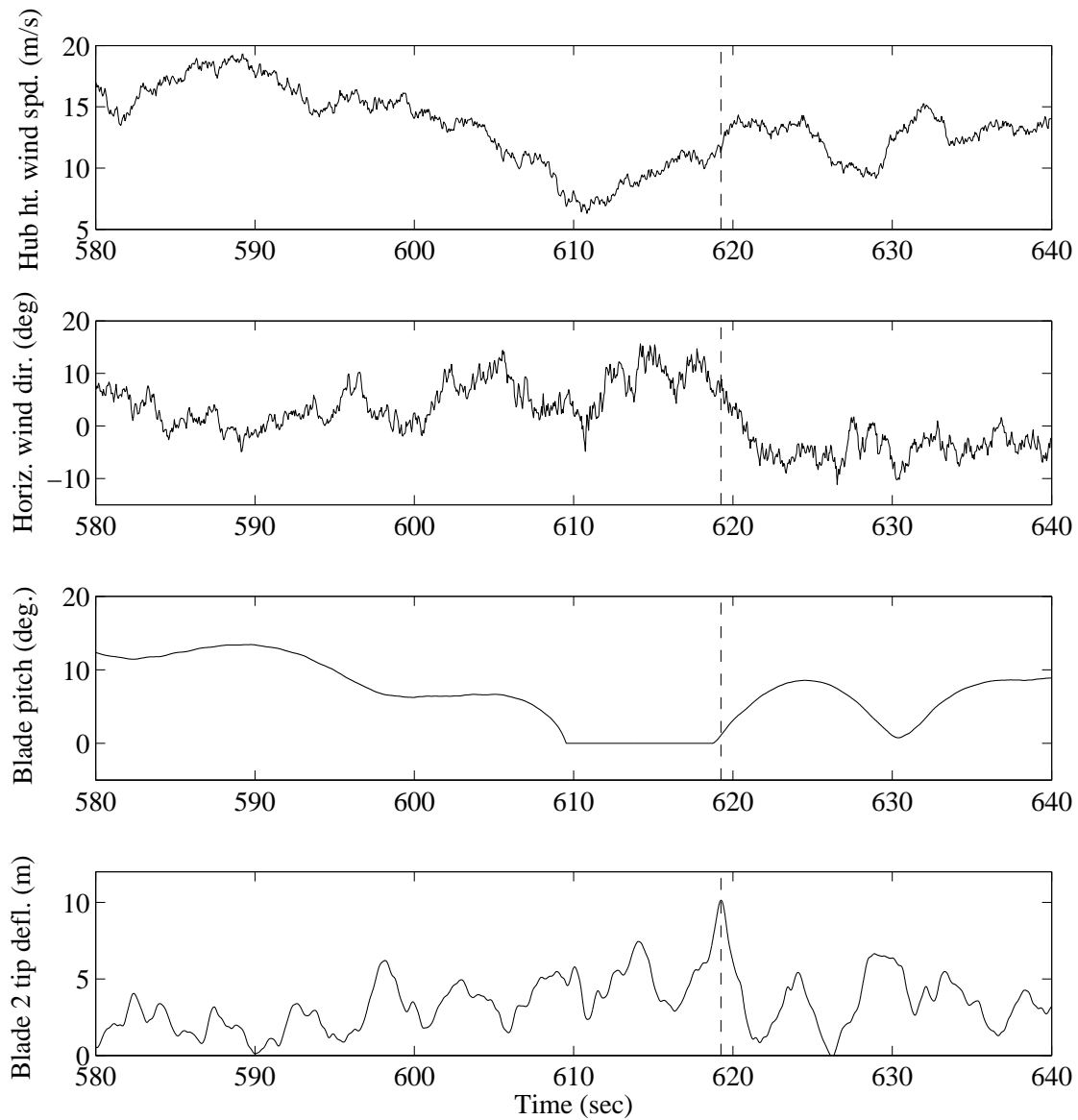
Figure 8. Time history of hub height longitudinal wind speed, hub height wind direction in the horizontal plane, and blade 2 out-of-plane tip deflection. Simulation 403,729 (maximum out-of-plane tip deflection).

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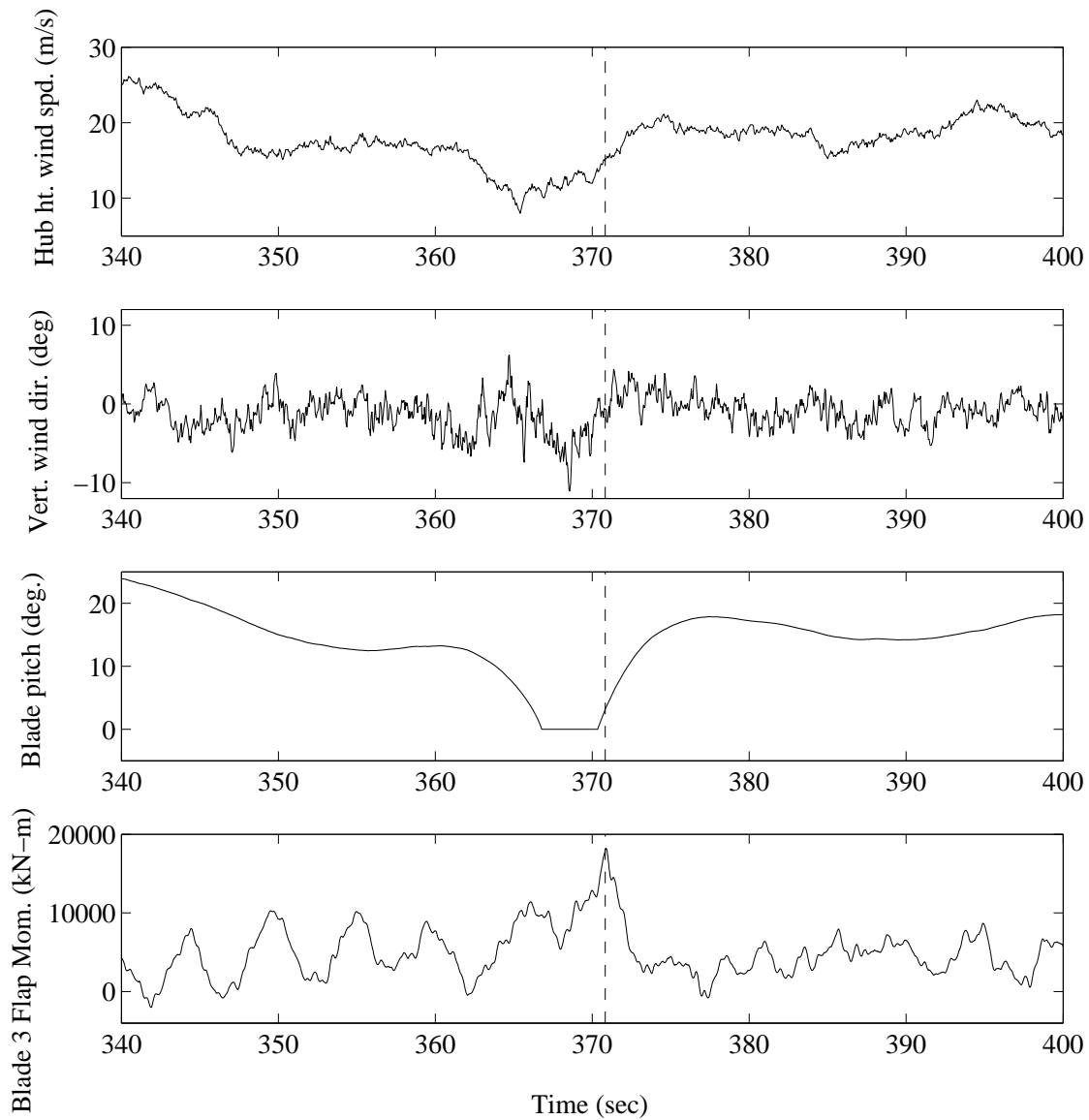
Figure 9. **Time history of hub height longitudinal wind speed, hub height wind direction in the vertical plane, blade pitch angle, and blade 3 root flap moment. Simulation 1,662,822 (maximum blade root flap moment).**

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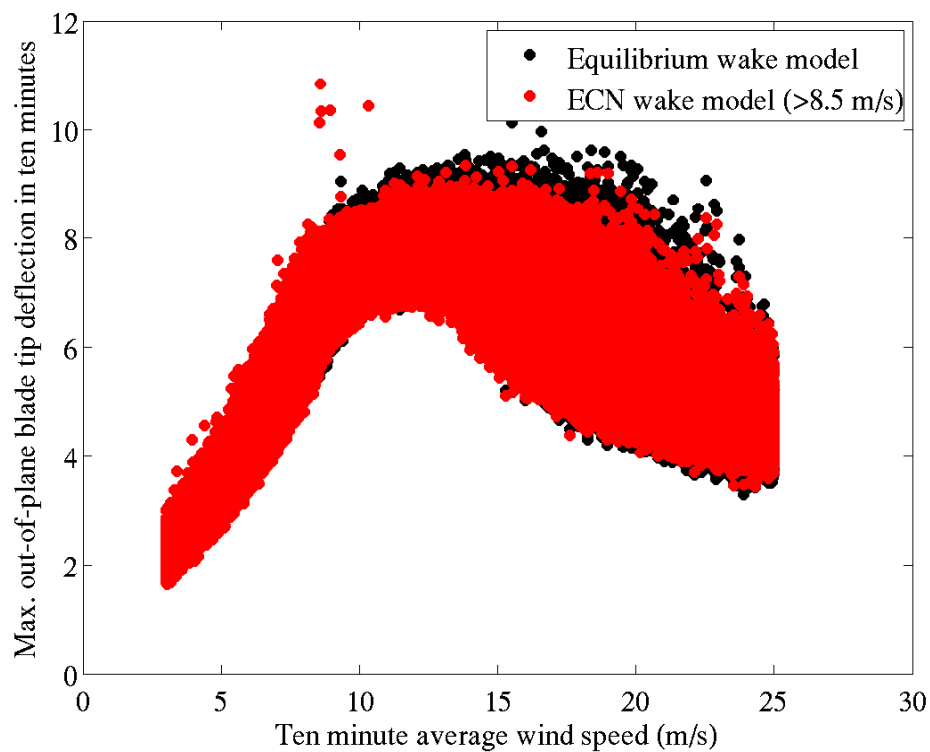
Figure 10. Comparison of extreme values for out-of-plane blade tip deflection predicted by the equilibrium and ECN wake models, derived from 16 years of simulation.

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