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Verification and Validation of Multisegmented Mooring Capabilities in FAST v8

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ABSTRACT

The quasi-static and dynamic mooring modules of the open-source aero-hydro-servo-elastic wind turbine simulation software, FAST v8, have previously been verified and validated, but only for mooring arrangements consisting of single lines connecting each fairlead and anchor. This paper extends the previous verification and validation efforts to focus on the multisegmented mooring capability of the FAST v8 modules: MAP++, MoorDyn, and the OrcaFlex interface. The OC3-Hywind spar buoy system tested by the DeepCwind consortium at the MARIN ocean basin, which includes a multisegmented bridle layout of the mooring system, was used for the verification and validation activities. This paper focuses on free-decay tests because the influence of the multisegmented moorings is most important for yaw motion, which is not excited by waves. All of the listed modules are able to represent the platform motion observed in the experimental data to a satisfactory degree. MoorDyn and the benchmark tool (OrcaFlex) yield almost indistinguishable results. But due to limitations of the system tested and data obtained, further work is needed to truly validate the multisegmented capability.

KEY WORDS: Floating offshore wind turbine; multisegmented mooring; modeling; verification; validation

INTRODUCTION

Offshore wind turbines are designed and analyzed using simulation tools (i.e., computer design codes) capable of predicting the coupled dynamic loads and responses of the system to prescribed environmental conditions. As these turbines are moved to deeper waters, the substructure used to fix the system to the sea floor is replaced

by a floating platform constrained by moorings. For these floating systems, the ability to accurately predict the loads in the mooring lines is integral to the design process to ensure the safe operation of the offshore turbines.

Two tools that are commonly used for the design of floating offshore wind systems are the open-source aero-hydro-servo-elastic wind turbine simulation tool FAST, developed by the National Renewable Energy Laboratory (NREL), and FAST coupled to the commercial-software tool OrcaFlex. To achieve a more accurate estimation of the loads in the mooring lines without using OrcaFlex, the newest version of FAST (version 8) was updated to include two new mooring modules: MoorDyn and FEAMooring. These mooring modules are in addition to the previously available mooring module, MAP++. The two new mooring modules offer the capability of modeling the dynamics of the mooring lines, which greatly improves the accuracy of the mooring load predictions, as demonstrated in the verification and validation of these modules in (Wendt et al., 2016). In addition, MoorDyn offers the ability to model multisegmented lines, such as a bridle connection, which is important for some mooring configurations. MAP++ also offers the capability of modeling multisegmented moorings, but it does not consider the dynamics of the mooring lines. This paper focuses on verifying and validating the capabilities of FAST v8 in modeling systems that have multisegmented mooring designs, which is possible using either the MAP++ or MoorDyn mooring modules. (FEAMooring does not have this capability.)

The verification and validation of the multisegmented mooring capability was performed using the OC3-Hywind spar buoy system (Fig. 1) tested by the DeepCwind consortium at the MARIN ocean basin (Goupee et al., 2012). This system was chosen because the

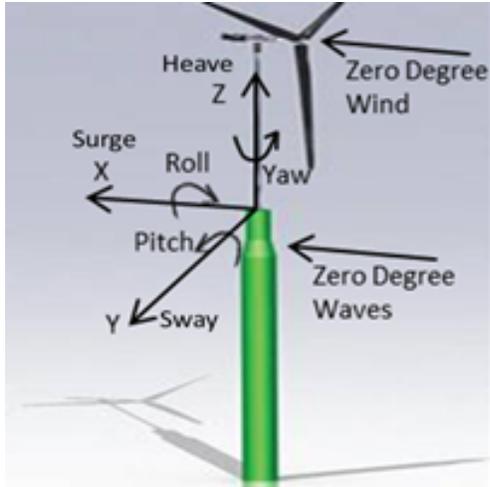


Fig. 1. Convention for degrees of freedom of the system.

platform relies on a multisegmented bridle layout of the moorings to obtain sufficient yaw stiffness, and both numerical and experimental data are available. Verification was accomplished by comparing simulations of the OC3-Hywind system with the two mooring modules (MAP++ and MoorDyn) to simulations performed in FAST v8 coupled to OrcaFlex. OrcaFlex (OrcaFlex, 2015a) is a comprehensive commercial maritime engineering tool that is widely used for the design and analysis of floating systems in the offshore industry, and the mooring line modeling capabilities have therefore already been extensively verified and validated (OrcaFlex, 2015b). Validation was then accomplished by comparing the simulations from all three models to measured test data from the DeepCwind test campaign (Goupee et al., 2012). The validation in this paper is limited to the use of free-decay tests because the influence of the multisegmented moorings is most important for yaw motion, which is not sufficiently excited in the wave tests. Due to limitations of the system tested and data obtained, further work is needed to truly validate the multisegmented capability.

Moreover, the comparison of the MoorDyn and OrcaFlex modeling results to the results obtained from MAP++ show the improvements obtained with the mooring dynamics modeling capability. In addition, the MAP++ and MoorDyn modeling results with the multisegmented mooring layout (Fig. 2) are compared to those from models that have single mooring lines (bisecting the bridle) and an additional yaw spring to augment the yaw stiffness, as has been considered in previous FAST-based studies of the OC3-Hywind system, to show the improvements obtained by the multisegmented modeling capability. But ultimately the aim is to circumvent the need for this by proper direct modeling of the multisegmented moorings via the new mooring capabilities in FAST v8.

The remainder of this paper is outlined as follows. The next section provides a description of the properties and differences among each of the mooring modules that are compared in the paper.

Then the properties of the OC3-Hywind system are given, along with the tuning that was needed to get the models of this system to better match the response seen during testing. Results are presented and discussed in terms of impact on verification and validation. Finally, conclusions are drawn, and recommendations based on the work are given.

MOORING MODULE DESCRIPTIONS

MAP++

MAP++ is the previously available quasi-static mooring model available in FAST v8 that was developed by Marco Masciola while both at the NREL and the American Bureau of Shipping (Masciola et al., 2013). It is a relatively simple model that allows for a robust first-pass evaluation of a mooring system by considering the average mooring line loads and nonlinear geometric restoring for both catenary and taut mooring systems. MAP++ simultaneously solves the nonlinear analytical catenary equations for individual lines with elastic stretching and the apparent weight of the lines in water as well as the force-balance equations at the line-to-line interconnections points (for two or more lines), where clump weights and buoyancy tanks may also be located. MAP++ also accounts for seabed friction, which is presently not considered by the two new dynamic mooring modules, MoorDyn and FEAMooring. MAP++ does not consider any dynamic line loads (neither structural inertia nor hydrodynamic drag and inertia loads), nor does it consider line bending stiffness and the three-dimensional shape of lines (each individual line in MAP++ lies within a vertical two-dimensional plane). MAP++ went through a thorough code-to-code verification, which was carried out at NREL as part of the verification of the new hydrodynamic capabilities available in FAST v8 (Wendt et al., 2015). MAP++ has also been validated against wave tank test data from test campaigns with singlesegment mooring lines (Wendt et al., 2016) (Coulling et al., 2013) (Prowell et al., 2013). Prior to this publication, MAP's multisegmented mooring line capabilities had not been validated against wave tank test data.

MoorDyn

MoorDyn was developed by Matthew Hall at the University of Maine (Hall, 2015). It is based on a lumped-mass modeling approach that is able to capture mooring stiffness and damping forces in the axial direction, weight and buoyancy effects, seabed contact forces (without friction) and hydrodynamic loads from mooring motion using Morison's equation. Bending and torsional cable stiffness are not con-

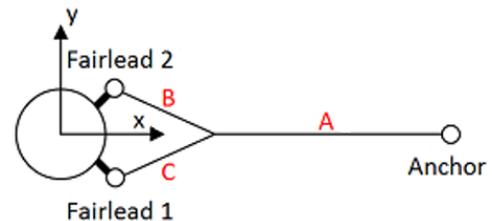


Fig. 2. Top view; conceptual sketch of bridle mooring configuration.

sidered. MoorDyn also allows for modeling segmented cables with multiline connection points (e.g., bridle configurations). Presently, there is no direct coupling between MoorDyn and FAST’s HydroDyn module, which means that all hydrodynamic line loads are computed in still-water conditions. For a system without multiline connections, MoorDyn has been successfully validated against wave tank test data from a previous 2011 test campaign of the DeepCwind system (Hall and Goupee, 2015). This validation was conducted with a stand-alone version of MoorDyn as well as with a version that was coupled to a previous release of FAST. The verification and validation of this dynamic mooring module coupled to FAST v8 can be found in Wendt et al. (2016).

FAST-OrcaFlex

OrcaFlex is a comprehensive commercial maritime engineering tool that is widely used for the design and analysis of floating systems in the offshore industry. It contains a proprietary lumped-mass-based mooring line model that has been extensively verified and validated against real-world systems (OrcaFlex, 2015b). OrcaFlex is considered the benchmark solution in this paper.

MODEL DESCRIPTION

General Model Properties

The current model of the OC3-Hywind spar is based on the work of Browning et al. (2014). The experiments have all been conducted at 1:50 scale, but in the present paper all dimensions and results are reported in full-scale values. The DeepCwind tests of the OC3-Hywind were conducted with taut mooring, which will also be the case for the models presented in this paper. Table 1 shows some of the dominant characteristics of the system. Note that the values presented for the mooring are mainly from the DeepCwind test campaign. Changes to these values to better match the experimental data as suggested by Browning et al. (2014), are the platform displacement and the mooring line length, diameter, mass, and stiffness. Added mass and drag coefficients for the lines are standard values proposed by Hall (2015).

Model Configurations

FAST v8 models with five different mooring configurations were built for comparison:

1. MAP++ with three single mooring lines (bisecting the bridle).
2. MAP++ with three multisegmented bridle moorings.
3. MoorDyn with single mooring lines (as in 1, but with mooring dynamics via MoorDyn)
4. MoorDyn with multisegmented bridle moorings (as in 2, but with mooring dynamics via MoorDyn)
5. OrcaFlex with multisegmented moorings (as in 4, but with OrcaFlex) – considered the benchmark in the comparisons.

For simplicity, the capabilities of the five different model setups are listed in Table 2. To obtain comparable results, the quasi-static single

Table 1. Model properties of full-scale OC3-Hywind turbine concept.

Wind Turbine		
Tower-Base Height (above MSL)	10.0	m
Hub Height	89.6	m
Blade Length	61.5	m
Tower-Top Mass	394.5	10 ³ kg
Tower Mass	303.1	10 ³ kg
Platform		
Total Length	130.0	m
Draft	120.0	m
Diameter (of Main Draft)	9.4	m
Displacement	7947.8	m ³
Platform Mass	7279.6	10 ³ kg
Platform Roll and Pitch Inertia*	3966.2	10 ⁶ kg m ²
Platform Yaw Inertia*	98.6	10 ⁶ kg m ²
<i>*Defined about the platform center of mass.</i>		
Mooring		
Fairlead Depth	70.0	m
Fairlead Radius	5.2	m
Anchor Depth	200.0	m
Anchor Radius	445.0	m
Unstretched Single Line Length	450.5	m
Unstretched Line Length, A	423.6	m
Unstretched Line Length, B, and C	30.0	m
Line Diameter	90.0	10 ⁻³ m
Mass per Length	13.5	kg/m
Cross-sectional Axial Stiffness (EA)	106.0	10 ⁶ N
Transverse Added Mass Coefficient	1.0	-
Tangential Added Mass Coefficient	0.0	-
Transverse Drag Coefficient	1.6	-
Tangential Drag Coefficient	0.1	-

Table 2. Overview of model configurations

	Quasi-static	Dynamic
Single line	Model 1	Model 3
Multisegmented line	Model 2	Models 4 & 5

line model (1) needs an additional yaw spring-damper to augment the yaw response as has been used in previous FAST-based studies of the OC3-Hywind system. This is, to a lesser degree, also the case for Models 2 and 3. This yaw spring-damping will be described later.

Model Calibration

All models have been tuned with an additional platform heave damping of 71×10^3 N-m/(rad/s) to better match the heave free-decay of the system (Browning et al., 2014). The different mooring configurations are expected to have a significant impact on the yaw stiffness and damping. As mentioned, the simplified mooring layout with a single line from anchor to fairlead can be tuned to closely match the behavior of a multisegmented mooring configuration (at least in terms of response of the spar). This paper will determine estimates for the required additional yaw stiffness and damping via physical system decay tests.

RESULTS

From the DeepCwind test campaign at MARIN, different data sets are available. These sets include decay tests, regular wave tests, irregular wave tests, as well as sets with different combinations of wind/waves. It is important to note that the models simulated via the FAST/OrcaFlex interface have both their moorings and hydrodynamics solved externally in OrcaFlex. This gives rise to some inherent minor discrepancies relative to the results with standalone FAST because the differences in the input are more extensive than only altering mooring configurations.

Decay Tests

Decay tests are useful for system identification and tuning. In the following they are used to display the simulated decay tests because they also grant information on how well the different model configurations are able to represent the system behavior.

Translational Decay

Fig. 3 and 4 show that all models calculate the translational free decay response of the system very well. The error in surge and heave natural frequencies is low, and the minor discrepancies at the end of each decay test can be explained by other degrees of freedom being excited; no pure single degree of freedom oscillation is maintained. In the heave decay, all models maintain the same oscillation; whereas in the surge decay, the dynamic mooring solvers match the experimental response slightly better than the quasi-static. This can be explained by the fact that the heave response is mainly driven by the hydrostatic stiffness of the system, and on the contrary, the surge stiffness is solely obtained via the mooring lines.

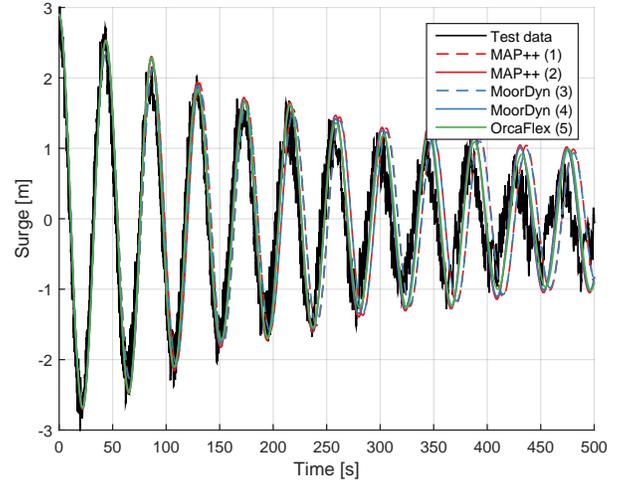


Fig. 3. Surge decay test.

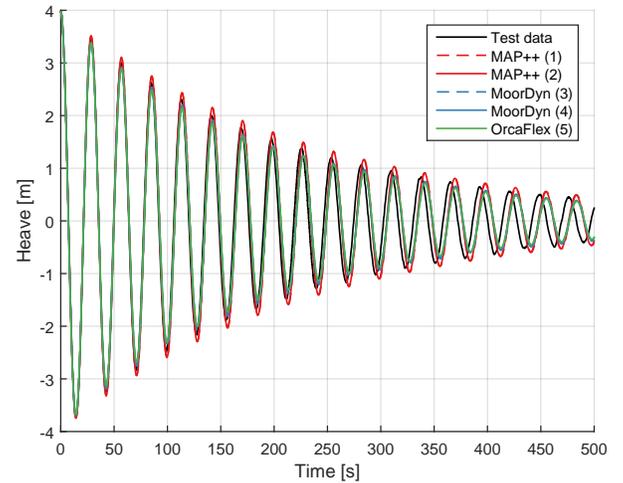


Fig. 4. Heave decay test.

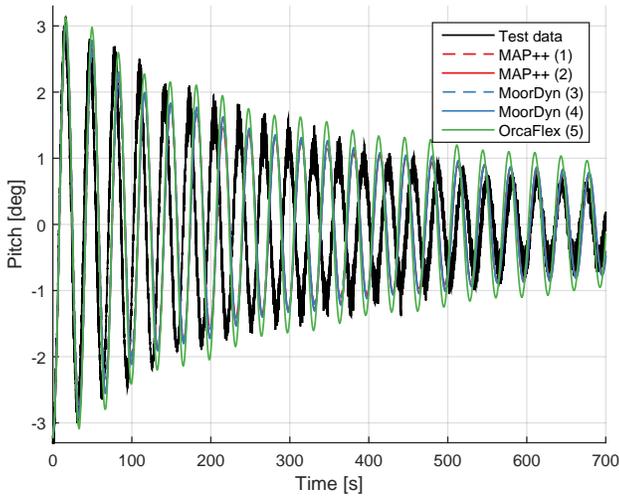


Fig. 5. Pitch decay test.

When observing the damping, all five models agree fairly well in the surge decay. The heave decay shows a little wider spread among the different models. There is, as expected, hardly any difference between the single/multisegmented mooring configuration. The main difference is observed between the quasi-static and the dynamic mooring solvers. Here the MAP++ simulations are slightly underdamped and the MoorDyn and OrcaFlex simulations are slightly overdamped compared to the measured data. This difference between the quasi-static and dynamic mooring solver is to be expected, and is a result of the extra damping captured by the mooring line drag. It should be mentioned that the two multisegmented dynamic solutions (Models 4 and 5), are practically indistinguishable.

Rotational Decay

Fig. 5 shows the decay of the system in pitch. Here, the mooring has very little influence on the motion of the system, which is mainly driven by the inertia versus the hydrostatic stiffness. The slight uneven changes of the amplitude during the decay can be explained by the fact that a pitching system of this type will almost certainly excite a small surge motion. The discrepancy between the damping of the four models running HydroDyn and the benchmark model running OrcaFlex, is mainly due to the differences in the viscous drag modeling. The member geometry and viscous drag coefficient definition in OrcaFlex and FAST v8 are inherently different, which makes the corresponding tuning procedure too tedious for the scope of this paper.

When observing the yaw decay in Fig. 6, a vastly bigger difference is seen among the different models. This is to be expected because the yaw stiffness and damping of the system is mainly, if not only, driven by the mooring system. At this point, we have not yet

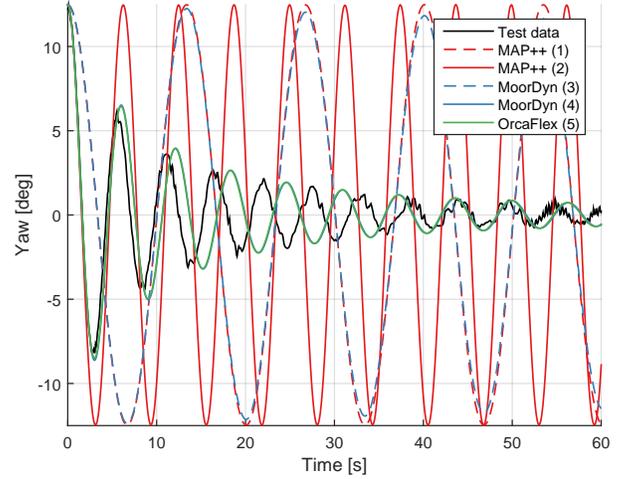


Fig. 6. Untuned yaw decay response. Models 4 and 5 indistinguishable.

applied any artificial yaw stiffness or damping. Fig. 6 serves to show the performance and inherent differences between the models. It is clearly seen that both the stiffness and damping are not well captured by the single line models (1 and 3). The quasi-static multisegmented simulation (Model 2) captures a better estimate of the stiffness of the system while still not obtaining any damping, as expected. The dynamic multisegmented solutions (Models 4 and 5) are once again in complete agreement, leaving the blue and green lines indistinguishable in the figure. They capture the damping of the system very well, but with small differences for the stiffness relative to the MARIN test data. This shows the benefit of direct modeling. The difference in yaw stiffness between the numerical models and the test data might be due to the cable bundle that hung from the system during tests, or the fact that the decay tests had significant motions in the surge and sway degrees of freedom (likely due to how the free-decay was initiated at MARIN).

To obtain better representations of the yaw response of the system, some additional tuning is done. For all systems, additional linear yaw stiffness, linear yaw damping and/or quadratic yaw damping were added. Because the damping is already well captured by the dynamic multisegmented simulations (Models 4 and 5), the adjustment of the stiffness in these models is straightforward. On the contrary, the tweaking of the linear and quadratic damping of the other models can be quite tedious. This is again seen as a clear benefit of the direct modeling of the physical system. The parameters needed to adjust each model are shown in Table 3. The damping values are found by visual fitting, and presented in the correct order of magnitude. Fig. 6 shows a minor difference between the damping of Models 1 and 3, and hence these will also have different additional tuning values if an even more precise estimate is needed.

Fig. 7 shows the response of the tuned models. They all obtain

Table 3. Additional yaw stiffness and damping applied to each model.

	Linear Stiffness N-m/rad	Linear Damping N-m/(rad/s)	Quadratic Damping N-m/(rad/s) ²
MAP++ (1)	140×10^6	10×10^6	100×10^6
MAP++ (2)	35×10^6	10×10^6	100×10^6
MoorDyn (3)	140×10^6	10×10^6	100×10^6
MoorDyn (4)	35×10^6	-	-
OrcaFlex (5)	(35×10^6)	-	-

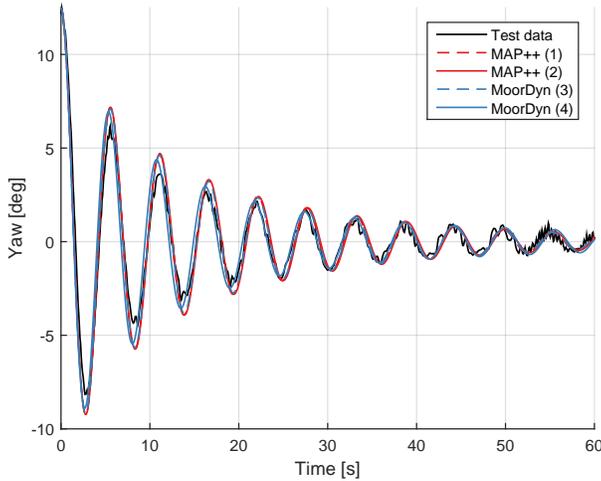


Fig. 7. Yaw decay test.

good representations of the desired behavior. Note that OrcaFlex is left out of the figure. This is due to the fact that in OrcaFlex it is not possible to make external changes to the hydrostatic stiffness in surge, sway, and yaw (hence why the linear stiffness for OrcaFlex in Table 3 is marked with parentheses). Due to the exact match between the multisegmented MoorDyn simulation and OrcaFlex for the untuned case, the adjustment of the models are expected to be identical.

Besides observing the motion response of the system, an important factor in the mooring design is the mooring line tension. Fig. 8 shows the mooring line tension at one of the anchors during a yaw decay from a large initial yaw angle (15 degrees). A purely numerical comparison was chosen because the measured mooring line tensions under the yaw decay were highly dominated by the system surge and sway motions, and hence not highlighting the differences between the models. To be able to compare all five models, the extra linear yaw stiffness of 35×10^6 N-m/rad from was neglected from models 2, 4 and 5, and models 1 and 3 were instead tuned by 105×10^6 N-m/rad. Fig. 8 shows a good match between multisegmented models, and a near perfect match between Models 4 and 5. The two quasi-static models both underestimate the tension in the mooring lines. The dominant underlying frequency in Fig. 8 is roughly twice that

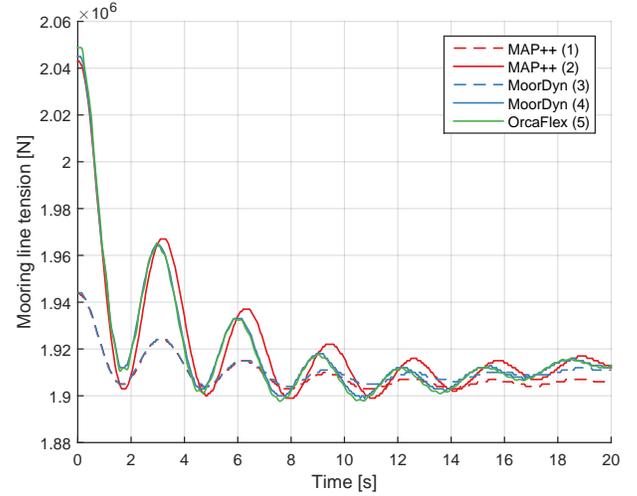


Fig. 8. Tension in mooring lines at anchor during yaw decay.

of Fig. 7 because the tension peaks at the peak of both the maximum and minimum yaw angles.

Wave Tests

When examining the system response in different sea states, not much difference is seen among the spar motions from the four FAST v8 models. This is to be expected because the difference in the mooring configurations have very little influence on the major system motions excited by the passing wave – surge, pitch, and heave. Fig. 9 shows the measured surge response from a regular wave test. The waves in the presented test had a wave height of 10.74 m and a period of 14.3 s, and the same realization of the wave time series was fed into each model. There are some differences in energy levels, but all models capture the same main dynamics of the system as those shown in the decay simulations.

DISCUSSION

In the surge, heave and pitch degrees of freedom, very little difference between the mooring configurations is seen. As stated earlier, the OC3-Hywind tests at MARIN was conducted with taut mooring, and the inherent properties of a taut moored spar buoy minimize the influence of the station keeping system. The interesting differences occur in the investigation of the yaw response of the system. Due to the inherently large yaw stiffness of the taut system, the only significant yaw motion is seen in the yaw decay tests, and hence the focus has been put in calculating this behavior.

Fig. 6 explicitly shows the main differences between the system properties captured when using a quasi-static or a dynamic mooring solver. It also highlights the influence of properly modeling the multisegmented bridle mooring configuration. It is evident that the combination of multisegmented mooring and a dynamic

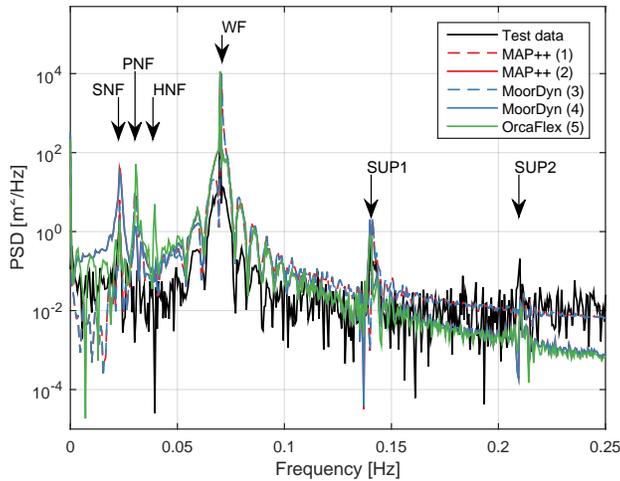


Fig. 9. Spectral density of the surge motion observed in regular waves. Annotation: Surge natural frequency (SNF), pitch natural frequency (PNF), heave natural frequency (HNF), wave frequency (WF), 1st wave super harmonic (SUP1) and 2nd wave super harmonic (SUP2).

mooring solver yields a good system description without tuning the system. This is a significant benefit when designing systems where experimental data is not available for response tuning.

While the dynamic multisegmented solver proves to describe the system well without tuning, Fig. 7 shows that all the models can of course be tuned to better match experimental data. While all models are able match the response of the system, a difference is still seen in the anchor loads in Fig. 8, meaning that for mooring design, the dynamic multisegmented approach is suggested.

CONCLUSION

Five different model configurations have been validated against wave tank measurement data. Two of these models (one single line and one multisegmented bridle configuration) use the dynamic mooring code MoorDyn coupled to FAST v8. The quasi-static mooring code MAP++, also coupled to FAST v8, is used for the next two models that use a single line and bridle mooring system configuration, respectively. The fifth model is a dynamic multisegmented bridle mooring model, realized through the commercial tool OrcaFlex, coupled to FAST v8 - this last solution serves as a benchmark for the performance of the other models.

The investigation of the different models showed that the approach of modeling a multisegmented bridle system through a single mooring line, in combination with additional tuning of platform stiffness and damping, can achieve satisfactory results, but also that the direct modeling of the actual multisegmented mooring system yields far more desirable results (especially with respect to the predicted anchor/fairlead loads). The results obtained from dynamic multisegmented simulations were close to identical between the

open-source module MoorDyn and the commercial tool OrcaFlex, which serves as verification of MoorDyn's modeling capabilities.

For system motions not dominated by the mooring system, all five configurations described the system well, and little difference was seen between the models. The only true differences were observed in the fairly stiff yaw free-decay motion. Due to limitations of the system tested and data obtained, further work is needed to truly validate the multisegmented capability. To further investigate the influence of multisegmented mooring on floating wind turbine foundations in the future, a slack mooring layout combined with an operating wind turbine excited by misaligned turbulent winds could be of interest.

The introduction of multisegmented mooring capabilities in FAST v8 extends the capability of FAST for detailed mooring system design and analysis. Further, all mooring modules are very similar in terms of the required computational expenses, and they are not a major contributor to the required simulation time of FAST v8 floating offshore wind turbine simulations.

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