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Calibration and validation of a spar-type floating offshore wind turbine model using the FAST dynamic simulation tool

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Abstract. High-quality computer simulations are required when designing floating wind turbines because of the complex dynamic responses that are inherent with a high number of degrees of freedom and variable metocean conditions. In 2007, the FAST wind turbine simulation tool, developed and maintained by the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL), was expanded to include capabilities that are suitable for modeling floating offshore wind turbines. In an effort to validate FAST and other offshore wind energy modeling tools, DOE funded the DeepCwind project that tested three prototype floating wind turbines at 1/50th scale in a wave basin, including a semisubmersible, a tension-leg platform, and a spar buoy. This paper describes the use of the results of the spar wave basin tests to calibrate and validate the FAST offshore floating simulation tool, and presents some initial results of simulated dynamic responses of the spar to several combinations of wind and sea states. Wave basin tests with the spar attached to a scale model of the NREL 5-megawatt reference wind turbine were performed at the Maritime Research Institute Netherlands under the DeepCwind project. This project included free-decay tests, tests with steady or turbulent wind and still water (both periodic and irregular waves with no wind), and combined wind/wave tests. The resulting data from the 1/50th model was scaled to full size and used to calibrate and validate a full-size simulated model in FAST. Results of the model calibration and validation include successes, subtleties, and limitations of both wave basin testing and FAST modeling capabilities.

1. Introduction

Simulation tools that are suitable for modeling offshore floating wind turbines are required for the design of utility-scale offshore systems because of both the increased loading expected in offshore systems from inertial effects and the economic impracticality of full-scale testing in the marine environment. One such tool, the FAST coupled aero-hydro-servo-elastic dynamic simulator, was developed for use with offshore floating wind turbines from the original FAST land-based simulation tool [1]. This paper focuses on an effort to use the DeepCwind 1/50th-scale test data to calibrate and validate a FAST turbine model of a spar buoy floating wind turbine.

1.1. The FAST wind turbine simulation tool

FAST is a nonlinear time-domain simulation tool that is capable of modeling the coupled aero-hydro-servo-elastic response of floating offshore systems that are operating in an environment with combined wind and wave loading. Rotor aerodynamics are calculated using the AeroDyn software library—which relies on blade-element/momentum theory or generalized dynamic wake theory for the calculation of wake effects—and the Beddoes-Leishman model for calculation of dynamic stall, and provides the user with the option of incorporating the effects of tip losses and hub losses [2]. Structural components of the turbine are modeled as a combination of coupled rigid and flexible bodies. Flexible bodies include the blades, tower, and drive shaft [3, 4]. Time-domain hydrodynamics include the effects of hydrostatic restoring, viscous drag from waves and turbine motion, added mass and damping from wave radiation, and linear wave diffraction. Mooring lines are modeled as quasi-static taut or catenary lines and include the effects of stretching, mass density, buoyancy, geometric nonlinearity, and seabed interactions. Dynamic mooring line effects and mooring line drag are not included in the model [1].

The degrees of freedom (DOF) of the complete wind turbine and floating platform FAST model include edgewise and flapwise blade motions, rotor rotation, driveshaft torsion, nacelle/rotor yaw, first and second modal tower-bending motions (both side-to-side and fore-aft), as well as six degrees of platform motions, including surge, sway, heave, roll, pitch, and platform yaw. Surge, sway, and heave are translations in the X, Y, and Z directions, respectively; whereas roll, pitch, and yaw are rotations about the X, Y, and Z axes, respectively. Coordinate systems and platform DOF definitions used in this paper are illustrated in Figure 1.

1.2. The spar-type floating wind turbine

The Maritime Research Institute Netherlands (MARIN)/University of Maine (UMaine) scale test model and FAST full-scale, three-bladed horizontal-axis wind turbine model are based on the National Renewable Energy Laboratory's (NREL's) offshore 5-megawatt (MW) baseline wind turbine [5]. The turbine was attached to a spar buoy platform that was adapted from a spar design developed for Phase IV of the Offshore Code Comparison Collaboration (OC3), which is based on Statoil's Hywind spar [6]. The spar has three equally spaced mooring lines in a water depth of 200 meters (m). The UMaine model uses a bridle system for the attachment of the three mooring lines to the spar, providing additional yaw stiffness; whereas the FAST model has a direct attachment to the spar of each mooring line at a radius of 5.2 m and a draft of 70 m because of FAST mooring line geometrical definition limitations. Pertinent dimensions of the FAST model are given in Table 1.

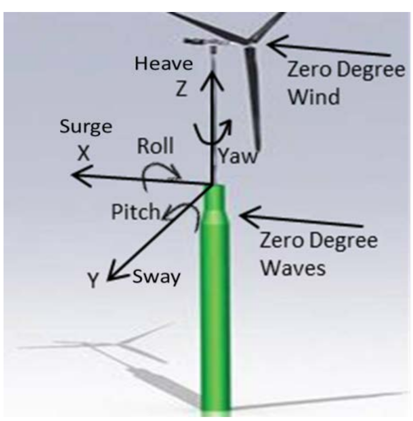

Figure 1. Coordinate system and definitions for platform DOF used in this paper. (Source: University of Maine)

Table 1. Dimensions of the spar type floating wind turbine model.

Hub Height [m]	90
Flexible Tower Length [m]	77.6
Blade Length [m]	61.5
Tower Top Mass [kg]	394,000
Tower Mass [kg]	303,145
Tower Base Above MSL [m]	10
Spar Length [m]	130
Spar Center of Mass Below MSL [m]	90
Spar Mass [kg]	7,280,000
Displacement Volume [m^3]	7,948
Total System Mass [kg]	7,977,337

1.3 MARIN wave tank testing (1/50thscale)

Tests were carried out in MARIN's wind/wave basin on a 1/50th Froude-scaled model of the spar system built by UMaine and MARIN [7]. Researchers conducted static offset tests, six DOF decay tests, periodic wave tests with and without wind, and combinations of stochastic wind and wave conditions. In addition, hammer tests were performed on the system to obtain fundamental modal responses. Data recorded during the tests included six platform DOF positions and accelerations; rotor torque and position; accelerations at three locations spanning the tower, forces, and moments at the tower base and tower top; and mooring line tensions. The sampling frequency was 100 hertz (Hz), corresponding to a Froude-scaled sampling frequency at full scale of roughly 14 Hz. All data from the MARIN tests were converted to full scale using Froude scaling prior to analysis [8]. All test data provided in this paper were presented at full scale, unless otherwise noted.

1.4 Introduction to calibration and validation

The FAST model was calibrated prior to validation to match the UMaine test model as closely as possible by using free-decay and periodic-wave tests (a small subset of the total experimental data available). Parameters in the FAST model were calibrated to match the test model when there was a known potential for discrepancy between the two. These discrepancies took the form of simplifications in the FAST model or simulation algorithms, or uncertainties in the characteristics of the scale test model. Once calibrated, the FAST model was validated by comparing the responses of the FAST model and test model for several tests, again including the free-decay and periodic-wave tests, with the addition of tests with irregular waves and steady wind.

2. Calibration

The parameters of the FAST model, which were calibrated prior to validation, are included in Table 2, along with a brief justification for calibration. Additionally, prior to this study, the aerodynamic coefficients of the blade were calibrated to match rotor thrust between FAST full-scale simulations and scaled-up test data because of poor aerodynamic performance of the UMaine test model resulting from Reynolds number (Re) dissimilitude [8].

Table 2. FAST model parameters calibrated prior to validation with a brief reason for calibration.

Calibrated Parameter	***Justification for Calibration***
Mooring Line Mass, Stiffness, and Length	Matching the mooring system tensions in the FAST model caused by horizontal displacement to the UMaine test model; necessary because of a delta connection in the UMaine test model that was not directly modeled in FAST
Tower Stiffness	Matching of first tower vibrational mode in the FAST model to the UMaine test model because of uncertainty in its stiffness, which was altered by sensors and sensor cables
Platform Displacement at Equilibrium	Matching zero heave at equilibrium of the FAST model and the UMaine test model because of uncertainties in mooring line fairlead angle and equilibrium displacement in the test model
Platform Yaw Stiffness	Emulating the added yaw stiffness created by the UMaine mooring system's delta connections in FAST
Heave and Yaw Damping	Fixing discrepancies between the UMaine test model and the FAST model because of FAST viscous drag simplifications

2.1 Mooring system calibration

The mooring system used in the MARIN tests consisted of three equally spaced primary mooring lines connected to the spar via delta connections that provided additional platform yaw stiffness than a single (direct) connection. Each of the three primary lines contained an inline linear spring intended to simulate the combined stiffness caused by mooring line axial stiffness and mass density of a full-scale catenary mooring line. Because FAST was not able to simulate the more complex delta connection of the UMaine test model, and because it relied on a quasi-static catenary solution (rather than an inline spring), the FAST mooring model was calibrated, as described in the following paragraph, to mimic the steady-state reaction of the MARIN model to X-direction displacements. Static offset tests in the

X-direction were performed by MARIN for offset values ranging from 0 to 12.4 m; whereas heave was kept constant at the equilibrium value. The length, axial stiffness, and mass density of the FAST mooring lines were tuned until lines 1 and 2, at 120 and 240 degrees from the X-axis, respectively, and line 3, at zero degrees from the X-axis, matched the MARIN results for line tension at offsets of 12.4 m and at equilibrium (i.e., zero offset for all platform degrees of freedom). The anchor locations were kept fixed at a radius of 445 m for both models. The resulting line tensions at the spar connection for several offsets for the FAST model and UMaine test model are shown in Figure 2. The two models were in agreement for all offsets, with the largest discrepancy of 39 kN occurring for line 2 at an offset of 9.9 m.

2.2 Tower calibration

The as-tested UMaine test model included an instrument cable attached to the tower and a force and moment sensor at the base of the tower of unknown stiffness. To represent the interaction of the cable and the sensor with the structure, a single stiffness multiplier was used at all FAST tower nodes to decrease the stiffness from nominal UMaine test model design specifications. The multiplier was calibrated so that the tower's first fore-aft frequency mode matched between MARIN and FAST, as measured by a fast Fourier transform (FFT) of tower-top acceleration with the turbine operating in periodic waves. The multiplier decreased the FAST model's first tower-bending mode from 0.49 Hz to 0.42 Hz.

2.3 Platform displacement, DOF stiffness, and damping calibration

Platform yaw stiffness was added to the FAST model until the yaw natural frequency matched that of the MARIN tests. The first natural frequencies in yaw for both models were measured using an FFT of a time series from a yaw decay test.

The platform draft at zero heave was reduced from the design specification value of 8,029 m^3 to 7,948 m^3 so that the model would float at zero heave in its equilibrium state with the calibrated mooring system.

FAST includes the capability of modeling nonlinear viscous drag on the platform in the X and Y directions via a user-specified coefficient of drag and varying platform diameter. The coefficient of drag (C_d) for the FAST spar model was calculated as the coefficient of drag for an infinite cylinder, which was determined based on the oscillatory Re of the relative water flow [9]. Re, however, does not scale consistently with Froude scaling. Because the goal was to model the test model, the range of Re values used for calculating the appropriate C_d were based on the $1/50^{th}$-scale test data rather than the full-scale data. It was found that the likely range of Re for the scaled data corresponded to an area of low slope in a C_d versus Re curve, with a mean value of approximately 1.0. Therefore, a value of 1.0 was used for C_d in the FAST model. It should be noted that the maximum Re expected from full-scale test data (using Froude scaling) was roughly 10^6, corresponding to a C_d of approximately 0.6 for an infinite cylinder, thereby illustrating the importance of using Re from scale test data when approximating C_d for viscous drag for the purposes of simulating the behavior of a model-scale system.

Because viscous drag in FAST was calculated only in the X and Y directions, it had a damping effect on the surge, sway, pitch, and roll motions of the spar platform. Additional linear damping was added to the heave and yaw DOFs in the FAST model to account for damping characteristics that are currently not modeled in FAST—such as skin friction, drag on mooring lines, and the drag caused by the abrupt edge at the bottom of the spar—that would be present in the MARIN tests. During calibration, 71.0×10^3 N/(m/s) and 10.1×10^6 N·m/(rad/s) of damping were added to heave and yaw, respectively, so that the average damping ratio over several peaks from the time series of heave and yaw decay tests were consistent between FAST simulations and MARIN tests.

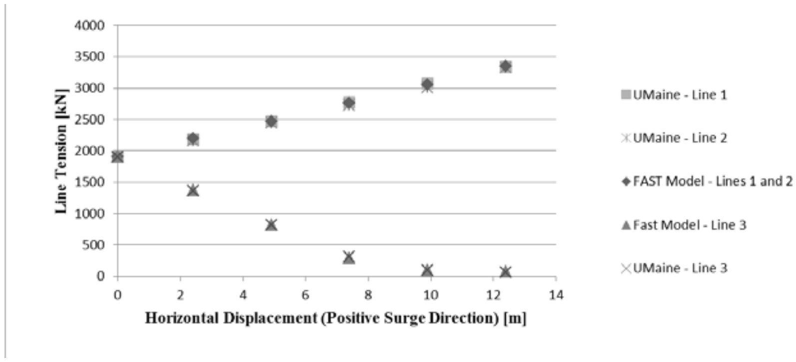

Figure 2. Mooring line tensions at the spar connection for the FAST model and UMaine test model.

3. Validation

After calibrating the FAST model to account for any known discrepancies between it and the UMaine test model, the FAST model was validated by comparing the results between the simulation and test for a series of tests, including free-decay tests, periodic-wave tests with no wind, and irregular-wave tests [Joint North Sea Wave Project (JONSWAP) waves] with wind.

3.1. Free-decay tests

After calibration, damping properties and natural frequencies for the six platform DOFs were compared between the FAST model and the UMaine test model via decay tests. The tests were performed by translating or rotating the model in the direction of each of the platform DOFs and letting the model return to equilibrium. The tests were performed with no incident waves or wind and a stationary rotor. Natural frequencies were calculated by locating the dominant frequency in the FFT of the resulting free-decay time series. Figure 3 shows the resulting natural frequencies for the FAST model and UMaine test model. As described, yaw stiffness and damping, as well as heave damping, were added to the FAST model during calibration. All frequencies matched well between FAST and the UMaine test model with the exception of pitch and roll, for which FAST exhibited a noticeably lower frequency response than the MARIN test data (0.0290 Hz and 0.0315 Hz for FAST and MARIN, respectively). This lower frequency response may have been because of incorrect placement of mass along the tower during the tower mass calibration process, which would have resulted in an incorrect moment of inertia for the system and incorrect pitch and roll restoring associated with the system center of mass.

The damping ratio for the platform motions were calculated from the average ratio of successive peaks using peaks 2–9 and peaks 9–16 from the decay tests. Averages of two ranges of time series peaks were used because the FAST model included nonlinear viscous drag, which increased with the higher platform velocities that occurred with high-amplitude oscillations; whereas damping during lower amplitude oscillation was primarily because of radiation damping. The damping ratios are presented in Figure 4. Heave and yaw were consistent between FAST and the UMaine test model for peaks 9–16. The MARIN surge damping ratio increased for lower amplitude oscillations, which may have been caused by a problem with the test procedure or the average successive peak ratio analysis procedure. FAST showed self-consistency between surge and sway (small variations were caused by different initial offset values to match MARIN tests as well as the greater influence of rotor drag in the surge direction) but did not match the MARIN test values. This inconsistency may be explained by large displacements of the mooring systems in surge and sway, leading to nonlinearities and differing behavior of the mooring systems in the FAST model and UMaine test model. This explanation would also account for the lack of self-consistency in the MARIN test data for surge and sway because the initial offset for sway was significantly larger than for surge, at 10 m and 4 m, respectively. In general, the FAST model appeared to have greater damping in surge and sway and less damping in pitch and roll relative to the UMaine model. Drag on the mooring lines was not modeled in the current version of FAST, which may have accounted for some of the discrepancy in surge and sway.

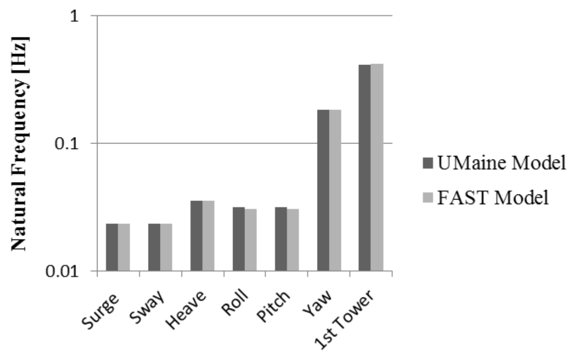

Figure 3. Natural frequencies of platform motions for the UMaine test model and FAST model.

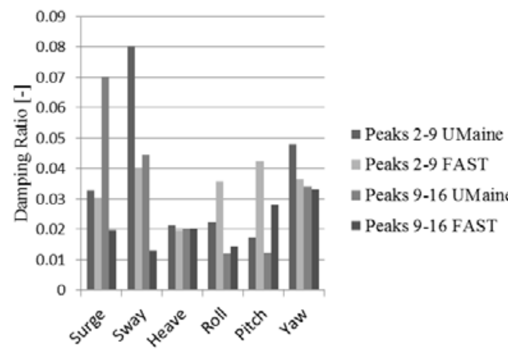

Figure 4. Average damping ratios from peaks 2–9 and peaks 9–16 of platform DOF decay tests.

3.2. Periodic wave tests

The results of two periodic wave tests, with wave heights of 1.92 and 7.14 m and wave periods of 7.5 and 14.3 s, were compared between the FAST model and the UMaine test model to validate the system response to a relatively simple sea state. These tests were run with no wind, a stationary rotor, and waves propagating along the positive X-axis (i.e., toward the rotor in the direction of platform surge).

Figure 5 shows the resulting power-spectral densities (PSDs) of the response to a periodic wave test with low-height (1.92 m) and low-period (7.9 s, 0.13 Hz) waves. Both heave and tower-top acceleration response at the wave frequency was consistent between the MARIN experiment and FAST simulation. The response of the tower top at the pitch frequency as well as the heave response at the heave natural frequency was stronger for the simulation than the experiment. The difference in heave response at the natural heave frequency suggested insufficient heave damping in the FAST model. However, the damping ratios in Figure 4 indicated agreement for the heave DOF. Similarly, Figure 4 indicates that pitch had greater damping in FAST than the experiment for both of the large displacements. This fails to explain the greater response of the tower top in the FAST model at the natural pitch frequency.

The PSD of the tower top X-acceleration for the experimental data showed a strong response at 0.26 Hz, which was twice the wave frequency. This could have been caused by second-order hydrodynamic excitation. The simulation did not show that this response was likely because it was not capable of modeling second-order hydrodynamic loading.

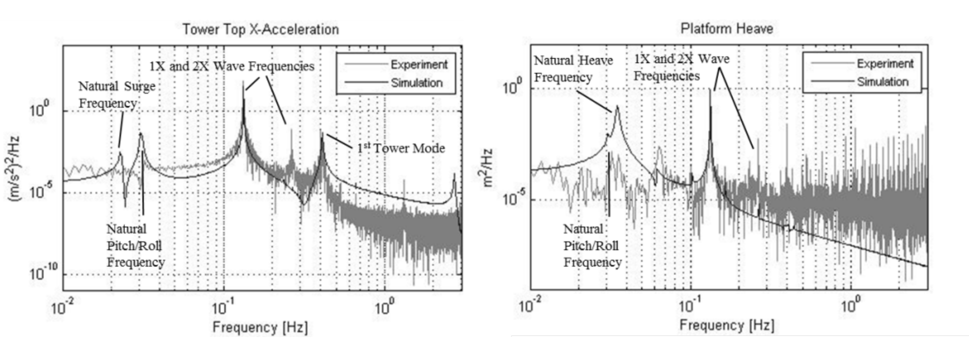

Figure 5. Tower-top X-direction acceleration response and platform-heave response of the UMaine test model and FAST model in periodic waves with a height of 1.92 m and a wave period of 7.5 s.

PSDs from a periodic wave test with a wave height of 7.15 m and a period of 14.3 s (0.070 Hz frequency) are shown in Figure 6. Response of both platform-heave and tower-top acceleration at the wave frequency was fairly consistent between the simulation and the experiment. However, the simulation resulted in a significantly greater tower-top response at the platform-pitch frequency than the experiment, as well as greater heave response at the heave frequency than the experiment. Again, this outcome may point toward differences in damping between the two systems that are still occurring with larger waves and platform motions and may be partially explained by damping in the UMaine test model that was caused by nonlinear drag of the mooring lines (not modeled in FAST). The MARIN test data showed large responses at two and three times the wave frequency, 0.14 Hz and 0.21 Hz, respectively; whereas the simulation showed only the 0.14 Hz response. This response was likely because of the quadratic viscous damping term in FAST, which caused a pronounced response at twice the regular wave frequency when subjected to higher waves and greater motions.

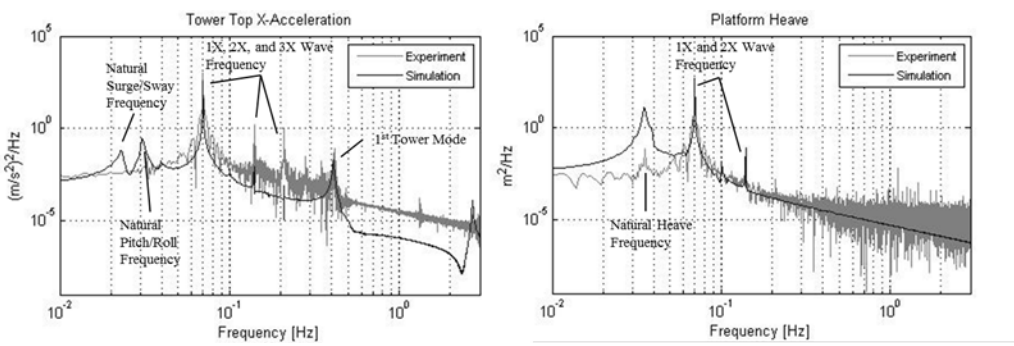

Figure 6. Tower-top X-direction acceleration response and platform heave response of the UMaine test model and FAST models in periodic waves with a height of 7.14 m and a wave period of 14.3 s.

3.3. Irregular wave tests

The MARIN spar model was tested under a variety of metocean conditions with irregular waves and steady wind. Waves in both the experiment and simulation were based on JONSWAP spectra [1]. The recorded wave parameters in the experiment and wave spectra parameters in FAST were the same, and included significant wave height, peak-spectral period, peak shape factor, and propagation direction. The FAST simulation used these four parameters to produce a wave height time series that was based on the JONSWAP spectrum, which was then used in the simulation. This method resulted in sea surface elevations that were not identical in time, but had more consistent spectra than the MARIN tests.

The first irregular wave test used for validating the FAST model consisted of a significant wave height of 2 m, a peak-spectral period of 7.5 s (0.133 Hz), and a shape factor of 2.0. The steady horizontal wind speed was 11.23 meters per second (m/s) and the rotor was kept at a constant speed of 7.8 rpm (0.13 Hz). The wave direction was zero degrees (i.e., propagation was toward the downwind side of the turbine). Figure 7 shows PSDs of the moment about the Y-axis at the base of the tower, and the tower-top acceleration in the X direction. Both plots show a similar response shape within the region of the JONSWAP wave frequencies (roughly 0.009 to 0.035 Hz) between both measurements and between the experiment and simulation, as expected because of the influence of the tower-top motions on the tower-base moments. The response of the tower-top acceleration at the platform-pitch frequency was also similar between the experiment and simulation. It would be expected that similar tower-top motion spectra in the vicinity of the platform-pitch frequency would translate into similar tower-base moment spectra in that frequency range. However, it can be seen in Figure 7 that the magnitude of the tower-base moment response was somewhat larger for the FAST simulation than the experiment at the platform-pitch frequency (0.030 Hz). This outcome may have been caused by an incorrect tower/nacelle/rotor system rotational inertia, and thus a larger moment at the base for a given tower-top acceleration. This would also account for the lower pitch natural frequency for the FAST model than in the MARIN experimental model previously noted.

In both spectra, the experimental data showed prominent peaks at the blade-passing frequency (3P) of 0.39 Hz, as well as the first two blade-passing frequency harmonics (6P and 9P). Although an effort was made to produce a low turbulence and constant wind field over the rotor area for the experiments, wind calibration results showed both vertical and horizontal variation in wind velocity, with a minimum wind speed measured across the rotor of roughly 70% of the maximum. The prominent 3P, 6P, and 9P peaks may be because of these inconsistencies in wind velocity over the rotor. In comparison, the FAST simulations (for these tests) modeled wind velocity as a constant wind field over the rotor area; thus, for this experiment, the spectra did not exhibit pronounced peaks at the blade-passing frequency or its harmonics. FAST does include the capability for modeling wind fields with horizontal and vertical shear. These effects may be examined in the future.

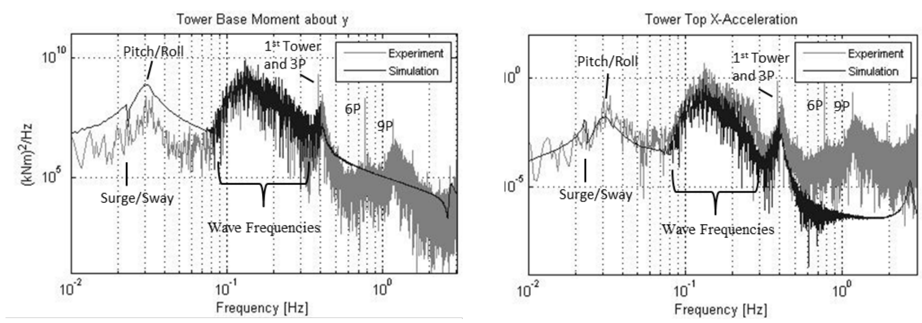

Figure 7. Response in irregular waves of significant wave height, peak-spectral period, and shape factor of 2 m, 7.5 s, and 2.0, respectively. The horizontal wind speed was 11.23 m/s and the rotor speed was 7.8 rpm.

The next irregular wave test used for validation consisted of an increased wave height and peak-spectral period of 7.1 m and 12.1 s (0.083 Hz), respectively. The shape factor increased to 2.2 and the wind velocity and rotor speed were kept the same as the previous test, at 11.23 m/s and 7.8 rpm (0.13 Hz). As pitching motions increased, it was expected that yaw-pitch coupling would be present because of rotor gyroscopic forces. Figure 8 shows that the tower-top X-accelerations increased with the higher height and longer period waves relative to the previous test shown in Figure 7. As shown in the PSD of the yaw response, the simulation data showed the expected pronounced peak corresponding to the model's natural platform-pitch frequency. However, rather than having a peak at the pitch frequency, the experimental data has a peak that corresponds with the natural heave frequency of 0.036 Hz. Another clear discrepancy was in the experimental peak yaw response at 0.08 Hz, or roughly the peak spectral wave frequency, which shifted to the right for the simulation response. The reason for these discrepancies is currently unknown. FAST currently utilizes the Massel wave cut-off frequency criterion, for which the JONSWAP wave spectra is truncated at three times the peak-spectral frequency [1].

An irregular wave test designed to emulate a survival condition was performed. The wave height and period were increased to 10.5 m and 14.3 s (0.070 Hz), respectively. Constant horizontal wind velocity was increased to 21.8 m/s and the rotor speed was increased to 12.7 rpm (0.21 Hz). The waves propagated at a 45-degree angle to the X-axis; the wind direction stayed at zero degrees.

The X and Y tower-top accelerations, shown on the left-hand side of Figure 9, showed agreement between them as well as between the experimental and simulation data. Unlike previous tests, a distinct peak was present at the 3P frequency for both the experiment and the simulation in both the X- and Y-acceleration plots. The presence of this 3P response in the simulation may have originated from the oblique 45-degree wave propagation direction. A noticeable discrepancy between the experiment and the simulation was the large 6P peaks in the X- and Y-acceleration PSDs that occurred only for the experimental data. Again, this discrepancy was likely caused by variations in wind speed over the rotor for the UMaine test model. Pure vertical shear produces 3P excitations because each blade passes through a high and low wind speed region of the rotor plane once per revolution. Other nonuniformities in the wind field will result in 6P excitations. More complex variations, as were observed during the wind calibration process at MARIN, could result in a noticeable response at higher order multiples of 3P. Although 3P response may occur in the simulation data because of platform pitching and the resulting misalignment between the rotor plane and the wind vectors, higher order responses will not be present because of the constant wind field modeled in the simulation.

As with the X and Y tower-top accelerations, surge and sway responses in Figure 9 show agreement between them as well as between the two experimental and simulation data in the range of wave frequencies. However, the simulation data has a distinct peak in surge response, at 0.023 Hz, and in sway, at 0.028 Hz, neither of which were apparent in the experimental data. The 0.023-Hz surge response was easily identified as the FAST model surge/sway natural frequency.

The UMaine test model demonstrated significantly greater response than the FAST model in the region of wave frequencies for heave; the opposite was true for yaw response.

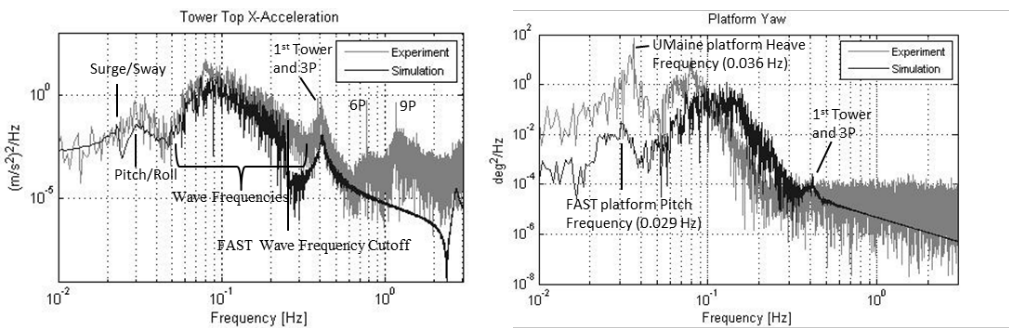

Figure 8. Response in irregular waves of significant wave height, peak-spectral period, and shape factor of 7.1 m, 12.1 s, and 2.2, respectively. The horizontal wind speed was 11.23 m/s and the rotor speed was 7.8 rpm.

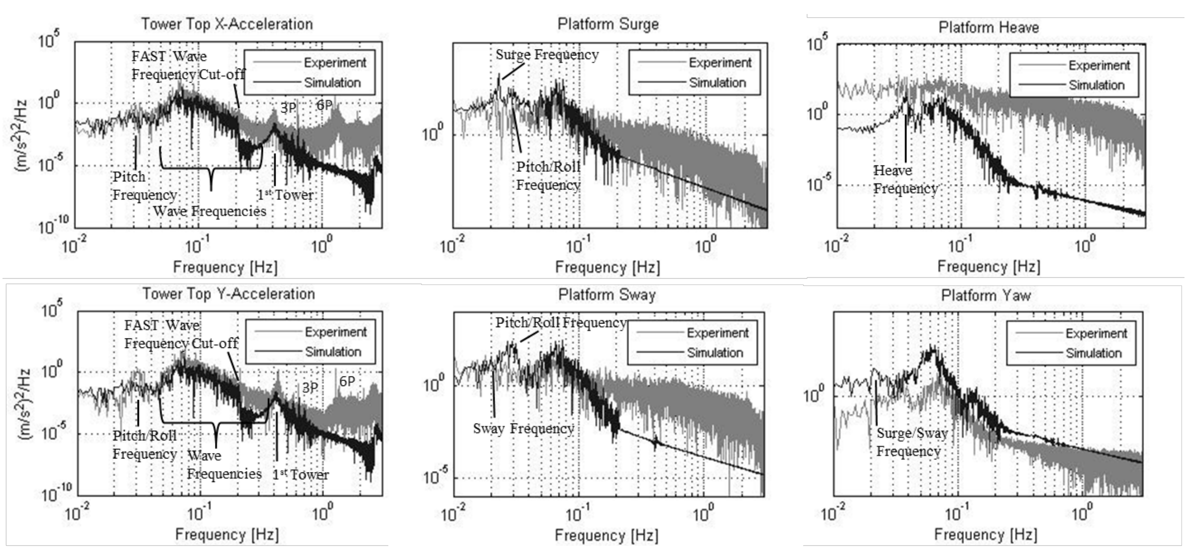

Figure 9. Response in irregular waves of significant wave height, peak-spectral period, and shape factor of 10.5 m, 14.3 s, and 3.0, respectively. The horizontal wind speed was 21.8 m/s and the rotor speed was 12.7 rpm.

4. Conclusions

FAST simulations of a 5-MW spar-type offshore floating wind turbine operating in various metocean conditions were compared to results of tank tests of a $1/50^{th}$ Froude-scaled model of the same system for the purposes of calibration and validation of the FAST model. The FAST model was calibrated to account for differences in mooring systems between the FAST model and UMaine test model and simplifications in the modeling of nonlinear viscous damping. Once calibrated, the natural frequencies of the platform DOFs, as well as the first tower mode, were mostly consistent between the experiment and the simulation, with a roughly 3% inconsistency in pitch and roll. Damping of the platform, as measured by the damping ratio from free-decay tests, was reasonably consistent between the simulation and experiment for heave and yaw decay (particularly for lower height motions), but was inconsistent for surge, sway, pitch, and roll. FAST surge and sway appeared to be less damped than the UMaine model; whereas pitch and roll appeared to have increased damping relative to the UMaine model.

The response of the two systems to periodic waves and zero wind compared well at the wave frequency and fundamental tower frequency, but the FAST model tended toward a greater response at the natural frequencies of platform DOFs. In addition, the experimental data showed greater responses at the first and second harmonics of the wave frequency than the simulation. A quadratic effect was noticeable at twice the wave frequency in the simulation data for higher waves, but was not present for lower waves.

Several irregular wave tests with wind were compared. The response of the two models was generally consistent at frequencies corresponding to the wave spectra. At lower wind velocities, the experimental data showed a 3P response that was not apparent in the FAST simulations until wind speeds were increased to 21.8 m/s, at which point the 3P FAST response exceeded that of the experiment, indicating an increased 3P simulation response with higher platform pitching and increased rotor loads. Responses of 6P and 9P were present in the test data but not in the simulation data. A yaw response at the heave natural frequency was present in the test data but not in the simulation. The response of the two systems in the pitch/roll and surge/sway frequency range was more consistent for simulations including wind, indicating that wind effects dominated in these lower-frequency ranges.

In general, the responses compared well between the experiment and the simulation, particularly in the region of the wave-spectra frequencies. However, differences existed in the responses to periodic and irregular waves, which may be important for full-scale turbine design. More research is needed to understand the discrepancies between the simulation and experiment before an assessment of FAST's ability to accurately model floating wind turbines can be made. In particular, there appears to be significant discrepancies in damping behavior between the experiment and the FAST simulation.

5. References

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