Summary of Conclusions and Recommendations Drawn from the DeepCWind Scaled Floating Offshore Wind System Test Campaign

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SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS DRAWN FROM THE DEEPCWIND SCALED FLOATING OFFSHORE WIND SYSTEM TEST CAMPAIGN

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ABSTRACT

The DeepCwind consortium is a group of universities, national labs, and companies funded under a research initiative by the U.S. Department of Energy (DOE) to support the research and development of floating offshore wind power. The two main objectives of the project are to better understand the complex dynamic behavior of floating offshore wind systems and to create experimental data for use in validating the tools used in modeling these systems. In support of these objectives, the DeepCwind consortium conducted a model test campaign in 2011 of three generic floating wind systems: a tension-leg platform (TLP), a spar-buoy (spar), and a semi-submersible (semi). Each of the three platforms was designed to support a $1/50^{th}$-scale model of a 5-MW wind turbine and was tested under a variety of wind/wave conditions.

The focus of this paper is to summarize the work done by consortium members in analyzing the data obtained from the test campaign and its use for validating the offshore wind modeling tool, FAST.

1. INTRODUCTION

The floating offshore wind power industry is still in a development stage. No commercial projects have been constructed, but demonstration projects such as Statoil's Hywind and Principle Power's WindFloat are building confidence in this industry. In addition, the DOE has awarded $4M of funding each to three floating demonstration projects in the United States to perform a one-year front end engineering study, with the potential of future deployment.

The DeepCwind project represents a significant resource in the research and development of floating wind. It is the first project to offer public data of the response of floating offshore wind systems in a wave tank setting for use in validating offshore wind modeling tools. Computer-aided-engineering (CAE) tools that model the coupled aerodynamic, hydrodynamic, control system, and structural response of floating wind systems are needed to develop innovative technologies that are reliable and cost effective. For CAE tools to be used effectively, their accuracy needs to be assured through verification and validation efforts. The DeepCwind model test campaign will provide data to the public so that anyone may use it in their validation efforts. In addition, the openness of the project provides an opportunity for researchers and developers to learn from the mistakes and issues encountered in the test program.

The DeepCwind test campaign was performed at the Maritime Institute of the Netherlands (MARIN) in Wageningen, the Netherlands. The turbine was a $1/50^{th}$-scale horizontal-axis model of the NREL 5-MW Reference Wind Turbine [1] with a flexible tower affixed atop three distinct platforms: a TLP, spar, and semi. The three generic platform designs are intended to cover most of the popular concepts, each based on proven floating offshore structure technology. The models were tested under Froude-scaled wind and wave loads; see Jain [2] for more details on the scaling process. The high quality wind environments, unique to these tests, were realized in the offshore basin via a novel wind machine that exhibits negligible swirl and low turbulence intensity in the flow field. Recorded data from the floating wind turbine models included rotor torque and position, tower-top and -base forces and moments, mooring line tensions, six-axis platform motions, and accelerations at key locations on the nacelle, tower, and platform. A large number of tests were performed ranging from simple free-decay tests to complex operating conditions with irregular sea states and dynamic winds.

The focus of this paper is an examination of the test data from the DeepCwind tests and ongoing efforts to validate the overall coupled offshore floating wind system solution of FAST [3], a CAE tool for modeling offshore wind systems, which was developed by the National Renewable Energy Laboratory (NREL) with DOE support. The outline of the paper is as follows: the remainder of Section 1 will review the systems and tests performed in the basin, Section 2 will examine the system response behavior, and Section 3 will examine current efforts to validate FAST using the test data. Finally, Section 4 will

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summarize conclusions and recommendations drawn from the DeepCwind test campaign.

1.1 Description of Systems

The approach for designing a floating offshore wind system is to create a structure with positive buoyancy and sufficient restoring stiffness to resist the overturning moments created from both the wind and the waves. In addition, the natural frequencies of the structure must be placed to minimize excitation from the environmental conditions and periodic forcing from operation of the turbine. This includes avoiding wave frequencies of significant energy, from about 0.05 Hz up to 0.25 Hz (or 4 – 20 s), and the frequencies at which the blades pass the tower (commonly called 1P and 3P for the rotational frequency of the rotor and the frequency at which a single blade passes the tower, respectively).

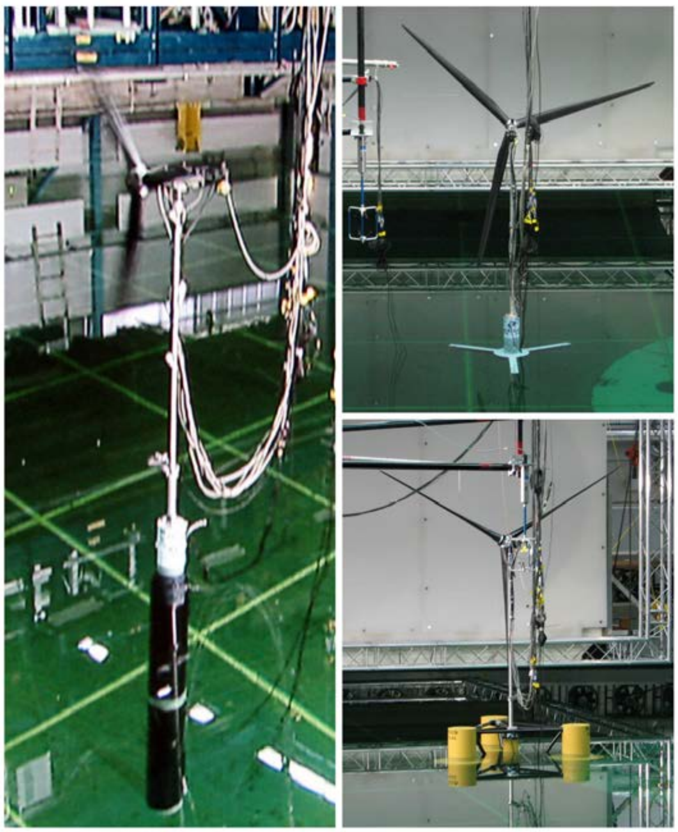

Figure 1. The three DeepCwind floating wind system designs, clockwise starting at left: spar, TLP and semi

The three systems tested in the DeepCwind measurement campaign span the space for how to achieve hydrostatic stability of the floating system in pitch and roll. The first is the TLP, which uses the approach of taut mooring lines and excess buoyancy to achieve hydrostatic pitch and roll stability (see Figure 1). The design is a generic one created by the University of Maine, but closely resembles Glosten's PelaStar concept [4]. The second design is a spar concept, which is based on the OC3-Hywind spar [5], and achieves hydrostatic pitch and roll stability through a low center of mass (CM) far from the center of buoyancy. The third design is a semi-submersible created by Technip and the University of Maine, which achieves hydrostatic pitch and roll stability through a combination of low CM and a large water-plane inertia. It should be emphasized here that these models are generic, publicly available designs that were created to provide fairly realistic approximations to floating platforms being proposed for commercial development.

Each of the three platforms was designed to support a 1/50th Froude-scaled model of the NREL 5-MW reference turbine. Tables 1-3 summarize some of the main properties of the turbine and support structures. For more details on these structures, please refer to Martin [6]. Note that all values in this paper are reported at full scale unless otherwise stated, though the testing was performed at 1/50th scale.

Table 1. Properties of the wind turbine

Property	Value
Rotor orientation, Configuration	Upwind, 3 Blades
Control	Fixed Speed
Rotor, Hub diameter	126 m, 3 m
Hub height	90 m
Freeboard to tower base	10 m
Overhang, Shaft tilt, Precone	10.58 m, 0°, 0°
Rotor mass	122,220 kg
Nacelle mass	274,940 kg
Tower mass	302,240 kg

Table 2. Properties of the platforms

Platform Properties (not incl. tower + turbine)	TLP	Spar	Semi
Diameter of members (m)	6.5 (column) 15 (tank)	6.5 to 9.4 (tapered)	6.5 (main col.) 12 (offset col.) 24 (heave plates)
Draft (m)	30	120	20
Water displacement (m^3)	2771	8029	13917
Mass, incl. ballast (kg)	6.616E+5	7.281E+6	1.344E+7
Platform CM below SWL (m)	11.2	91.1	14.4
Roll inertia @CM (kg m^2)	2.343E+8	3.966E+9	7.686E+9
Pitch inertia @CM (kg m^2)	2.208E+8	3.966E+9	8.335E+9
Yaw inertia @CM (kg m^2)	5.846E+7	9.860E+7	1.391E+10
Number of mooring lines	3	3	3
Depth to fairleads, anchors	28.5, 200	70, 200	14, 200
Radius to fairleads, anchors	30, 30	5.2, 445	40.87, 837.6
Unstretched line length (m)	171.4	424.4, 30	835.5
Line diameter (m)	0.6	0.285	0.08
Line mass density (kg/m)	301.2	43.5, 3.8	123.8
Line extensional stiffness (N)	7.500E+9	9.67E+7	7.529E+8
System Properties			
Total Mass (mt)	1361	7980	14040
System CM below SWL (m)	-34.1	76.3	9.9

Table 3. Eigenvalues of each of the floating systems (Hz)

	TLP	Spar	Semi	Fixed-base
Surge	0.026	0.023	0.0093	
Sway	0.026	0.023	0.0088	
Heave	0.86	0.035	0.058	
Roll	0.28	0.031	0.037	
Pitch	0.27	0.031	0.037	
Yaw	0.049	0.21	0.012	
1st Tower Fore/Aft	1.32	0.43	0.35	0.29
1st Tower Side/Side	1.30	0.44	0.38	0.29
2nd Tower Fore/Aft	3.12	2.35	2.55	1.24
2nd Tower Side/Side	3.24	2.39	2.66	1.24

1.2 Test Matrix

A large array of tests was performed at the MARIN wave basin for each of these three systems to characterize the behavior of the systems in a variety of conditions. The tests performed are summarized in Koo [7] and include:

- Hammer tests to identify natural frequencies
- Static offset and free-decay tests
- Wave-only tests using both regular and irregular waves (operational, survival, and white noise)
- Wind-only tests with both steady and dynamic wind
- Combined wind/wave tests, including bidirectional and oblique waves in addition to those listed above.

The sampling frequency for most tests was 100 Hz at model scale, corresponding to a Froude-scaled sampling frequency at full scale of roughly 14 Hz. The hammer tests were captured at 1000 Hz at model scale. All data from the MARIN tests were converted to full scale using Froude scaling prior to analysis [6].

1.3 Testing Issues

Because the DeepCwind tests are the first floating offshore wind tests to be open to the public, they provide an opportunity for others to learn from the issues encountered during the testing campaign. The following subsections describe some of the issues encountered.

Scaling of the Model

A major challenge in the scale-model testing of an offshore wind turbine that is excited both by wind and waves is deciding on the appropriate scaling approach for the experiment. For wind turbine testing, a scaling approach based on preserving the Reynolds number is typically used as this preserves the relationship of viscous and inertial forces for fluid flow. For offshore structural testing, however, a scaling approach based on preserving Froude number is more typical as this preserves the relationship between the gravitational and inertial forces of the waves. For the DeepCwind tests, a Froude-based scaling approach was used both to create the scaled geometry of the structure and to scale the environmental conditions of the tests.

The drawback of a Froude-based scaling approach is that the turbine airfoils are scaled geometrically, which does not preserve their aerodynamic performance. Under Froude-scaling, the Reynolds number at rated wind speed is severely reduced from 11.5×10^6 (turbulent flow) to 35.7×10^3 (laminar flow) [6]. Reducing the Reynolds number changes the lift and drag coefficients of the turbine blades, which determine the distributed forces the wind imparts on the blades. This drastic change in Reynolds number (between full and model scale) created a significant change in the lift and drag behavior for the airfoil sections, resulting in lower-than-desired values of generated torque and lift. Further discussion on this topic can be found in Molta [8].

To counteract the reduced aerodynamic forces on the turbine during testing, the wind speeds were increased to ensure appropriately scaled thrust forces, one of the key forcing components on the offshore wind system created by wind.

Model Fidelity

While not directly a testing issue, it is worth pointing out here that the wind turbine tested differed from a commercial-scale turbine. First, to eliminate any issues associated with scaling the stiffness of the blades, the blades of the model turbine were made to be as rigid as possible. Second, the turbine was forced to rotate at the appropriate speed for a given wind condition (based on the tip speed ratio), rather than trying to achieve the correct torque on the blades from the wind. Finally, no control system was implemented on the turbine. Therefore, the blade pitch was kept constant for all tests, and no above-rated wind tests were run except for a shut-down condition. Non-automated pitching of the blades was possible, but it was found that this resulted in problems with pitch slippage.

Wind

The wind in the model basin was generated by fans, which require special attention due to the recirculation of the wind field in the basin and the variation of the wind speed with the distance from the fans. For the DeepCwind tests, wind was generated by a bank of 35 fans with a honeycomb front plate to reduce swirl and a nozzle to reduce turbulence (Koo [7]). The output area of the nozzle covered the entire wind turbine rotor through its expected range of motion.

While the flow from the bank of fans was fairly consistent with minimal swirl and an average turbulence of less than 5%, there were some drawbacks. The bank of fans needed to be placed high enough as to not interact with the water. This height decreased the wind speed on the lower portion of the rotor; thus, the nozzle was tilted downward by 2.16 degrees. This downward angle improved the wind speeds at the bottom of the rotor, but introduced a vertical component to the wind velocity. Even with this modification, wind speeds at the lower end of the rotor decreased by 20% and the turbulence intensity increased to 15%.

Instrumentation

The total topside mass (at full scale), which includes the wind turbine, tower and all accompanying instrumentation, is 699,400 kg. This is 16.6% larger than the standard specifications for the combined NREL 5-MW Reference turbine and the OC3-Hywind tower, and was mostly a result of instrumentation cables. In addition to adding mass to the system, the instrumentation could have altered the dynamic response of the structure. As highlighted in the yellow circle in Figure 2 below, the cables used to record data from the turbine sensors were quite bulky. To mitigate the interaction of the cables with the dynamics of the system, the cables were attached to the tower, and then allowed to hang in a catenary configuration from a location just above the lower load cell. Though mitigation was attempted, it is likely that these cables altered the dynamics of the systems.

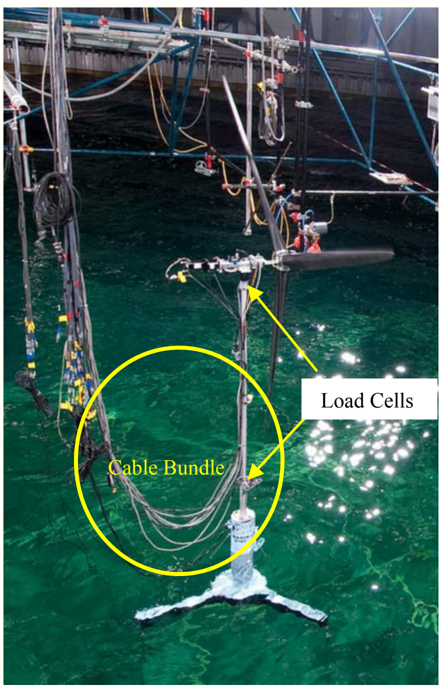

Figure 2. Sensor cable bundle for TLP

In addition, two load cells were placed at the connection points between the platform and the tower, and the tower and the turbine. The load cells enabled the measurement of tower loads/moments at the top and bottom, but also potentially induced compliance at the connection points, which could decrease the stiffness of the tower.

Finally, the 6-degree of freedom (DOF) response motion of the platform was measured via an optical sensor pointed at the base of the tower. While this system worked well in general, it was not sensitive enough to accurately capture the very small pitching and rolling motions of the TLP.

Platform Designs

It should be emphasized that the platform designs used were generic ones, with very little optimization of the system properties. The goal was to find a good representation of the general types of platforms being used or proposed in the market, which are largely based on oil and gas industry structures. However, the desire was to create systems that could be made available to the public and therefore did not rely on any proprietary information. As a result, the systems may not be sized or designed optimally for deployment.

For instance, the semi-submersible system is heavier than one would expect for a commercial system. Also, the heave natural period is 17 seconds, which is within the normal wave frequency range. Placing system natural frequencies within the wave frequency range should be avoided to limit large excitation of the system.

The TLP was designed to be quite small, and as a consequence, the mooring lines went slack during some extreme loading events. One of the reasons that slack-line events occurred is that the system was accidentally rotated 180 degrees in its placement in the tank, with the mooring line aligned with the waves being placed in back of the turbine rather than in front. Slack-line events are to be avoided for TLP designs as the snap-back of the line can cause damage to the mooring line and induce broad-band frequency excitation in the system. The presence of a slack-line event therefore indicates that the TLP system would need to be modified before it could be used as a commercial design.

The spar system did not have any major design limitations as it was more directly modeled after a commercial design, Statoil's Hywind spar.

2. FLOATING SYSTEM BEHAVIOR

The DeepCwind tests were useful in understanding how different generic floating wind designs respond to a variety of wind/wave conditions—providing an indication of their relative performance. However, the systems were not optimized designs, and therefore do not necessarily reflect the most favorable aspects of a given design approach. With this limitation in mind, this section will highlight some of the behavioral properties and issues observed during the testing of the three floating systems.

2.1 Aerodynamic Response

The limitations of the wind excitation system used in the basin resulted in a wind field that was not entirely homogeneous across the rotor. This inhomogeneity is most easily seen in the response of the systems during steady, wind-only tests by the presence of frequency peaks at one time (1P), six times (6P) and nine times (9P) the rotor's rotational frequency. For example, Figure 3 shows the power spectral density (PSD) of the tower bending response of the semi under steady wind at 16.1 m/s. The rotor speed for this case was 9.19 revolutions per minute (rpm), which results in a rotor frequency of 0.15 Hz with harmonics at 0.45, 0.90, and 1.35 Hz (3P, 6P, and 9P), all of which are clearly visible in Figure 3. For a homogeneous, steady-wind condition, only the 3P frequency should be present due to the dip in thrust as each blade passes the tower. The presence of harmonics means that for steady

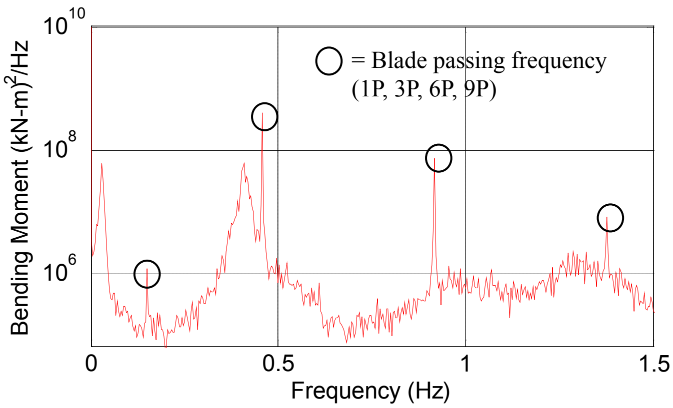

Figure 3. Power-spectral density of the tower-bending moment

wind conditions, we will see excitation of the system at these frequencies.

The same wind-field generation system was used for all three designs, so, even with the limitations identified, one can compare the platform-restoring forces of the three systems by examining their response to steady wind conditions. Figure 4 shows the surge and pitch offsets of each of the systems due to steady wind at varying speeds, and the bending moment of the tower at its base. The surge response shows that the systems displace more as the wind speed increases (and the thrust force from the wind increases), until the speed of 30.5 m/s is reached, at which point the rotor is braked and has no rotational speed. One would expect mean thrust to peak at rated wind speed and then drop. Due to the problems with the thrust of the turbine mentioned earlier, the rated wind speed is at 21.8 m/s, which is quite a bit different than the specified value of 11.4 m/s for the NREL 5-MW turbine. No above-rated wind cases were run (other than shut down) due to blade pitching issues.

The surge displacements are relatively similar between the three systems, with the spar displacement being the smallest. This is likely due to the fact that the stiffness in the pitch direction is small, and the system will therefore tend to pitch instead of surge. This is confirmed in the pitch response, where the spar clearly dominates. On the opposite extreme, the TLP has very little pitch motion due to the high stiffness provided by the taut mooring lines. The bending moment is highest for the spar system due to its large pitch angles, but all systems are fairly similar. It should be noted that the pitch motion of the systems is commonly decreased through control methodologies; however, no control was used here.

2.2 Response Amplitude Operators (RAOs)

The system response amplitude operators (RAOs) are a good means for understanding the behavior of an offshore wind system due to wave excitation. In the DeepCwind tests, two sets of white noise wave spectrums were used to excite the structure. Both were band-limited to excite frequencies between 0.05 and 0.2 Hz (5-25 s period), which is considered a normal wave-frequency range, but were set to two different energy

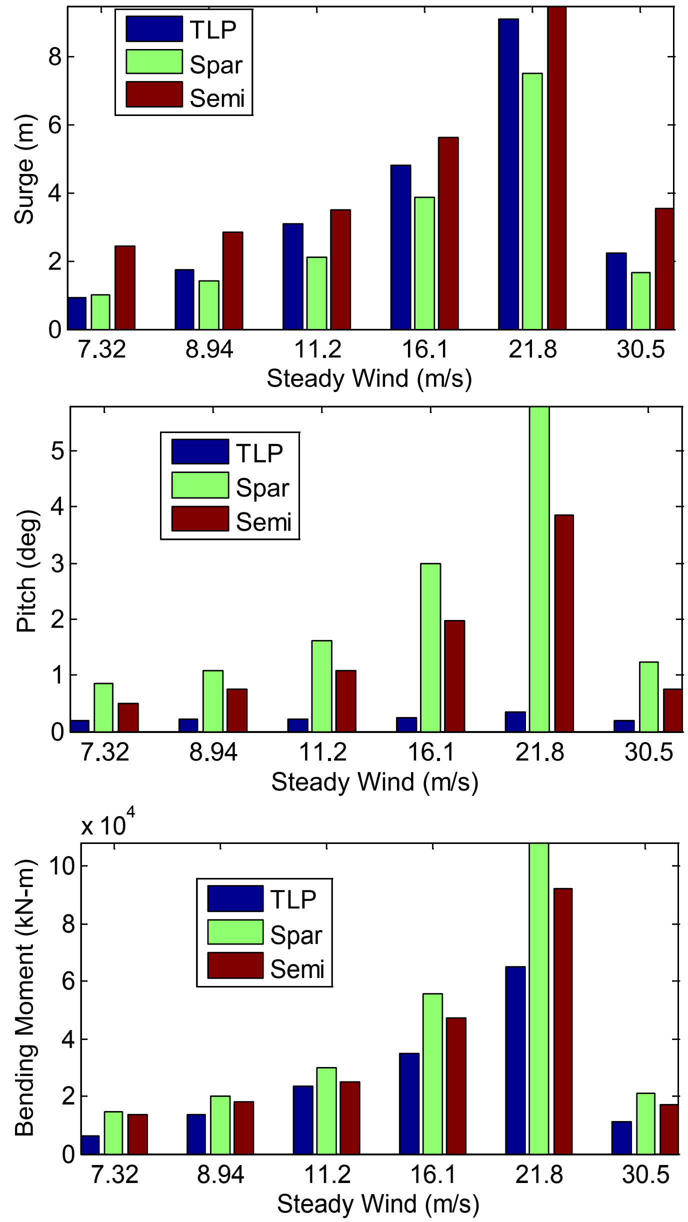

Figure 4. Steady-state response under steady winds for surge, pitch, and tower-base fore-aft bending moment

levels approximating a significant wave height of 7.1 and 11.3 m. Figure 5 shows the RAOs computed from the lower of the two white noise tests, both with steady wind present (at 21.8 m/s), and without. The RAOs were computed by dividing the response spectrum of a given DOF by the wave spectrum.

The three systems were designed such that most of the system modes did not lie in the wave-excitation region, so one can see that there is little response in the 0.05-0.2 Hz range. The only exception is the semi heave natural frequency at 0.058 Hz, which can be viewed in the heave RAO. Outside of the wave frequency range, several frequency peaks are seen, including the surge natural frequencies of all three systems (0.026 Hz – TLP, 0.023 Hz – Spar, 0.0093 Hz – Semi) in the

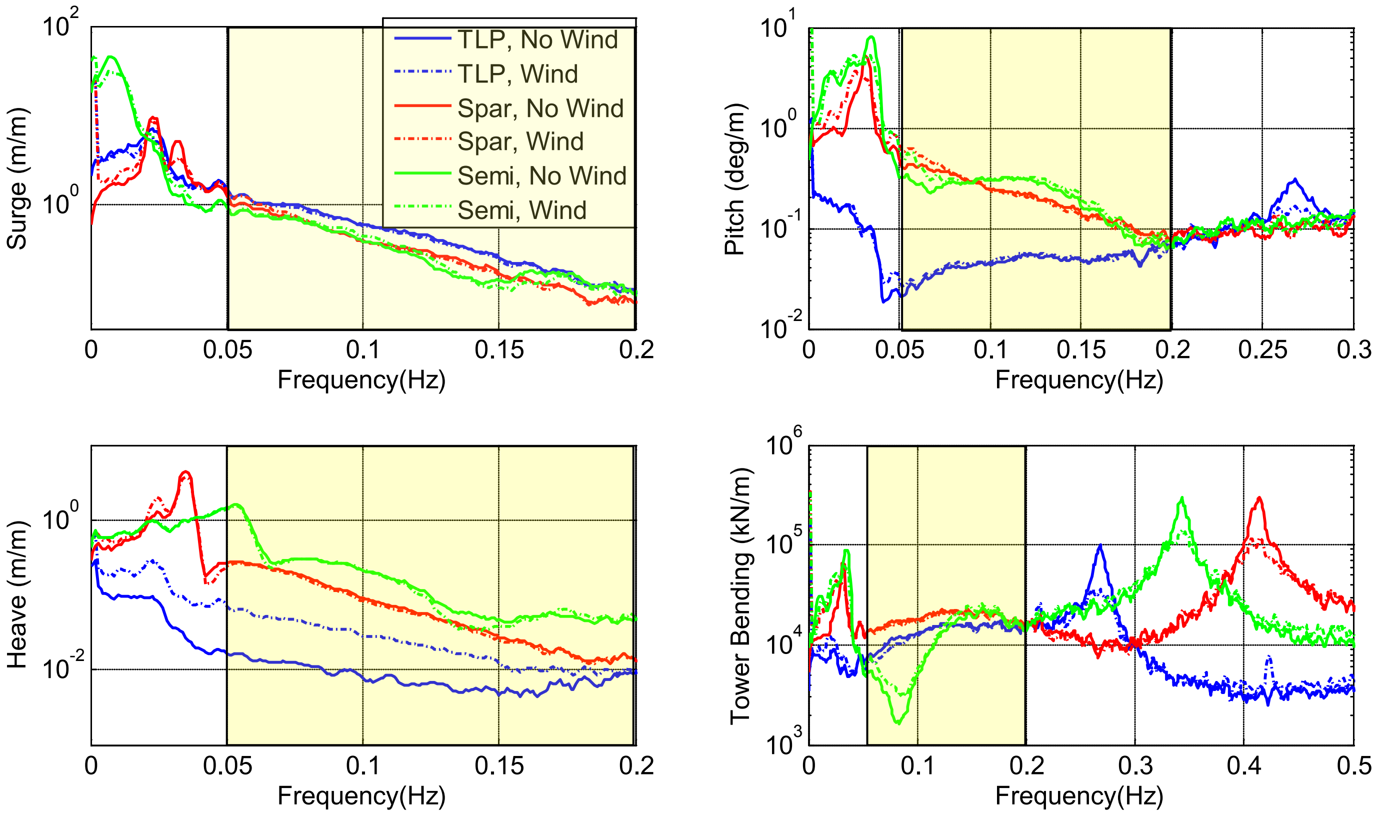

Figure 5. RAOs derived from white-noise wave excitation with 7.1-m significant wave height both with and without wind present at 21.8 m/s; colored box indicates wave frequency range

surge RAO, the pitch natural frequencies of all three systems (0.27 Hz – TLP, 0.031 Hz – Spar, 0.037 Hz – Semi) in the pitch RAO, the heave natural frequency of the spar (0.035 Hz) in the heave RAO, and the pitch and first tower-bending frequencies of the spar and semi (0.43 Hz and 0.35 Hz) in the tower-base bending moment RAO. The heave natural frequency and the first tower-bending moment of the TLP are not seen because they are above the 0.5 Hz frequency range shown here. The frequencies that are excited outside the wave frequency range likely indicate an excitation from second-order hydrodynamics, which will be discussed in the following sections. It is interesting to note that the second-order responses are just as significant as the heave response of the semi, which lies in the wave frequency region, indicating that it may be important to take into account second-order excitation in the design of an offshore wind system.

In general, the RAOs of the systems were relatively unchanged by wind, except at the natural frequencies of the systems where the wind damped the response. The exception to this is foremost in the lower frequency range, which is where the wind energy is highest. Other regions where the wind increases system response include the spar surge response in the 0.035 to 0.05 Hz range, the pitch response of all systems in the wave-frequency range, the TLP heave response at the lower frequencies, and the spar heave response at its surge natural frequency (0.023 Hz). The most noticeable deviation is for the heave response of the TLP, but the response amplitude is very low.

2.3 Second-Order Hydrodynamics

Linear hydrodynamic theory states that the hydrodynamic loads on an offshore wind turbine in an irregular sea can be approximated by superimposing the loads from individual regular wave components. This implies that only frequencies within the wave spectrum should be excited through hydrodynamic loading; but, as shown in the RAOs in Figure 5, in physical tests, frequencies outside the wave-frequency range are excited. This excitation arises from the interaction of the individual waves, which results in mean forces and forces oscillating at the differences and sums of distinct wave frequencies. Second-order hydrodynamic theory captures these effects.

The presence of a mean force from the waves can be seen by the non-zero value of the surge in the wave-only RAOs in Figure 5 at 0.0 Hz, though this could also be contributed to by drift of the sensors. The difference-frequency excitation can be seen in Figure 5 by the presence of frequency peaks below the wave frequency range (0.05–0.2 Hz). Each of the four response DOFs show significant peaks in the 0 to 0.05 Hz range, but the semi has by far the largest difference-frequency excitation.

Sum-frequency excitation can be seen by the presence of frequency peaks above the wave-frequency range. Figure 5 shows significant excitation at the TLP pitch frequency (0.27

Hz) and the tower-bending frequencies of the spar and semi (0.43 Hz and 0.35 Hz). Fewer peaks are seen in the upper frequencies because most of the system frequencies are placed below the wave frequency range. The exception is the TLP system that has pitch, heave (0.86 Hz), and first tower-bending (1.3 Hz) natural frequencies above the wave-frequency range, most of which are above the range plotted in this figure.

2.4 Mooring-Line Behavior

The mooring lines of the spar and semi systems are catenary configurations, which mean that they hang in a curve from the platforms and are predominantly used for restoring stiffness in the surge/sway directions to prevent the systems from drifting away. The TLP, on the other-hand, uses a taut mooring system, which also provides stiffness in the heave and pitch/roll DOFs, significantly limiting the motion of the system in these DOFs. The lack of motion of the TLP can be seen in Figure 5 in the lower magnitude response of the TLP in all DOFs. The trade-off, however, is an increase in mooring tension and unique mooring behavior for the TLP. Figure 6 shows the mooring-tension RAO for the mooring line aligned with the wave direction for each of the systems. For the TLP and spar, this mooring line is downwind of the turbine, but is upwind for the semi.

Sum-frequency forces can be problematic for the mooring lines of TLPs, which is evident in this RAO. In addition to response in the wave-frequency range (0.05-0.20 Hz), two significant peaks are seen at the pitch natural frequency (0.27 Hz) and the heave natural frequency (0.86 Hz). This type of response in a TLP is called springing, and can contribute to fatigue in the structure and in the mooring lines. In addition, for the case with wind, the TLP shows a response around 0.64 Hz, which is the 3P frequency of the rotor. This shows that dynamic excitation at the blade passage frequency can also excite the mooring lines, illuminating the coupled nature of the system response.

In addition to springing, TLP mooring systems can also create a ringing phenomenon, which is the broad-band frequency excitation of the mooring line due to a sudden loading of the line. Ringing can occur when a mooring line goes slack and then snaps back, or when a wave breaks over the platform. In the DeepCwind tests, ringing was observed due to slack-line events for the following cases: (1) the higher of the two white-noise cases without wind, (2) an operational case with winds at 21.8 m/s and a significant wave height (H_s) of 7.1 m, (3) a survival wave-only case with 10.5-m H_s, and (4) a survival case with winds at 30.5 m/s (turbine turned off) and an H_s of 10.5 m. The slack-line events occur just after a significantly large wave passes, as seen in Figure 7, with high-frequency ringing occurring just after. In the design of TLPs, slack-line events should be avoided, as the large loading and broad-band frequency excitation in the structure could cause significant damage. The presence of these events indicates that this TLP design was not sufficiently robust.

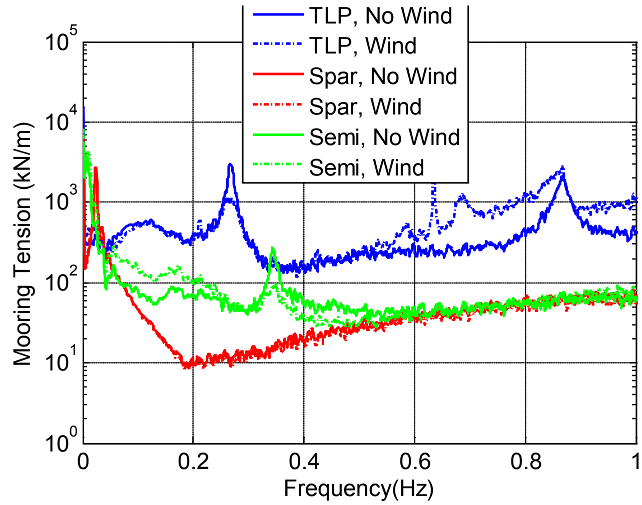

Figure 6. Wave-oriented mooring-line tension RAO from white noise waves (7.1 H_s) with and without wind (21.8 m/s)

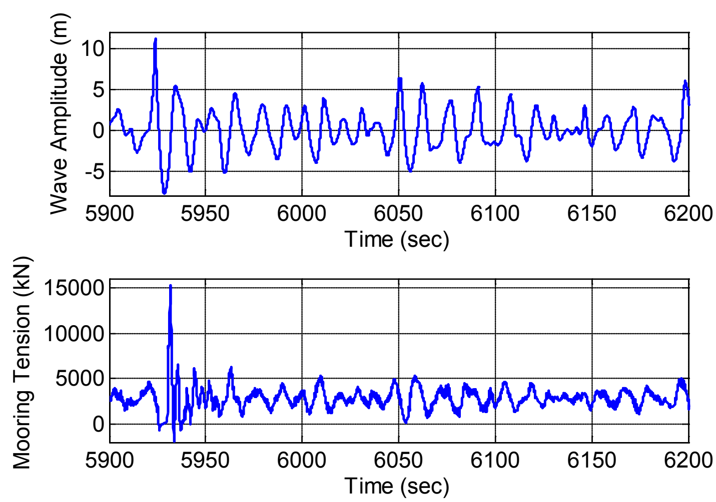

Figure 7. Ringing event for survival wind/wave case with H_s = 10.5 m and wind = 21.8 m/s

3. VALIDATION OF FAST

With DOE support, NREL has developed and maintains a robust open-source, modular CAE tool known as FAST, with state-of-the-art capabilities for modeling offshore wind systems. One of the key reasons for performing the DeepCwind tests was to obtain data for validating FAST as a tool capable of modeling the dynamic behavior of offshore wind turbines. FAST has been successfully verified and validated for land-based wind turbines, and the offshore functionality of FAST has been verified through model-to-model comparisons under the NREL-led International Energy Agency (IEA) Wind Task 23 Offshore Code Comparison Collaboration (OC3) project and the ongoing NREL-led OC3 Continuation (OC4) project, which operates under IEA Wind Task 30. However, data has not been available until recently for validating the offshore functionality of FAST and the coupled system response due to combined aerodynamic and hydrodynamic loading.

Validation of FAST is defined as the comparison of simulated responses from FAST to experimental test data. The DeepCwind tests have provided data useful to this process. In the following subsections, FAST simulations are compared to the DeepCwind tests to understand the limitations of the FAST tool in accurately modeling the dynamics of offshore wind systems.

3.1 Testing Issues

Efforts have been made to build validated models of each of the three floating systems within FAST; see Coulling [9], Browning [10], and Prowell [11]. Part of the process in building these models was a calibration step to tune system parameters so that simulation responses matched the behavior of the systems from a small subset of the tank tests. While tuning parameters can create a model that will give the right results, one must understand why the tuning is needed to be assured that the simulation tool (FAST) is working correctly. Even with this knowledge, the calibration process can mask issues with the model that are not well understood.

In the DeepCwind tests, issues arose that required calibration of the models created in FAST. First, the turbine/tower sensors and their cabling needed to be accommodated for in the model. This was accomplished by adding weight to the system at the location of each of the sensors, and at each of the node points on the tower where the cabling was tied to the tower. It was assumed that the cabling added negligible stiffness to the tower, but that the two force sensors at the top and bottom of the tower altered the tower stiffness. These connection points, as well as a connection point in the middle of the tower, could add compliance to the tower. In the end, all three systems needed to decrease the stiffness of the tower to achieve a match between the tower modal properties of the FAST model and the experimental tests.

The aerodynamics model also needed calibration due to test limitations. As mentioned in previous papers ([6], [12]), the altered performance of the wind turbine at model scale required large alterations to the airfoil data from what is appropriate at full scale. An attempt was made to create this model within XFOIL [13], but due to its questionable ability to model the separated flow experienced by this turbine, tuning of the lift and drag curves was needed using the experimental data.

Third, the wind in the tank is not as consistent as is possible in a wind tunnel. There were drop-offs in the wind velocity and increased turbulence at the edges of the rotor plane, as well as some low-level swirling behavior. To obtain an appropriate representation of the wind, a shear law with an exponent of 0.0912 was needed to represent the change in wind speed with height, as well as a slight decrease (a factor of 0.952) in the average wind speed. No accommodations were made in the simulations for the vertical wind speed components or turbulence variations. This helped to match the wind excitation; however, there was still unmodeled wind behavior in the FAST model due to not having a full spatial and temporal characterization of the velocity. These inconsistencies in the wind induced unwanted excitation in the system (such as the 3P, 6P, and 9P frequencies seen in Figure 3) that were not modeled in FAST, and therefore influenced the validation process.

The testing issues described in this section, as well as uncertainty in model properties and limitations of FAST, inhibited the ability to directly validate FAST using the tank test data. In some cases, calibration was performed to more closely match the response in the tank. Calibration procedures were performed to achieve the correct displacement in the water, the correct quasi-static mooring behavior, and the correct system frequencies and damping.

In the remainder of this section, we will discuss the limitations identified for FAST through this validation process.

3.2 Hydrodynamics

The hydrodynamic loading on an offshore wind turbine is typically categorized into contributions from hydrostatics, excitation from incident waves (including diffraction and Froude-Kriloff forces), radiation from outgoing waves (generated by the platform motion), added mass effects, and viscous forces. There are many different approaches to modeling these hydrodynamic forces. The two main approaches involve Morison's Equation - an empirical formulation typically used to describe the inertia, added mass, and viscous drag loads on slender structures; and, potential-flow theory, which defines the radiation and diffraction loads important for larger structures not subject to flow separation. FAST uses a combination of these two formulations to describe hydrodynamic loads, but with limitations. One limitation is that FAST presently only models the viscous drag forces on the central column of the structure. Second, FAST currently only uses the first-order approximation of the radiation and diffraction problem. The influence of these modeling assumptions will be discussed below.

Viscous Drag

Because the viscous-drag effects in FAST are only defined for the central column of the structure, this means that viscous drag on the arms of the TLP and the offset columns and cross members of the semi will not be modeled. This drag can have significant effects on the damping of the system motion. The DeepCwind tests showed that the system damping was under-predicted by the FAST models of all three systems, most likely due to this lack of viscous drag modeling on the TLP and semi. For the spar, this could be a result of not modeling the damping of the mooring lines. To accommodate this limitation, quadratic drag was artificially added to the FAST models globally, with one quadratic drag coefficient per mode of motion. The values for the drag coefficients were chosen such that the FAST simulations matched the damped behavior of the systems during the free-decay tests.

Second Order Hydrodynamics

As discussed in the section above, RAOs from the DeepCwind tests showed the presence of frequencies outside the wave-excitation range, which were assumed to be excited by the interaction of the wave components of the irregular,

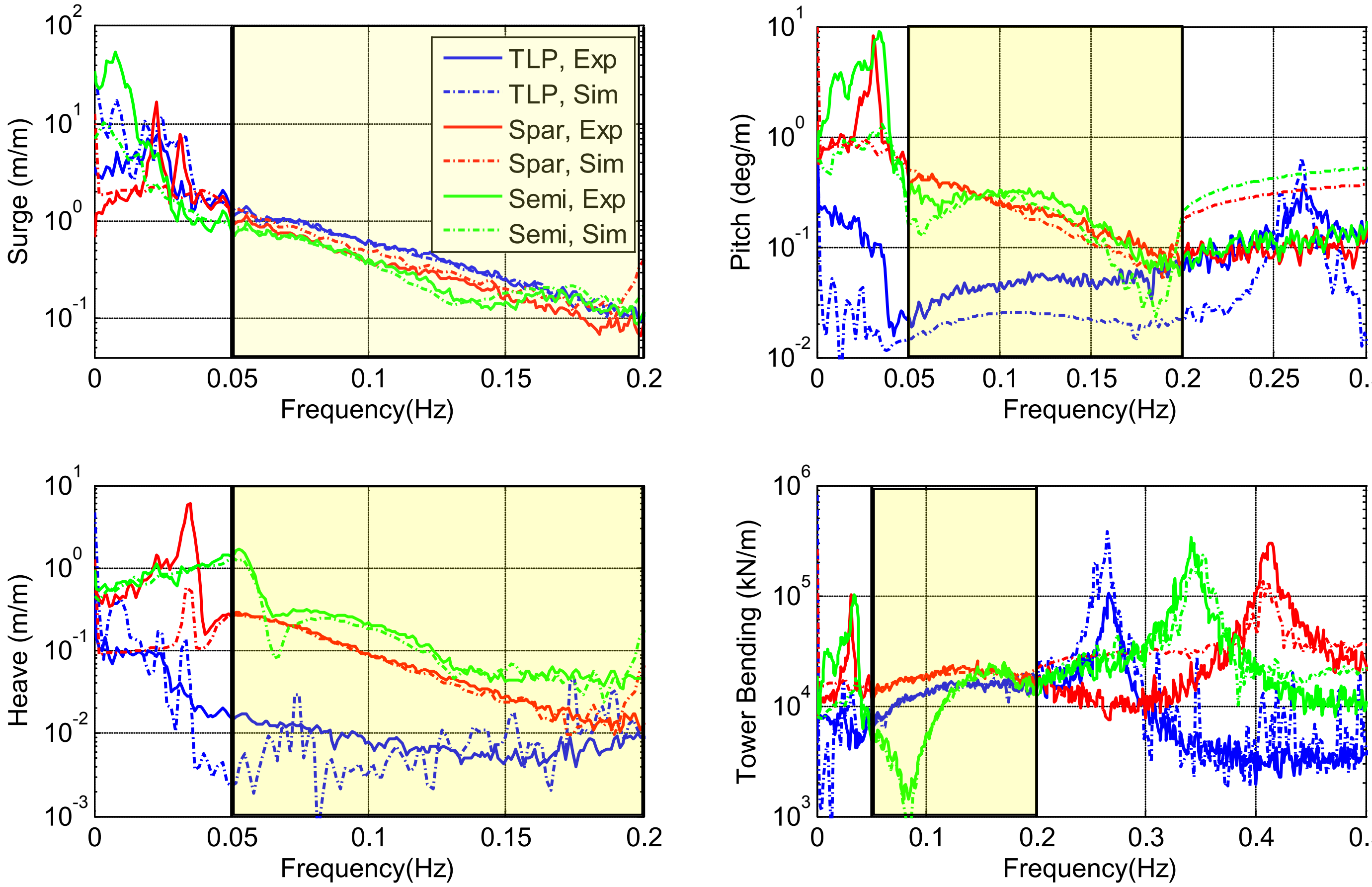

Figure 8. RAOs derived from white-noise wave excitation with 7.1-m significant wave height both from FAST simulations (sim) and the experimental data (Exp); colored box indicates wave frequency range

white-noise wave. In the present version of FAST, a linear approximation is used for the diffraction problem. A second-order model of the diffraction is needed to capture hydrodynamic loads at the sum and difference-frequencies of the waves.

To examine the influence of omitting second-order hydrodynamic effects, Figure 8 shows a comparison of the RAOs calculated for the white noise, wave-only experiment with 7.1 m H_s to RAOs generated from FAST simulations. Once again, the white noise excitation was band-limited to frequencies between 0.05 and 0.2 Hz. The RAOs show fairly good agreement between the experimental and simulated data in the wave region, with the exception of the TLP in the pitch DOF. Previous papers have highlighted issues in achieving good agreement for the pitching motion between the FAST model developed for the TLP and the experimental data, in large part due to the inability to accurately measure the small pitching motion of the TLP in the tank. Further discussion of the topic can be found in Prowell [11].

The FAST model is a nonlinear model and so some excitation outside the wave frequency range will occur, as can be seen in Figure 8. The peaks outside the wave frequency range are, in general, much smaller in the simulated response than those observed in the experimental data, and we assume that this difference is the contribution of second-order effects.

In addition, some of the excitation outside the wave frequency range could be caused by transient behavior produced by the initial interaction between the waves and structure, which has not completely died out. The results presented here do not consider the first 2,000 seconds of the simulated FAST data in an attempt to remove transient behavior, but this time may need to be increased. The tests perform a ramp-up of the waves over a long period of time, and this portion of the response is also removed.

Figure 9 shows results from Coulling, et al. [9] to approximate the influence of second order difference-frequency diffraction terms added to FAST using Newman's approximation. Surge displacement is presented for an irregular wave-only test with a peak spectrum of 0.133 Hz, or wave period (T_p) of 7.5 s. The wave energy is clearly seen in this figure starting at about 0.08 Hz, but the largest peak is the surge frequency of the system (0.0093 Hz), which is well below the wave-excitation range. Using a linear solution, FAST severely underestimates the response at the surge natural frequency; however, using Newman's approximation, FAST is able to get much closer to the experimental data. Tuning the damping of the system allows FAST to match the surge response almost

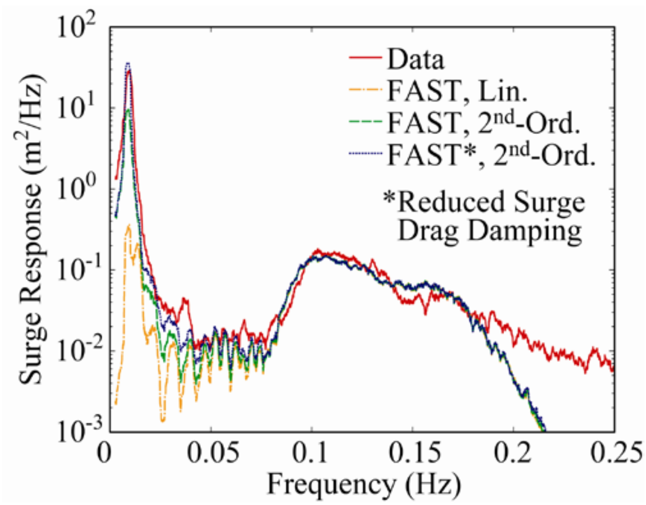

Figure 9. Comparison of simulated to experimental surge response of the semi for a regular wave-only test (T_p = 7.5 s)

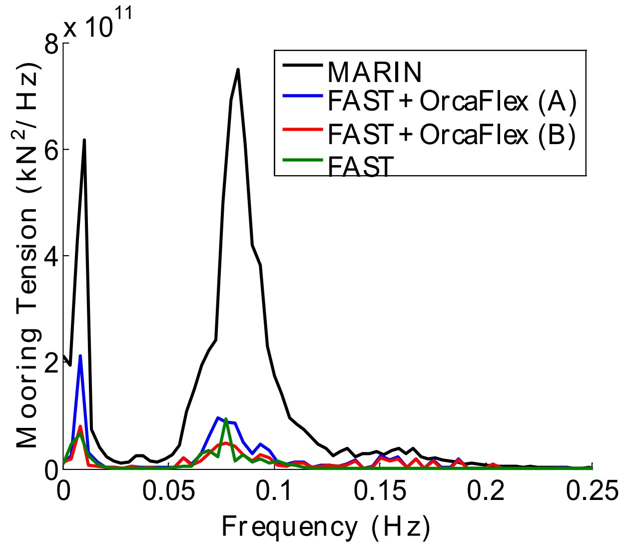

Figure 10. Mooring line forces for a wave-only case, Hs = 7.04 m , Tp = 12.18 s JONSWAP spectrum

exactly. This example shows that second-order hydrodynamics are needed within FAST to capture the appropriate system behavior.

3.3 Mooring Model

The mooring-line model used within FAST is a quasi-static, catenary solution, which means that it is able to capture the nonlinear mooring tension associated with slowly-varying motion. The model does not include dynamics of the cable itself, or drag on the cable from the interaction of water.

Mooring Dynamics

These two limitations were investigated by Masciola [14] in terms of the significance in FAST's ability to model the mooring-line behavior observed in the DeepCwind tests. For the wave-only JONSWAP excitation case with H_s = 7.04 m (see Figure 10), it was found that a FAST model of the semi significantly underpredicted the mooring tension for line 2, which is in line with the wave excitation. The discrepancy between the results at the surge natural period is theorized to be caused by the presence of difference-frequency diffraction excitation in the tank, which is not present in the FAST model. This is confirmed by an underprediction of the surge motion of the structure at the surge natural frequency (see Masciola [14]). The surge and heave motion, however, match well in the wave-frequency range (0.05 to 0.20 Hz), but the mooring response is different.

To examine this behavior more closely, Masciola modeled the DeepCwind semi-submersible system in a coupled FAST-OrcaFlex model [14], which has the ability to model the dynamics of the moorings and the drag on the lines along with the turbine dynamics. These results are presented with the MARIN experimental results and FAST results in Figure 10. The OrcaFlex (A) solution does not deviate far from the FAST solution in the wave frequency region, implying the mooring dynamics and cable drag do not influence the ability to capture mooring tension at the wave frequencies. The reason for the major difference in the mooring tension between the MARIN tests and numerical models is unknown, but the presumption is that it is related to the simplification of the mooring line representation within the modeling tools. Because the mooring tension does not affect the global motion of the structure for this case, the limitation in FAST is in the ability to capture the large mooring loads, which need to be known to correctly design the mooring system to avoid failure. Masciola did find that for larger wave scenarios, the mooring dynamics and drag were important in capturing the correct mooring behavior, so this work solidifies the need for these capabilities within FAST. Further investigation is needed to understand the limitations of both the FAST and OrcaFlex models in being able to capture the correct interaction between the waves and the mooring.

Slack-line Events

During the DeepCwind tests of the TLP, several slack-line events occurred for wave-only and combined wind/wave cases with large wave heights. Each of the events was caused by the passing of a large wave that allowed the tension in one of the tendons to go negative as the trough of the wave passed the structure. FAST was able to predict some of the slack-line events, but not all of them (see Prowell [11] for more details). One of the reasons was that the FAST simulations used a wave spectrum that only approximated the waves used in the tests, but did not have the exact same wave elevation time series. So, FAST did not always simulate waves as extreme as those occurring in the tests. Other issues are that FAST does not model the second order pitch loads and the wind drag on the tower and the exposed portion of the platform above the waterline. This increased loading could contribute to the pitching of the system and the development of slack-line events.

4. CONCLUSIONS AND RECOMMENDATIONS

The two main purposes for the DeepCwind testing campaign were to better understand the behavior of floating offshore wind systems and to obtain experimental data to be used for validating offshore wind system modeling tools. The tests were essential in meeting these goals, and were groundbreaking in regard to producing data that will be made publicly available. This section summarizes the lessons learned from the experimental tests in regard to the limitations of FAST as a modeling tool for offshore wind turbines, as well as the scaled-model testing of these systems.

4.1 Suggestions for Future Test Campaigns

From this process, we are able to share some of the lessons learned involving what to do differently if future testing of this kind were to be pursued. First, in regard to the testing methodology itself, here is a list of suggestions for future test campaigns:

- **Scaling approach:** While a Froude-based scaling approach is, in general, a sound methodology, the approach must be modified in regard to the rotor due to the aerodynamic loading being so dependent on Reynolds number. It is suggested that future coupled wind/wave turbine testing under a Froude-scaled environment should use a blade geometry which is specifically designed for a low Reynolds number environment [8]. This can easily be accomplished by simply increasing the blade chord, which is often done in wind tunnel tests. While the blade geometry will likely not represent the full-scale architecture, the blade should be designed to increase torque output, match full power and thrust coefficient curves and, if possible, closely match the change in total blade lift force with respect to blade pitch. The first two points will ensure that the global mean forces on the structure are maintained in a Froude-scaled environment, while the second will help maintain the effect of turbine damping forces due to either changing wind speed or global motion of the floating wind turbine structure.
- **Instrumentation:** The DeepCwind tests highlighted the importance of having instrumentation that is light-weight and does not alter the dynamic behavior of the offshore wind system. At $1/50^{th}$ scale, the systems are so small that the weight of the sensors and the cabling becomes significant. The effect of the cable bundle on the dynamics of the systems in the DeepCwind tests could not be fully characterized. Therefore, it is suggested that, if possible, wireless sensors or smaller cabling should be used for small-scale testing. In addition, we suggest avoiding adding additional compliance to the tower through sensor placement, such as the load sensors used in these tests. If they are needed, periodic inspection should be done to assess that the tower properties have not changed due to loosening of a joint, perhaps through hammer tests.
- **Wind quality:** It should be the normal procedure in offshore testing to apply the correct wind load instead of the correct wind speed. The wind load should be correct in all directions relative to the model. Finally, the wind should be modeled as a constant force or with the appropriate wind spectrum to take into account real wind gusting.
- **Wind turbine testing:** An integral part of validating an offshore wind modeling tool is building an accurate model of the wind turbine. For the DeepCwind tests, the performance of the wind turbine limited the ability to model it accurately within FAST, and instead, the FAST model had to be tuned to represent the behavior of the test turbine. In future campaigns, it would be advantageous to validate the wind turbine behavior independent of the support structure. This was done partially in the DeepCwind tests by fixing the wind turbine in the tank testing. However, with the limited wind quality of the tank, it would be best to first perform testing of the wind turbine in a wind tunnel, to be able to accurately validate a model of the turbine.

Second, in regard to providing data to validate offshore wind modeling tools, a list of suggestions are given to better provide the data needed:

- **Focus on water/structure interaction:** Since FAST was originally a land-based wind turbine modeling tool, extensive work has previously been done on verifying and validating the aerodynamic models used. The validation of FAST as an offshore wind turbine modeling tool should therefore be most focused on validation of the hydrodynamic loads and the coupled system behavior. Future testing campaigns should isolate and focus more closely on hydrodynamic loads. Performing wave-only cases as was done supports this. In addition, current-only tests would be beneficial in isolating the viscous-drag loading on the structure from the water. Viscous loading for a single cylinder is well understood, but its loading contribution for a complicated structure such as the TLP and semi with multiple connecting members is more complex. In addition, it may be good to step back and also do some component-level tests. For example, it would be good to include a test that examines the drag on a cylinder of the same size as the column of the semi in a current. This will help identify whether test/simulation inconsistencies come from the modeling of the water/structure interaction or effects of water blockage by complicated geometry.
- **Obtain a higher-quality wind excitation:** While measures were taken to reduce swirl and turbulence, there was still significant change in velocity and turbulence in the lower region of the rotor. The more consistent the wind can be, the better we would be able to assess modeling approaches.
- **Focus on steady wind**: As asserted by Kimball [15], the FAST simulations predicted the response of the systems for steady wind with reasonable accuracy, but not for dynamic wind. Therefore, for model validation purposes, we propose focusing more on steady-wind tests. Until we can accurately predict the response for steady wind, there is limited advantage in moving to dynamic wind tests.

However, dynamic wind tests will be important in understanding the coupled behavior of the system and should be performed once confidence is obtained for steady-wind tests and one can produce a well-defined dynamic wind condition.

- **Damping**: Coulling [9] shows discrepancy in the tower-bending response between simulation and experiment for the semi, but is unsure whether this is due to second order excitation or incorrect modeling of damping. Tests should be performed to better estimate the damping value—either by means of a hammer excitation test or purposely having a wave excitation in this frequency band.

4.2 FAST's Modeling Limitations

Based on the validation work from the DeepCwind tests, the following limitations of FAST have been identified as important areas for improvement to successfully model a floating offshore wind system:

- **Viscous drag:** FAST can only model viscous drag for a constant-diameter cylinder at the centerline of the platform. This is a severe limitation for structures such as the semi that has columns offset from the centerline and the TLP that has arms off the centerline, causing the need to add additional damping to the structure to match the response seen in the tank tests.
- **Mooring model:** FAST uses a quasi-static mooring line model. The main limitations of this model are that it cannot capture the dynamic characteristics of the mooring line, it does not model the interaction between the water and the mooring line, and it does not model the dynamic interaction between the mooring line and the seabed. These limitations result in an underprediction of forces in the mooring line and the inability for the mooring line to induce dynamic excitation in the structure, or perhaps damp dynamic behavior of the structure.
- **Second-order hydrodynamics:** FAST uses a linear diffraction model that does not capture the mean drift force, difference-frequency excitation, and sum-frequency excitation captured by second-order models. This means that not all frequency excitation of the system is being captured by FAST, which could result in an under prediction of fatigue estimates and extreme responses.
- **Wave models:** FAST models wave excitation through a definition of the wave spectrum. In general, this is a sufficient approach for modeling the wave excitation on a given design. However, for validation purposes, it would be beneficial to directly input a time signal of the wave height so that tests and simulations could be more directly compared.
- **Other:** While the tests did not reveal this, other improvements to FAST are also important for accurate modeling of large-scale floating wind systems, including higher fidelity structural and aerodynamic modeling.

4.3 Future Efforts to Complete Validation of FAST

The present limitations of FAST's modeling capabilities for both hydrodynamics and mooring line dynamics prevents the ability to fully validate FAST as a tool for modeling offshore wind turbines. Work is presently ongoing to augment FAST's modeling approach to overcome the limitations identified. When this work is complete, efforts will be redone to compare the DeepCwind data with the new and improved FAST simulation tool.

The comparison work with the DeepCwind data is just one step toward the validation of the coupled offshore floating wind system solution of FAST. FAST's simulation capabilities will also need to be compared to other datasets to ensure a complete validation of the tool. Work is ongoing to compare FAST simulations to those from deployed, open-ocean floating offshore wind systems. In addition, future efforts will be focused on obtaining and comparing data from fixed-bottom structures, such as monopiles, jackets, and tripods that have their own unique characteristics that differ from floating systems. While FAST can be validated for a set of generic structures, it may have limitations for structures that deviate from FAST's modeling approach or assumptions. Examples include structures that have sloped or multiple towers.

On the aeroelastics side, FAST is also presently being modified to be able to model the torsional motion of the blades. This degree of freedom has been identified as being important for the larger-sized blades that are anticipated for use on offshore wind turbines.

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