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Simulation-Length Requirements in the Loads Analysis of Offshore Floating Wind Turbines

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SIMULATION-LENGTH REQUIREMENTS IN THE LOADS ANALYSIS OF OFFSHORE FLOATING WIND TURBINES

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ABSTRACT

The design standard typically used for offshore wind system development, the International Electrotechnical Commission (IEC) 61400-3 fixed-bottom offshore design standard, explicitly states that "the design requirements specified in this standard are not necessarily sufficient to ensure the engineering integrity of floating offshore wind turbines" [1]. One major concern is the prescribed simulation length time of 10 minutes for a loads-analysis procedure, which is also typically used for land-based turbines. Because floating platforms have lower natural frequencies, which lead to fewer load cycles over a given period of time, and ocean waves have lower characteristic frequencies than wind turbulence, the 10-min simulation length recommended by the current standards for land-based and offshore turbines may be too short for combined wind and wave loading of floating offshore wind turbines (FOWTs). Therefore, the goal of this paper is to examine the appropriate length of a FOWT simulation—a fundamental question that needs to be answered to develop design requirements.

To examine this issue, we performed a loads analysis of an example FOWT with varying simulation lengths, using FAST, the National Renewable Energy Laboratory's (NREL's) nonlinear aero-hydro-servo-elastic simulation tool. The offshore wind system used was the OC3-Hywind spar buoy, which was developed for use in the International Energy Agency (IEA) Offshore Code Comparison Collaborative (OC3) project, and supports NREL's offshore 5-MW baseline turbine. Realistic metocean data from the National Oceanic and Atmospheric Administration (NOAA) and repeated periodic wind files were used to excite the structure. The results of the analysis clearly show that loads do not increase for longer simulations. In regard to fatigue, a sensitivity analysis shows that the procedure used for counting half cycles is more important than the simulation length itself. Based on these results, neither the simulation length nor the periodic wind files affect response statistics and loads for FOWTs (at least for the spar studied here); a result in contrast to the offshore oil and gas (O&G) industry, where running simulations of at least 3 hours in length is common practice.

1. INTRODUCTION

To ensure the structural integrity and stability of a wind turbine system, standards and guidelines prescribe a loads-analysis procedure that uses system-dynamics models to determine the extreme and fatigue loads expected over the system's lifetime. IEC offers two standards for that process—one for land-based wind turbines [2] and one for fixed-bottom offshore wind turbines [1]. Both assume that the structures supporting the rotor-nacelle assembly are fixed to the ground (or sea floor). Those standards explicitly state that the current design requirements may not be sufficient for FOWTs, due to the lower natural frequencies of FOWTs, which lead to fewer load cycles over a given period of time, and the lower characteristic frequencies of ocean waves compared to wind turbulence. Therefore, the loads subgroup (Group 2) of the IEC Working Group (WG) 3-2, tasked with developing FOWT design requirements, has proposed a research project aimed at developing a loads-analysis procedure sufficient to ensure the engineering integrity of FOWTs.

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The work summarized in this paper outlines the first part of this overall project to modify existing design-load cases (DLCs) and/or develop entirely new DLCs for FOWTs. The project goals are to evaluate two principle questions: what is the required simulation length, and what is the method for incorporating metocean conditions from an offshore site in the loads-analysis process of a FOWT. In this paper, we address the first of these issues—the required length of FOWT simulations. To answer this question, we performed two separate studies to examine the dependence on simulation length of loads due to aerodynamics and loads due to hydrodynamics/floating platform motions.

For the simulations presented in this paper, we used the OC3-Hywind spar buoy [4], which was developed for use in the International Energy Agency (IEA) Offshore Code Comparison Collaborative (OC3) project, and supports NREL's offshore 5-MW baseline turbine [3]. [4]. Realistic metocean conditions were generated by analyzing National Oceanic and Atmospheric Administration (NOAA) buoy data, concatenated into a representative U.S. East Coast site. The expected significant wave height and peak-spectral period, dependent on the wind speed, were used. Turbulent wind speed data were produced using TurbSim [9], which is able to generate periodic random turbulent wind fields that can be repeated to generate wind files of longer length.

To investigate the dependence of aerodynamically derived loads on simulation length, we compared loads statistics from 10x1-hour, 12x50-min, 15x40-min, 20x30-min, 30x20-min, and 60x10-min FAST [5] simulations. A land-based turbine was used for this study to ensure a comparison based on only aerodynamic loads. To investigate the dependence on simulation length of loads due to hydrodynamics and floating platform motion, we evaluated loads statistics from simulations with a length of 10 minutes, 20 minutes, 1 hour, 3 hours, and 6 hours, with the numbers of independent wave and wind seeds chosen to yield the same amount of random information in each group of simulations.

After these two studies were performed, we investigated the minimum requirements for a statistically significant ultimate load calculation. So far, the standard recommends "in general, at least six 10-min stochastic realizations" [1, 2], but it is well known that this minimum number is not always sufficient.

2. LOADS-ANALYSIS APPROACH

To examine the influence of simulation length on the resulting loads observed in a FOWT, we conducted a series of load analyses, each with varying simulation length. The overall procedure for these load analyses consisted of the following eight steps:

1. Identify a suitable FOWT to analyze: This paper used the platform model that can most accurately be modeled in the present version of FAST, the OC3-Hywind spar buoy with the NREL 5-MW turbine. This model was identified as the most suitable because second-order hydrodynamics, which have not yet been incorporated into FAST at the start of the project, have been shown to have little influence on the OC3-Hywind system behavior during normal operation (whereas second-order hydrodynamics are more important in semisubmersibles and tension-leg platforms) [17].

2. Identify load-case simulations that address the simulation-length questions best: In this study, we focused on the gap of knowledge regarding operational loads. A comparison to loads from extreme wind and waves under parked/idling conditions will be made in the future.

3. Adapt the nonlinear aero-hydro-servo-elastic tool (FAST), the script to run the simulations, and the needed post-processing scripts to perform the loads-analysis process. Modifications were needed because simulations of more than 3 hours have not been performed with these tools and scripts before.

4. Perform an initial analysis to examine the needed wind grid size and initial conditions to minimize transient start-up time.

5. Identify metocean data to use: We used NOAA data buoys to define joint probability distributions of the parameters: mean wind speed at hub height, wind-wave misalignment angle, significant wave height, and wave peak-spectral period. Three ocean sites representative of the U.S. East Coast, Gulf of Mexico, and West Coast were developed to ensure realistic conditions for the simulations—but only the U.S. East Coast site was used in this project so far.

6. Using a full-system dynamics model in FAST, run a series of load simulations in groups with increasing simulation length and calculate the ultimate loads and fatigue loads expected over the lifetime of the wind turbine system based on these simulations.

7. Compare the load results from the different simulation groups (with increasing length) to the 10-min simulations (standard), and identify any differences in the ultimate loads and/or fatigue loads: The influence of simulation length on both aerodynamically derived loads and loads due to hydrodynamics and floating platform motions was determined.

8. Investigate the number of independent simulations (random seeds) required for convergence of the ultimate load statistics, a topic intrinsically related to the simulation length.

The paper is organized as follows. The floating platform model (Step 1) and simulation tools (Steps 3) are described in Section 3. Section 4 presents the DLCs (Step 2), initial analyses performed (Step 4), and metocean data used in this project (Step 5). The results of Steps 6, 7, and 8 are presented in Section 5.

3. SIMULATION TOOLS AND MODELS

This section describes the simulation tools and floating wind turbine model used.

3.1 Simulation Tool Capabilities

This work utilized the models and simulation tools developed by NREL. The time-marching simulations were performed with FAST [5], which is coupled with the rotor aerodynamics module, AeroDyn [6], and the platform hydrodynamics module, HydroDyn [7, 8]. TurbSim [9] was used to generate the random full-field turbulent wind fields. We used a modified version of the NREL internal perl-script RunIEC to submit the required simulations to the NREL's Windows-based high-performance computing server cluster (HPC) with 240 cores and 2 GB of RAM per core. The outputs from the aero-elastic simulations in FAST were analyzed with the post-processing tools MExtremes [10] for the ultimate loads and MLife [11] for the fatigue loads. We used MLife to calculate the fatigue damage and the fatigue damage-equivalent loads (DELs) over the lifetime of the turbine. Binary FAST output files were used as a necessity for simulations longer than 1 hour.

3.2 Floating Wind Turbine Model

In this study, we used the NREL offshore 5-MW reference wind turbine, a "representative utility-scale, multimegawatt turbine" [3] for offshore system development. Equipped with variable-speed and collective-pitch control, the machine is rated at 5 MW at a wind speed of 11.4 m/s. The turbine has a hub height of 90 m and a rotor diameter of 126 m, and is supported by the OC3-Hywind spar-buoy floating platform in this study. The platform model is based on the spar-buoy concept "Hywind," developed in Norway by StatoilHydro (now called "Statoil ASA"). Compared to the Hywind concept, the OC3-Hywind spar buoy is suitable for public research activity and is able to support the NREL 5-MW turbine. The OC3 Hywind platform model has been selected as the initial platform for this project because it can be accurately modeled with the existing capabilities of FAST. Thus, the focus can be on the simulation-length question and not on simulation inaccuracy.

4. ANALYSIS SPECIFICATIONS

In this section, we describe the details of the simulations that were performed.

4.1 Initial Analysis

It is important to minimize the effects of the initial simulation transients on the resulting load statistics. The IEC standards recommend that "the first 5 s (or longer if necessary) shall be eliminated" to reduce the impact of initial transients [1, 2]. With the long natural periods of the support structure, simulations may need more than 10 minutes for start-up transients to damp out. We conducted simulations to determine initial conditions (ICs) that minimized the transients and allowed for shorter simulation times. Our analyses determined that the initial simulation time impacted by transients, which should be ignored, is at least 60 seconds when proper ICs are used for rotor speed, blade pitch, out-of-plane blade deflection, and platform surge, pitch and heave displacements. Furthermore, the proper ICs must be chosen specifically for the given wind and wave conditions.

4.2 Periodic Wind Files

To examine the required simulation length for a FOWT, long simulations are required, with a maximum length of 6 hours. Due to the size of the NREL 5-MW turbine and expected range of motion when installed on a floating platform, full-field turbulent wind files of sufficient size and resolution require large amounts of memory to generate and store. A single 10-min wind file of appropriate size and resolution requires about 155 MB of storage space, whereas a 6-hour wind file would require about 5.6 GB. The entire wind file must be stored in memory upon execution of a FAST simulation, and so wind files larger than 1 hour are not feasible on most computers (a 32-bit Windows operating system has a 2-GB limit on RAM). Our solution was to use repeated periodic wind files for simulations longer than 10 minutes. Using periodic wind files also ensures that the total length of stochastic wind is the same for the varying length simulations (see Section 4.3). TurbSim was modified to output a periodic wind file, comprised of repeated shorter wind files. For example, a 1-hour simulation can be run successfully by repeating six identical 10-min wind files. Due to the inverse FFT method used in TurbSim, the resulting time series is periodic with a period equal to the length of the wind file. The periodicity means that there are no discontinuities in concatenating wind files together, as shown in Figure 1.

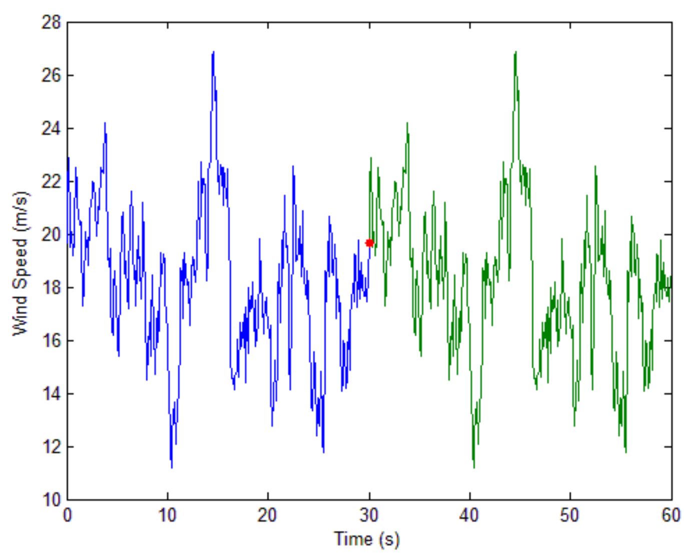

Figure 1. Two repeated periodic time histories of a 30-s wind realization.

We calculated a grid height of 179.26 m and a grid width of 248.26 m for our simulations, based on the rotor diameter of the turbine and the maximum expected value of the platform motions in the surge and heave directions (estimated from a set of trial simulations), as well as an additional safety factor of 15%. We used the maximum surge value instead of the maximum sway value, because it was larger than the maximum sway values in all initial simulations. With the use of a periodic 10-min turbulent wind file, a grid discretization of 40x55 grid points with a spacing of 4.6 m (roughly equivalent to the average blade chord) in the vertical and horizontal directions was realized.

4.3 Reference Metocean Data

We created a database of realistic metocean input conditions for use in this and future studies concerning the design standards for FOWTs, using data from the NOAA floating data buoys. As upcoming studies with this metocean dataset will investigate the effect of wind and wave misalignment, buoy data with wind and wave directionality was needed, which limited the number of available sites. Data from sites on the East and West coasts of the United States and the Gulf of Mexico were downloaded from the NOAA website (http://www.ndbc.noaa.gov/) and were post-processed to remove measurement errors in the data. Figure 2 shows the geographical distribution, mean wind speeds, and mean significant wave heights of the sites.

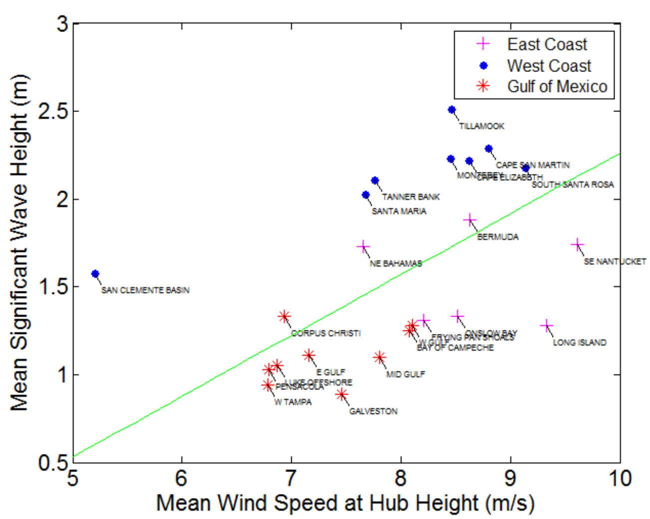

Figure 2. Geographical distribution of mean wind speeds and wave heights.

Using the data from these sites, we created conditional probability functions for four variables: wind speed, significant wave height, wave peak-spectral period, and wind/wave misalignment angle. Wind speed is treated as independent, and an unconditioned 2-parameter Weibull distribution was used. Wind/wave misalignment angle is conditioned on wind speed alone, significant wave height is conditioned on wind speed and misalignment angle, and peak-spectral period is conditioned on wind speed and significant wave height. The peak-spectral period and significant wave height are defined by 2-parameter gamma distributions, and a Von-Mises distribution (also known as a circular normal distribution) is used for wind/wave misalignment. These analytical distributions were chosen based on their ability to fit the empirical measured data.

The sites were divided into groups based on geographical region, and the conditional probability distributions from each site within the regions were averaged to create three representative sites. The results presented in this paper used data from the averaged East Coast site, and the simulations used the expected value of significant wave height and median peak-spectral period for each mean wind speed for zero degree wind/wave misalignment, as shown in Table 1.

Table 1. Expected wave parameter values for the U.S. East Coast site.

Mean Wind Speed (m/s)	Significant Wave Height (m)	Peak Spectral Period (s)
4	1.102	8.515
6	1.179	8.310
8	1.316	8.006
10	1.537	7.651
12	1.836	7.441
14	2.188	7.461
16	2.598	7.643
18	3.061	8.047
20	3.617	8.521
22	4.027	8.987
24	4.516	9.452

4.4 Load Cases and Simulations

Our research focus in this study was on DLCs 1.1 and 1.2 from the IEC 61400-3 offshore wind turbine design standard. If the loads of a floating wind turbine system are dictated by extreme wind and waves when the turbine is parked/idling (non-operating), then existing standards may be applicable. But it is unclear upfront whether the loads on a given FOWT are dictated by operational or parked/idling conditions. This study focused on the gap of knowledge regarding operational loads.

In our first study, to investigate the dependence of aerodynamically derived loads on simulation length, we ran simulations with increasing length using the land-based system of the 5-MW baseline turbine, to eliminate the effects of hydrodynamics and platform motion. For three mean wind speeds: 8 m/s, 11.4 m/s (rated), and 18 m/s, we ran 10 separate 1-hour, 12 50-min, 15 40-min, 20 30-min, 30 20-min, and 60 10-min simulations, so that the same total amount (10 hours) of random information existed in each group of simulations. Each separate simulation was run with a different wind file, each with a unique random seed. Periodic wind files were not used for these simulations because a smaller wind grid (150 m x 150 m grid with 13x13 grid resolution) could be used for the land-based version, which has less motion than with the floating system, and because a more coarse resolution was deemed sufficient for the purposes of this study.

In our second study, to investigate the dependence on simulation length of loads due to hydrodynamics and floating platform motion, we ran DLC 1.1 with five different simulation lengths: 6 hours, 3 hours, 1 hour, 20 minutes, and 10 minutes using the generalized reference metocean data from the U.S. East Coast from Section 4.3. Table 2 summarizes the applied simulation conditions. The FAST simulations for DLC 1.1 were run at mean wind speeds of 3 m/s to 25 m/s in steps of 2 m/s each (11 wind-speed bins total, using the midpoint of each bin) with the expected significant wave height and median peak-spectral wave period conditioned on the mean wind speed, as shown in Table 1 (i.e., neglecting the range of significant wave height and peak-spectral wave period values for a given wind speed). DLCs 1.1 and 1.2 were represented by the same wind conditions, wave conditions, and simulation times. In the current IEC standard for offshore wind turbines, six wind seeds are recommended. We decided to use 10 wind seeds per wind bin to assess the convergence of the loads, as discussed in Section 5.3. In this second study, all simulations were run with 10-min periodic wind files using the normal turbulence wind model (NTM). Overall, we generated 100 minutes of unique stochastic wind data length for each of the 11 wind-speed bins regardless of the simulation group. For the simulation length of 6 hours, we used 10 wave seeds with a normal sea-state model (NSS) for each wind bin. We increased the number of wave seeds per wind-speed bin for the shorter simulation groups to ensure that each simulation group has the same length of total unique wave data of 60 hours. Consequently, in each simulation group, a total of 110 (6-hour), 220 (3-hour), 660 (1-hour), 1980 (20-min), and 3960 (10-min) simulations were run, for a total of 6930 simulations.

For the ultimate load analysis, extreme-event tables were generated for each simulation length group using all simulations within the group. Only ratios of the ultimate and fatigue loads are presented in this work. Therefore, no extrapolation or safety factor is necessary for comparison.

For the calculation of the fatigue loads, we used the IEC standard as a guide. Although the IEC standard [2] demands that for DLC 1.2 the full long-term joint-probability distribution of wind speed, significant wave height, and peak-spectral wave period should be applied, we used the already completed simulations from DLC 1.1, and changed the post-processing. The fatigue analysis used in this study follows a process that is explained in more detail in [11] and [12]. The rainflow-cycle counting algorithm uses a binning of the cycle ranges and means of each load time series. The number of bins is computed based on the maximum load-range cycle of each channel. All load-range cycles with a varying mean load are transformed to a load-range at zero mean with the use of a Goodman correction (requiring an ultimate load derived from an ultimate load factor (the ULF) and load extremes from the simulation results). Three different S/N-curves were used to represent the range of assumed Whöler exponents. To ensure a comparison of the rainflow cycles only, we used the ultimate loads from the 10-min simulation group for all fatigue load calculations. The lifetime damage and DELs are extrapolated to a 20-year design lifetime and weighted with a Rayleigh probability distribution based on a mean wind speed of 10 m/s. Matha showed in [12] that the DELs don't change significantly for ULFs of 5 or greater; instead, they asymptotically approach a constant value with increasing ULF up to 20. Therefore, we chose a ULF of 20.

Table 2. Simulation conditions for the simulation-length study due to hydrodynamics and floating system dynamics.

	DLC		1.1 and 1.2				
	Simulation Groups	(-)	6-hours	3-hours	1-hour	20-min	10-min
Wind Conditions	Number of Wind Seeds per Wind Bin	(#/WndBin)	10				
	Wind Model	(-)	NTM / Grid size 40x55 (HxW: 179.26m x 248.26m) / B (I_{ref} = 0.14)				
	Mean Wind Speed	(m/s)	3 to 25, 11 wind bins				
	Unique Wind Data Length per Wind Bin	(min/WndBin)	100				
Wave Conditions	Incident Wave Kinematics Model	(-)	NSS / JONSWAP/Pierson-Moskowitz spectrum (irregular)				
	Significant Wave Height values	(m)	Generalized US East Coast (s. Table 1)				
	Peak Spectral Period values	(s)	Generalized US East Coast (s. Table 1)				
	Number of Wave Seeds per Wind Bin	(#/WndBin)	10	20	60	180	360
	Number of Wave Seeds per Wind Seed	(#/WndSeed)	1	2	6	18	36
	Unique Wave Data Length per Wind Bin	(h/WndBin)	60				
Simulation Times (for each simulation)	Analysis Time	(s)	21600	10800	3600	1200	600
	Transient Start-up Time	(s)	60				
	Total Simulation Length	(s)	21660	10860	3660	1260	660
	Total Number of Simulations	(#)	110	220	660	1980	3960
	Ultimate Load Factor for Fatigue Loads	(-)	20				

5. LOADS-ANALYSIS RESULTS

In Section 5.1, we discuss the loads-analysis results of our first study, which investigated the dependence of aerodynamically derived loads on simulation length for a land-based turbine. Section 5.2 presents the loads-analysis results from our second study, based on DLCs 1.1 and 1.2 and using the simulation specifications and analysis procedures described in the Section 4.4. Section 5.2 analyzes groups of different simulation lengths for a FOWT to investigate the dependence on simulation length of loads due to hydrodynamics and floating platform motion. Section 5.3 focuses on the minimum data requirements for mean extreme load calculations, investigating the number of simulations required for statistics to converge.

About 1 TB of data was created during this project. Due to the large amount of data, only a small subset can be presented here. A more detailed description of the project's results will be available in Ref. [15].

5.1. The Dependence of Aerodynamically Derived Loads on Simulation Length for a Land-Based Turbine

During the analysis of the ultimate loads for the FOWT simulations, there was concern that changes in the discretization of the wind turbulence spectrum that TurbSim uses were creating higher maximum wind speeds, and thus higher maximum loads, for longer simulations. This concern prompted an investigation that used a land-based turbine model to isolate loading from the wind inputs only.

TurbSim uses a spectral sampling method to create a wind time series from a target wind turbulence spectrum. In this method, the spectrum is discretized and sine waves at each discrete frequency are created with amplitudes corresponding to the power in the spectrum at that frequency and randomized phases. The number of sine waves that make up the time series corresponds to the level of discretization, which increases for longer simulations.

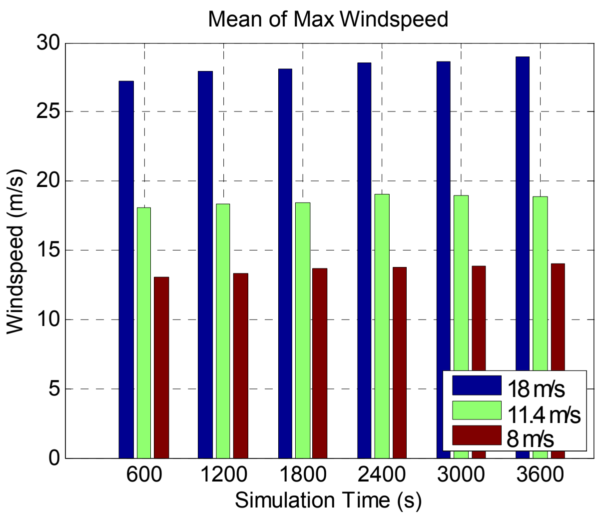

Figure 3. Mean of the maximum wind speeds from each simulation.

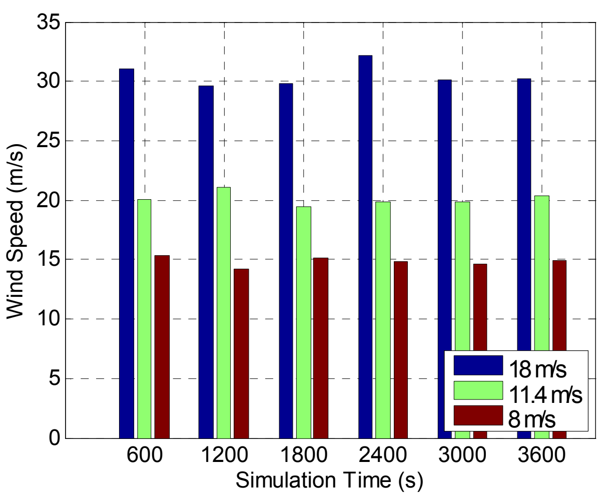

Figure 4. Absolute maximum wind speed across all simulations for each length.

Simulations using a land-based wind turbine were run for varying simulation lengths, and maximum loads and wind speeds from the simulations were found. We determined that the discrepancies that prompted the study were a result of the averaging method used to process the results, rather than any actual differences in the spectral sampling method. If maximum values that are averaged across simulations of a given length are compared to maximum values averaged across simulations from a different length, the longer simulation length will show higher maximums (see Figure 3). This indicates that average maximums from a long simulation cannot be compared to the average maximum from a short simulation. Instead, either a single maximum value from six 10-min simulations should be compared to the maximum value from one 1-hour simulation (Figure 4), for example, or the average maximum value of the six 10-min simulations should be compared to the average maximum value from breaking up the one hour into 10-min sections (Figure 5).

The turbine response and loads due to the wind followed the same trends as the wind statistics shown in Figures 4 and 5, and so these results are omitted. While these conclusions seem intuitive, it is important to consider the averaging techniques used when analyzing simulations of different lengths, and to ensure that the total length of the stochastic input is equal.

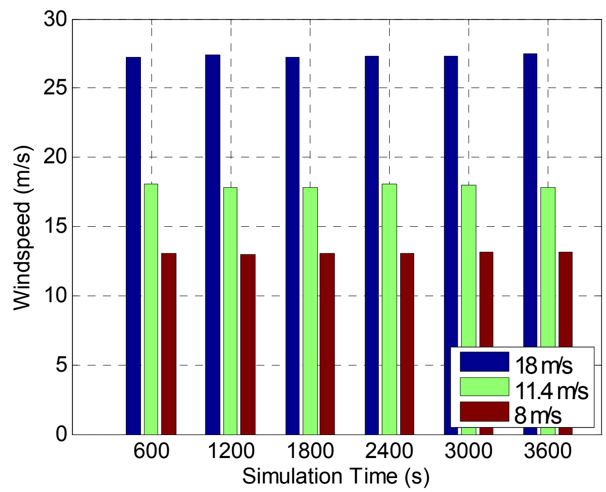

Figure 5. Mean of the maximum wind speed for simulations broken into 600-s groups.

5.2 The Dependence on Simulation Length of Loads Due to Hydrodynamics and Floating Platform Motion

In this section, the ultimate loads from the different groups of simulation lengths are presented first, followed by the fatigue-analysis results.

5.2.1 Ultimate Loads. We calculated the extreme-events statistics of the DLC 1.1 simulations for several FAST output channels. Figure 6 shows the statistics for the wave elevation and platform pitch for each simulation from the groups with simulation lengths of 6 hours (dark blue), 20 minutes (light blue), and 10 minutes (green). The differences between the 6-hour and 20-min simulations and the 10-min simulations are very small. Only in the wave elevation (upper chart) are a few simulations seen with a slightly greater value: at 22 m/s and 24 m/s, which could be due to the discretization of the wave-spectrum in FAST. For all simulations, a wave spectrum with the length of 6 hours is implemented in HydroDyn, but only the first part was used for simulations shorter than 6 hours. However, we couldn't find differences in other ultimate load channels that would correspond to these greater values; for example, as shown for the platform-pitch motion in the lower plot in Figure 6. No pitch motion from the 6-hour simulations has a significantly greater maximum value than for the 10-min simulations. Spars don't heave much due to waves, but other types of floating platform systems might be more affected by larger waves and will be considered in upcoming studies with semisubmersible and TLP support structures. For the spar, we assume that the differences in the wave elevation are too small to create further effects. The same statistics were created for other important load channels and for the other simulation lengths. The 1-hour and 3-hour simulations indicate approximately the same results, but are not shown here.

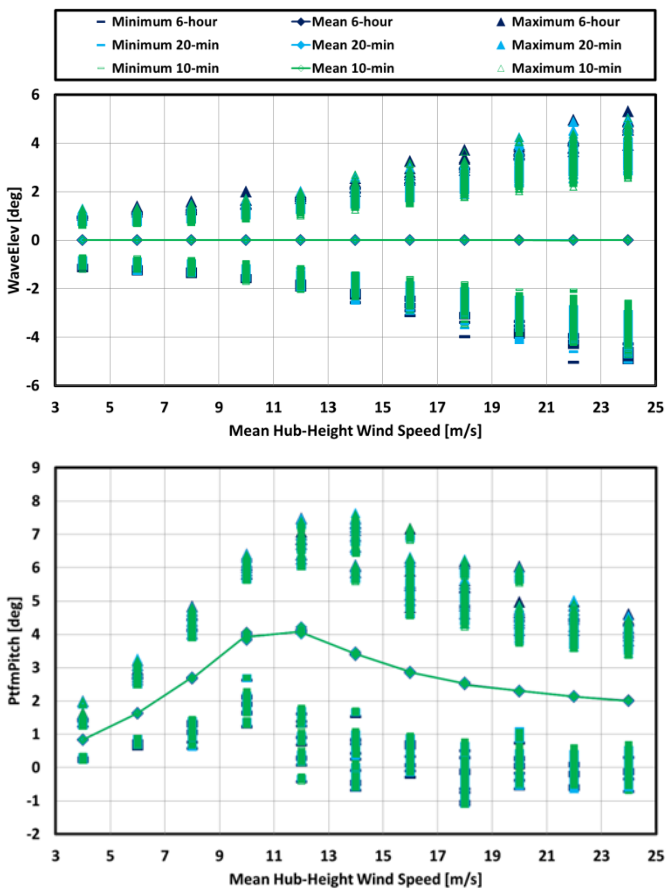

Figure 6. Minimum, mean, and maximum wave-elevation, and platform-pitch statistics from each 6-hour, 20-min, and 10-min simulation.

Similar conclusions can be drawn from Figure 7, which shows ultimate load ratios created by dividing the absolute maximum values from the extreme-event tables for the simulation lengths of 20 minutes, 1 hour, 3 hours, and 6 hours, by the corresponding extreme event from the 10-min simulations. A ratio of one represents the same maximum load between simulation lengths. A ratio greater than one indicates an increased ultimate load value. The four transverse bending moments shown in Figure 7 were calculated by taking the vector sum of the bending moments about the member's transverse axes. Figure 7 shows clearly for the transverse bending moments of the low-speed shaft at the main bearing (LSSgagMMyz), the root of blade 1 (RootMMxy1), the tower base (TwrBsMMxy), and the yaw bearing (YawBrMMxy) that longer simulation lengths are not warranted to estimate ultimate loads. When the total random time for the wind and waves is constant, the ultimate loads do not intensify with increasing simulation length.

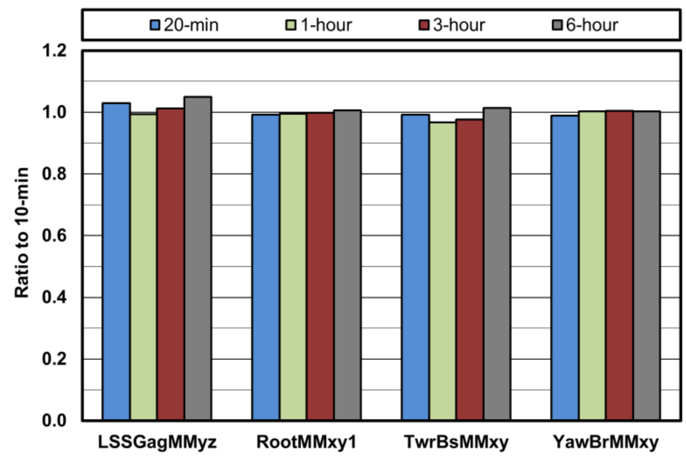

Figure 7. Ultimate-load ratios of longer simulation lengths to the simulation length of 10 minutes.

5.2.2 Fatigue Loads.

We calculated the lifetime fatigue damage and lifetime DELs for several output channels, and divided the 20-min, 1-hour, 3-hour, and 6-hour fatigue loads by the 10-min fatigue loads to calculate fatigue ratios. Each DEL for a given output channel is calculated using three different material exponents (m). For the output channels, low-speed shaft bending moments at the main bearing in 0° and 90° (LSSGagMya, LSSGagMza), yaw-bearing, and tower-base bending moments in side-to-side and fore-aft (YawBrMxp, YawBrMyp, TwrBsMxt, TwrBsMyt), and fairlead and anchor tensions in the mooring system (Fair1Ten, Anch1Ten for line 1), material exponents of 3, 4, and 5 were used, corresponding to steel components. For the blade root in-plane and out-of-plane bending moments (RootMxc1, RootMyc1) using composite material, the DELs were computed using m equal to 8, 10, and 12.

In Figure 8, the ratios for the lifetime DELs for different simulation lengths and a range of material exponents are presented. The figure shows slightly higher DELs with increasing simulation lengths. The channels RootMyc1, Fair1Ten, and Anch1Ten show the greatest differences. However, in general, the increase in the DELs of the 6-hour simulations compared to the 10-min simulations is very low.

The biggest increase can be seen for the output channel Fair1Ten, which is about 3.5% greater than unity.

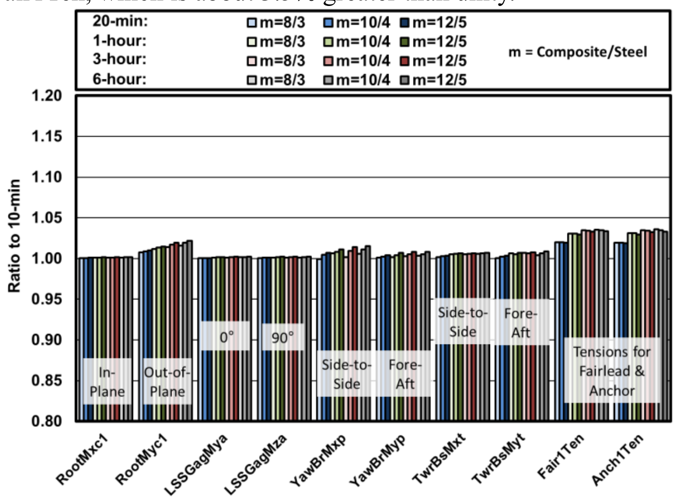

Figure 8. DEL ratios to the simulation group of 10 minutes for different material exponents and an UCMult-factor of 0.5.

5.2.3 Sensitivity Analysis of the Fatigue Calculation Due to Unclosed-Cycle Counting. While processing the fatigue loads analysis, we identified a sensitivity of the results to the unclosed-cycle counting factor (input UCMult in MLife). The value of UCMult dictates how unclosed (partial) cycles in the rainflow-counting algorithm are treated. By setting UCMult to zero, MLife neglects unclosed cycles. Setting it to one causes MLife to count unclosed cycles as full cycles. The first fatigue results presented in Figures 8 and 9 are calculated with UCMult equal to 0.5. In the MLife theory manual, and in most NREL studies, a value of UCMult of 0.5 is highly recommended [11]. Therefore, we presented the DELs with an UCMult setting of 0.5 first, before discussing the fatigue results for a range of UCMult values in this section.

Figure 9 shows the binned lifetime damages (LDs) versus load range at zero mean load for the root out-of-plane bending moment. Because we used a ULF value of 20, the binned damage on the Y-axis represents a very small value; therefore, only comparisons between the curves are logical. Figure 9, which shows the binned lifetime damage versus load range for the out-of-plane root bending moment, can be used to explain the results of Figure 8. There are no large differences between the various simulation lengths except on the far right side at the largest load ranges. These differences are enough to create slightly higher lifetime damages, as shown in Figure 8.

The largest load ranges are often where unclosed cycles occur. For simulation lengths of 6 hours, there is a higher chance of closing these partial cycles. Mouzakis and Morfiadakis showed that without counting the unclosed cycles, “the lifetime predictions based on segmented data can underestimate damage by 40 percent” [13] for a material exponent of 10. However, they showed that the difference in the predicted service lifetime between the time-series data concatenated into a single file and the time-series data counted in segments is about 10% for the blade out-of-plane bending moment. For other outputs, like the blade in-plane bending moment, the differences are only about 3% to 4%. These results indicate that the significance of counting the unclosed cycles in the signal is an order of magnitude more important than when merging all files together and counting the rainflow-cycles collectively. Thus, we concentrated our attention on calculating the lifetime damage for a range of factors for UCMult to determine its influence.

The results in Figure 10 present the LD-ratios for the blade out-of-plane root-bending moment. We computed the LD for each simulation length and weighted the unclosed cycles in the output signal with UCMult values of 0, 0.3, 0.5, 0.7, and 1. In Figure 10, it can be clearly seen that the importance of simulation length on the estimated fatigue life is highly dependent on the choice of UCMult. If unclosed cycles are neglected (UCMult = 0), the lifetime damage for the 6-hour simulations is four times greater than the 10-minute simulations. In contrast, with UCMult set to one, the fatigue damage is nearly independent of the simulation length. Moreover, the longer simulations of 1-hour, 3-hours, and 6-hours actually have slightly less damage compared to the 10-min simulations, and the 20-min simulations have a ratio of unity when counting unclosed cycles as full cycles (UCMult of 1.0).

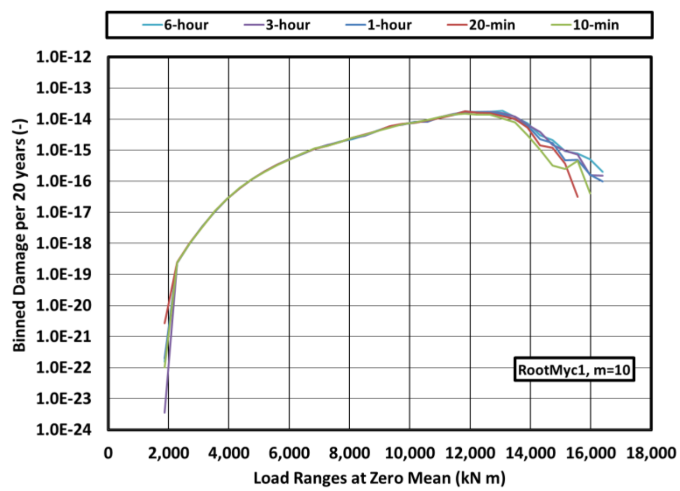

Figure 9. Binned lifetime damage versus load range for the out-of-plane root bending moment (m = 10, UCMult 0.5).

In our opinion, a value of UCMult between 0.5 and 1.0 should be used to have a balance between conservatism and accuracy. With a factor lower than 0.5, the damage induced by the (mostly large) unclosed cycles would be otherwise reduced in an unacceptable way. We have not yet identified if a specific UCMult is appropriate to a given simulation length; this will be a subject for further studies. However, the fatigue results shown for UCMult values larger than 0.7 make a strong case that there is no reason for longer simulation lengths, especially when coupled with the ultimate load results from Figure 7. The difference from the O&G industry may result, due to the wind-dictated loads of an operational FOWT instead of wave-dictated loads for an O&G floating platform. However, these results are based on a specific set of simulation conditions of an operational system. The recommendations may change for other floating platforms and/or for parked/idling conditions.

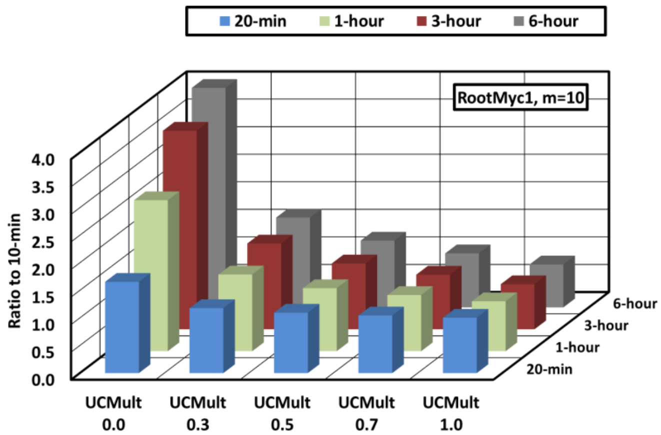

Figure 10. Lifetime-damage ratios of different simulation lengths to the 10-min simulations dependent on different values of UCMult for the root out-of-plane bending moment.

5.3 Minimum Data Requirements for Mean Extreme Load Calculation

The number of simulations required for statistics to converge was also investigated. Using bulk statistics from the simulations (mean and maximum loads), a Monte Carlo selection of varying size groups was conducted, and the statistics of the groups were compared to the average of all of the simulations. For this study, we are interested in the effects of waves on convergence only, so simulations with the same wind seed and varying wave seeds are considered. For a given wind speed, there were 360 ten-minute simulations, with 10 unique wind seeds, and 36 unique wave seeds per wind seed. Only the results for the maximum loads are presented here. The results for the blade root out-of-plane bending moment are summarized in Figures 10 to 12. The size of the random groups selected in the Monte Carlo sampling is along the X-axis, and the percent deviation from the average of the 36 10-min simulations is on the Y-axis. The red line shows the 95% confidence interval (the green line is the 68% confidence interval.

The mean of the maximum loads converge to about a 1% difference from the "true" answer between 5–10 simulations. These results are consistent for other loads as well. Figures 12 and 13 show the standard deviation convergence and the absolute maximum value convergence for the maximum loads. Interestingly, the standard deviation of the maximum values (Figure 12) in the randomly selected groups of simulations requires a very large group to approach the standard deviation of the 36 simulations. However, the absolute maximum value (Figure 13) shows that there is 95% confidence to be within 3.5% of the "true" value with 10 simulations. The results from this study suggest that approximately ten 10-min simulations for each wind speed bin should be used to obtain converged statistics. Further investigations into the cause of the large differences in standard deviation are being conducted.

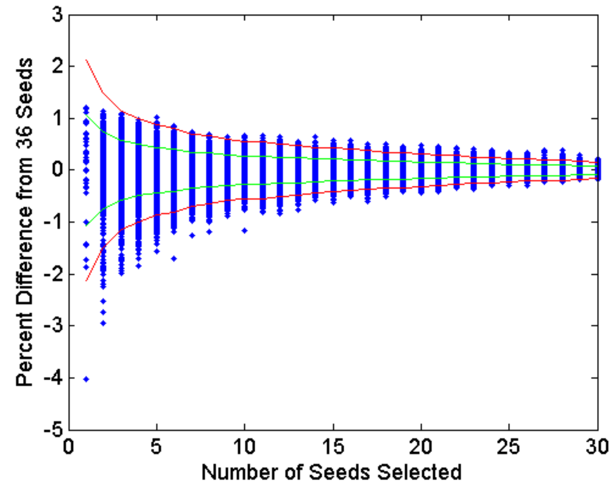

Figure 11. Mean of max root out-of-plane bending moment at 12-m/s wind speed.

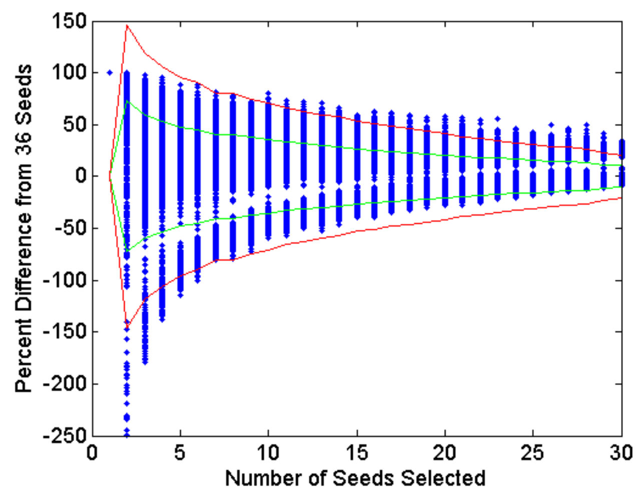

Figure 12. Standard deviation of max root out-of-plane bending moment at 12-m/s wind speed.

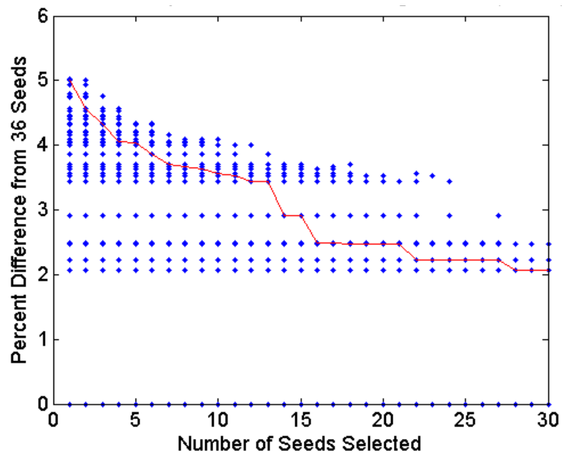

Figure 13. Absolute max of root out-of-plane bending moment at 12-m/s wind speed.

6. CONCLUSIONS AND RECOMMENDATIONS

From the research presented in this paper, we have drawn some initial recommendations in regard to performing a loads analysis of a floating offshore wind turbine. First, we recommend using proper initial conditions, as well as increasing the amount of initial simulation time that needs to be disregarded to 60 s to eliminate the effects of start-up transients. In the study regarding the dependence of aerodynamically derived loads on simulation length, it was shown that the length of the wind files did not have an effect on the loads produced on the turbine, as long as the total simulation time was kept constant. It was also shown that the use of repeated periodic wind files could possibly reduce computational effort without affecting loads. In addition, in the study, regarding the dependence on simulation length of loads due to hydrodynamics and floating platform motion, our results demonstrated that simulation length did not affect ultimate loads for the floating offshore wind turbine OC3-Hywind spar buoy; a larger number of shorter simulations (10 minutes at the shortest) led to the same loads as longer simulations (provided that the total simulation time is kept constant and that repeated periodic wind files are used). For fatigue loads, the results showed that there is greater sensitivity in the loads to the method of counting unclosed cycles, as compared to the simulation length. This topic will be investigated further in future studies.

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