SAND2011-3780C

Decades of Wind Turbine Load Simulation

Abstract for the 31st ASME Wind Energy Symposium

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1 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 deflection to 50-year return values.

Uncertainties in the design load assessment are present due to (among other factors) lack of information about infrequent loads. This uncertainty requires the use of load safety factors for extrapolation of extreme loads and for fatigue analysis. These 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.

*Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

High-performance computing (HPC) clusters 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 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 wind turbine design process.

2 Simulation Setup

Two wind turbine aero-elastic models are used in the present work: the onshore version of the 5 MW NREL reference turbine,[3] and the WindPACT 1.5 MW baseline turbine.[4] Preliminary results are presented for the 5 MW turbine, while the final paper will include results for both models, allowing examination of the effects of turbine scale on load distributions. 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 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, but may introduce innaccuracies in dynamic loads. The effect of this inflow model will be explored in future studies. 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] The corresponds to an average wind speed of 8.5 m/s. A Rayleigh mean wind speed distribution is specified, from which the mean 10 minute wind speed is sampled for each distribution. The turbulence intensity is specified deterministically as a function of mean wind speed according to the IEC normal turbulence model.[1] Two random seeds are specified for generating the turbulent wind field. These random seeds are both sampled from a uniform distribution bounded 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 15x15 square grid with width of 137 meters.

The DAKOTA software framework[8] was used for management of random sampling and simulation execution. 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 loads associated with certain extreme loads. 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 probability of exceedance (also called the complementary cumulative distribution function). 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.

3 Computing Hardware Environment

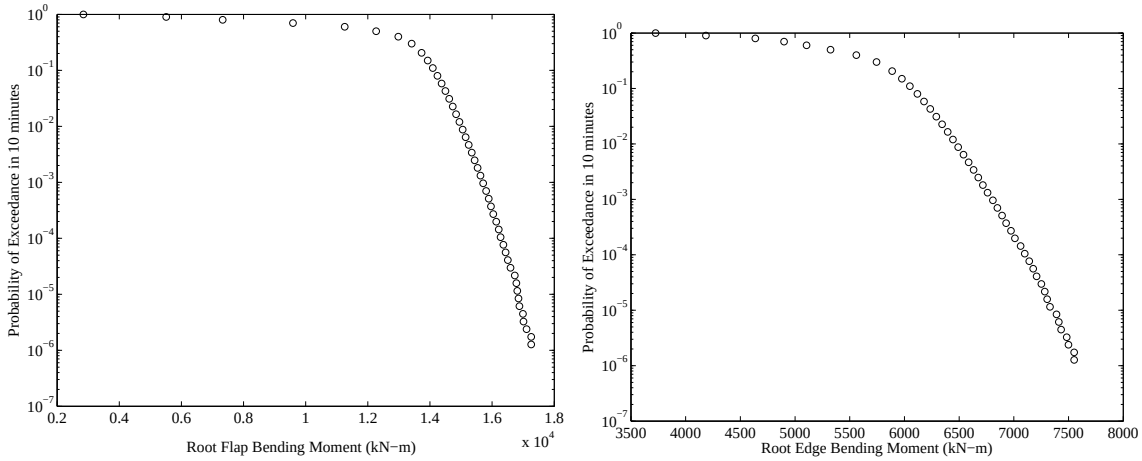
The aero-elastic simulations are run on the Sandia Red Sky computing cluster, a 264 Teraflop Linux computing cluster. Red Sky has 2823 nodes, each with 8 CPU cores, giving a total of 22,584 available cores. The present results were obtained using 1024 cores. This allows for simulation of 10 years of turbine operation in approximately 20 wall-clock hours. Use of a greater fraction of the cluster would result in faster simulation times. However, execution time must be balanced by queue wait time for jobs requesting a relatively large number of cores. The 1024 core job size was found to allow for fast job throughput on Red Sky.

4 Preliminary Results

Preliminary results are available for 20 years of simulation of the 5 MW wind turbine. A total of 1,131,440 simulations were executed. For the final paper this total will be increased to cover 100 years of turbine operation; this will allow for estimation, with great confidence, of the 50-year return load and quantification of confidence levels in the load estimates. Figures 1 and 2 show the probability of exceedance of blade root moments and tip deflections, respectively. The probabilities are available down to a level of approximately 10^{-6}, which corresponds to one ten minute period in 20 years. Distributions are in general well-behaved, with some expected waviness due to sampling error at the lowest probability levels. The out-of-plane blade tip deflection (Figure 2(a)) exhibits some leveling out of the probability for the largest deflections. This would indicate that there is some physical (or modeling) limitation on maximum tip deflection, and that extrapolation of the deflection to lower probabilities may be over-conservative. It will be interesting to determine if this trend is maintained with further simulation. Results are also available for tower and drive train loads, and will be presented in the final paper.

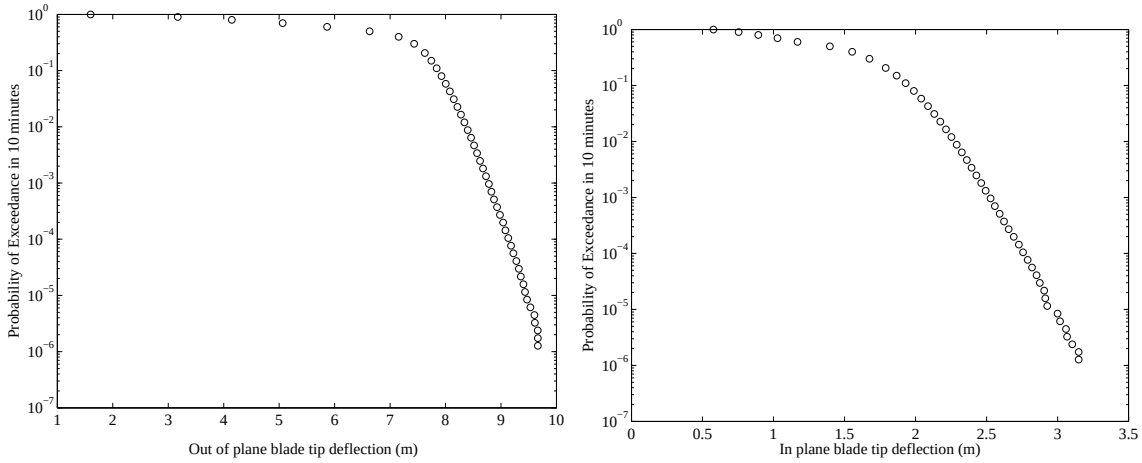
The following will also be included in the final paper:

- The full distributions, based on 100 years of wind simulations, for all loads investigated will be presented and discussed.
- Time histories of extreme load cases will be presented and interpreted.
- The sensitivity of blade root fatigue damage to statistical assumptions will be examined.



(a) Blade root flap moment (b) Blade edge moment

Figure 1: Probability of exceedance of blade loads.



(a) Blade out-of-plane tip deflection (b) Blade in-plane tip deflection

Figure 2: Probability of exceedance of blade tip deflections.

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