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# Validation of a FAST spar-type floating wind turbine numerical model with basin test data

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**Abstract.** Global development of the offshore wind energy is devoted to applying into deep water sea areas. Spar-type floating offshore wind turbine (FOWT) has been demonstrated as the most mature FOWT concept, which has been studied for the longest time by researchers among all of the FOWT concepts in the world. Due to its excellent hydrodynamic performance, spar-type FOWT is considered as the most suitable type applied in deep water and harsh sea environment conditions, which has a huge market application foreground in the future. As a consequent, investigation of the offshore wind energy requires the hydro-aero-elastic-servo simulation tools to predict the coupled complex behavior of the FOWT system. However, little validation work has been done by now in the public domain. Thus, the purpose of this paper is to validate the commonly used simulation tool, FAST (Fatigue, Aerodynamics, Structures, and Turbulence), by referring to published basin test data. Through in-depth analysis of its advantages and deficiencies, it provides a good reference for the further improvement of this floating wind turbine's numerical simulation tool in the future.

## 1. Introduction

With the environmental protection concerns of the public and increasing demand for energy, research on floating offshore wind turbines (FOWTs) has developed rapidly and become of considerable interest in recent decades. Among all the types of floating wind turbine, spar-type FOWT has the longest history and is the most mature type at present.

In 2009, Statoil installed the first prototype floating wind turbine concept named Hywind, at the southwest coast line of Norwegian Sea, which achieved a historic breakthrough of the offshore floating wind turbine technology development [1]. After nearly 6 years of research and testing, the floating wind turbine finally develops from test prototypes to commercial applications, with the first commercial offshore floating wind power station set up at "Hywind Scotland Pilot Park" in northeast coast of Scotland, becoming an engineering feat in the floating wind turbine development history.

The research of the FOWTs involves multidisciplinary theories, including aerodynamics, hydrodynamics, multi-structure dynamics (elastic), and automatic controls (servo) [2-6]. The simulation tools that can perform fully coupled calculation play an important role in the investigation of floating wind turbines [7-11], and many of them have been conduced code-to-code comparison in OC3 and OC4 projects [12-15]. Nevertheless, because of the complexity of the FOWT system, the accuracy of these simulation tools still needs more validation with prototype measured or model test data.

However, though Statoil and other companies have performed abundant prototype measurement with respect to real FOWT, their measured data have not been published to the public by now. Therefore, the basin model test has been considered as the most effective approach to validate the simulation tools [16].

The purpose of this paper is to validate the accuracy of the floating wind turbine numerical simulation software FAST, which is proposed by the National renewable energy lab (NREL), by referring to the published experimental data [17]. Through comparing the experiment and simulation results, the predicting accuracy with respect to the dynamic response behaviors of a spar-type floating wind turbine is validated, and some deficiencies are also analysed, for a better optimization of this simulation tool in the future.

## 2. Basin model test

### *2.1. Model description*

A diagrammatic sketch of spar-type floating offshore wind turbine under wind, wave and current environment load condition is shown in Figure 1. The model wind turbine shown in Figure 2 was scaled down from the 5 MW OC3-Hywind wind turbine of National Renewable Energy Laboratory (NREL) with scale parameter λ of 1:50 [17]. Main properties of the wind turbine are listed in Table 1 [12,13].

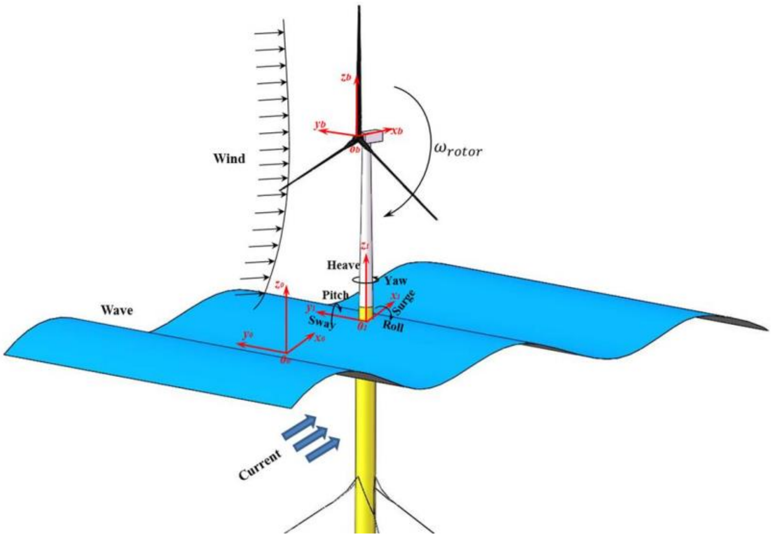


**Figure 1.** Sketch of a spar-type floating wind turbine.

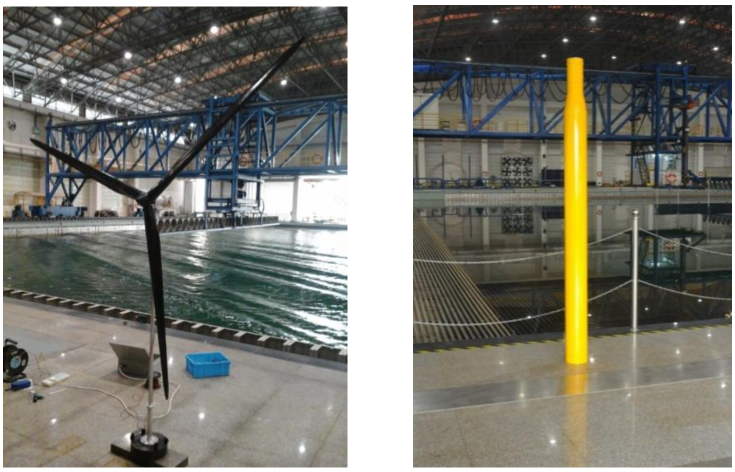

**Figure 2.** Photograph of model wind turbine and spar-type floater (Figures from [17]).

**Table 1.** Main properties of NREL 5 MW OC3-hywind wind turbine.

| Item | Value |
|---|---|
| Rated Power | 5 MW |
| Rated wind speed & rotor speed | 11.4 m/s, 12.1 rpm |
| Rotor type | Upwind, 3 Blades |
| Blade Length | 61.5 m |
| Rotor Diameter | 126 m |
| Hub Diameter | 3 m |
| Hub Height | 90 m |
| Tower Length | 77.6 m |

The wind turbine and spar-type floater models are shown in Figure 2, and the model floater is scaled down from the OC3-Hywind floater [13,17]. More detail about the floater can be found in [17].

The prototype water depth of 200 m was modelled in this test, which is referenced to MARIN's tests [18]. The taut mooring system was modelled with a delta line configuration to simulate the Statoil and Scotland Hywind type [19]. The layout of the model mooring system is shown in Figure 4. More details about the mooring system properties can be found in [17].

### *2.2. Data measurement*

A series of sensors in Figure 3 were utilized to measure the motions, dynamic loads and accelerations of this moored spar-type floating wind turbine system during model testing [17]. The 6 DOF forces and moments between the nacelle and tower were recorded by the Load cell # 1. The 6 DOF forces and moments in the nacelle were measured by the Load cell # 2. The 3 DOF nacelle accelerations were captured by the accelerometer that located in the rear of the nacelle. Moreover, motions of the floating system were measured by the Active Optical Motion Capture System with four Optical Markers located at the end of the tower. Additionally, three tension sensors for capturing mooring line tensions were configured at the joints of two short mooring lines, as shown in Figure 4. Besides, the direction of the simulated wind, wave and current is always pointed against the rotor plane.

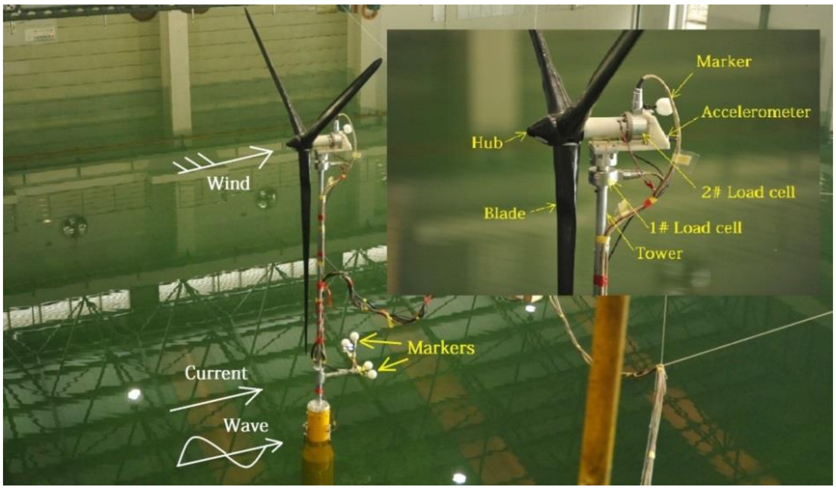


**Figure 3.** Arrangement of sensors in the model (Figure from [17]).

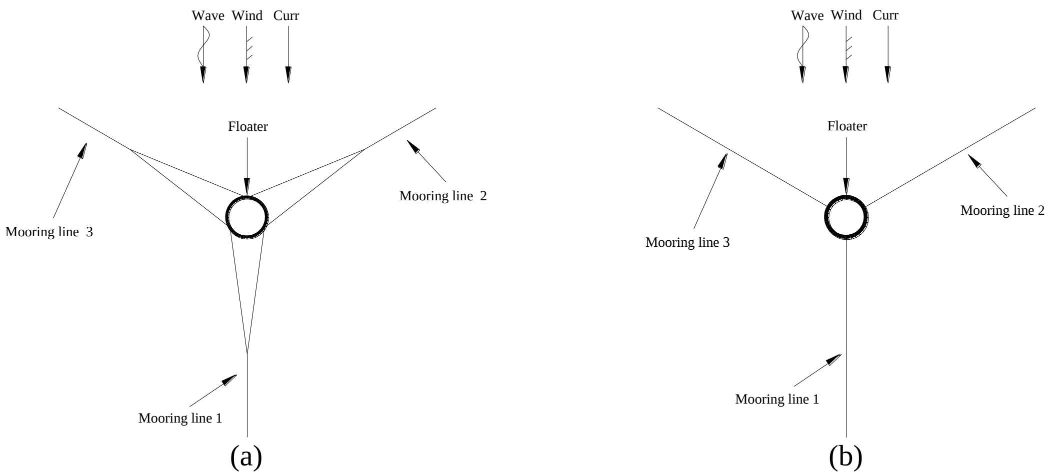


**Figure 4.** Mooring system layout in (a) basin test and (b) numerical model (Figure from [17]).

## 3. Validation of the FAST simulation tool

Utilizing the test results, the accuracy of the FAST simulation software is validated through the following aspects. The test results used in the following contents are referred to [17].

### *3.1. Wind turbine performance*

The Reynolds number is much lower than full-scale value because of the Froude-scale strategy in this basin model test. The airfoil lift and drag performance will alter drastically under the low model Reynolds number environment with a lower turbine axial thrust and power production comparing to the full-scale values of the NREL 5-MW reference wind turbine under a given wind speed. To more accurate simulate the actual aerodynamic performance of the FOWT under low model Reynolds number environment, this paper used the airfoil lift and drag coefficients at low model Reynolds number [20] to validate the accuracy of the thrust loading simulation (thrust loading is the most important aerodynamic driver for global motion of the system). The results are shown in Table 2.

**Table 2.** Comparison of FAST simulated and tested thrust results.

| wind speed (m/s) | rotor speed (rpm) | thrust loading (kN) | FAST calculated thrust loading (kN) | error (%) |
|---|---|---|---|---|
| 9.25 | 7.9 | 276 | 275.9 | -0.04 |
| 11.2 | 11.2 | 494.9 | 494.2 | -0.14 |
| 13.7 | 14.4 | 770.4 | 769.6 | -0.10 |
| 10.5 | 10.9 | 451.1 | 450.8 | -0.07 |
| 9.4 | 10.6 | 388.9 | 387.3 | -0.41 |
| 17.5 | 0 | 145 | 145.3 | 0.21 |

### *3.2. Mooring restoring stiffness*

The delta connection mooring line design was applied in Statoil and Scotland Hywind and also simulated in basin test [17], but it is hard to numerically model in simulation tools. Thus the delta connection had been simulated as a single mooring line with an equivalent yaw stiffness in numerical model, as shown in Figure 4.

In a static state, the tested and calculated pretensions of mooring system have listed in Table 3. As can be seen, the error is rather tiny, demonstrating the numerical model of mooring system under static state was accurately established.

**Table 3.** Comparison of the tested and simulated mooring pretension.

| Measured (kN) | FAST simulation (kN) | error (%) |
|---|---|---|
| 2762.375 | 2762 | -0.01 |

The tested and calculated mooring horizontal stiffness both in the surge and sway directions was compared in Figure 5.

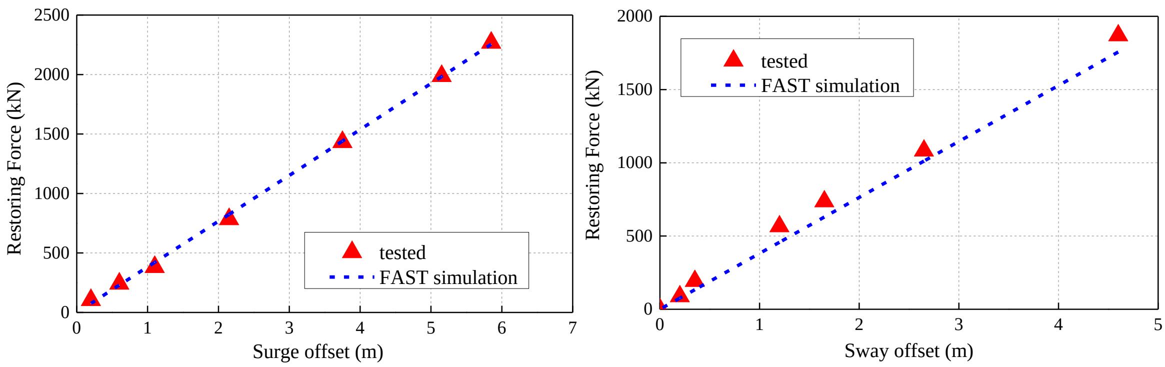


**Figure 5.** Comparison of restoring stiffness both in surge and sway direction for tested and simulation results.

The simulation results are in good agreement with the test results, validating the accuracy of the established mooring system numerical model.

### *3.3. Responses under wind and wave environment loads*

In the following content, the simulated responses will be compared with the test data based on wind/wave environment load conditions. Cases involve combined steady wind with regular wave and irregular wave conditions. This systematic approach provides an intuitive reflection of the accuracy of FAST prediction and also presents an easier way to reveal root causes for discrepancies between test data and FAST simulations, which highlight the potential shortcomings in the test data, as well as possible improvement for FAST. The load case of combined steady wind with regular wave is defined in Table 4, and the mean value of response results are shown in Figure 6.

**Table 4.** Load case definition.

| Wind Speed (m/s) | Regular Wave H (m) | Regular Wave T (s) | Remarks |
|---|---|---|---|
| 5 | 2 | 8 | wind with regular wave |
| 11.4 | 4 | 10 | |
| 18 | 6 | 11 | |

Figure 6 shows that the simulation results are in good agreement with the experimental results under the combined wind and regular wave condition, which means FAST can accurately model the regular wave environment, and can accurately simulate the load and motion responses under constant environment loads. In the following, the unsteady sea states will be simulated, that is, the response characteristics of the floating wind turbine under the combined wind and irregular wave conditions will be investigated, and the prediction accuracy of FAST simulation results will be studied. Figure 7 shows the comparison of the experimental and simulated response spectrum results. The load case is defined in Table 5.

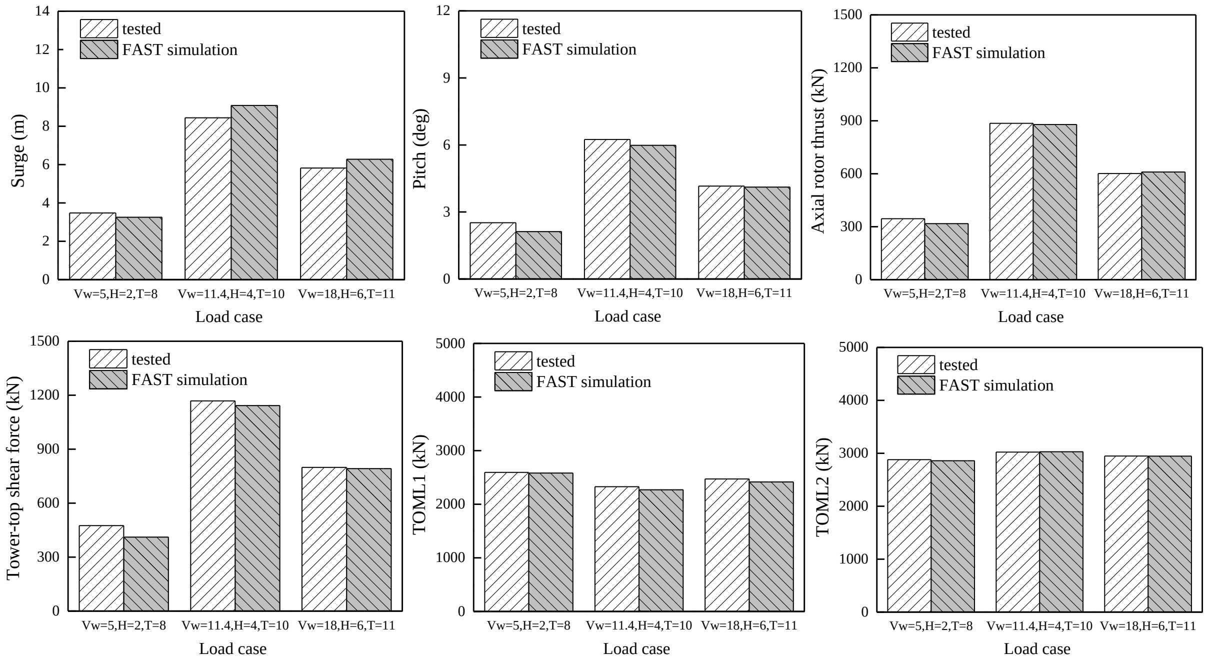


**Figure 6.** Comparison of simulation and tested response results under winds with regular waves.

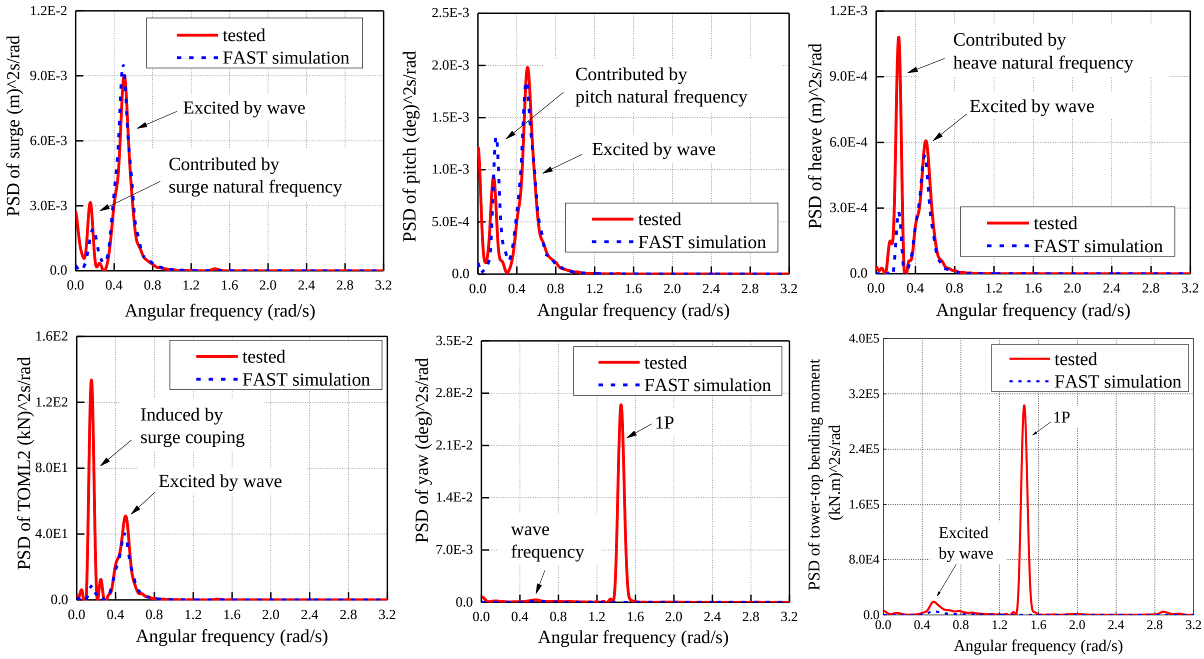


**Figure 7.** PSD comparison of simulation and tested response results under wind with irregular wave.

**Table 5.** Load case for wind with irregular wave.

| Wind Speed (m/s) | Jonswap irregular wave | | | Remarks |
|---|---|---|---|---|
| | Hs (m) | Tp (s) | γ | |
| 11.4 | 7.1 | 12 | 2.2 | wind with irregular wave |

Figure 7 shows that FAST can well simulate the responses within the wave frequency range (0.32-1.39 rad/s) in surge, pitch, heave and mooring line tension. However, the simulation is not that satisfactory when it comes to the second order difference frequency responses. For example, in the response spectrum, surge, pitch and heave's vibrations at their natural frequency can not be predicted accurately. In addition, surge has an obvious coupled effect on the mooring line tension [17]. However, since the vibration at natural frequency is not well simulated in surge, the coupled effect caused by surge also can not be reflected in the mooring line tension response as well.

From the test responses of the yaw motion and the tower-top bending moment shown in Figure 7, it can be seen that when the wind load is applied, the effect of rotor rotation caused great responses at 1P, making wave frequency responses could even be ignored. But this characteristic does not reflect in simulation result. This response characteristic in the model test is probably due to the rotor spinning induced gyroscopic moment, which makes the yaw motion rotate, and finally develops into the response at 1P under combined effect of wind loads and rotor spinning. As a result, the yaw motion's significant vibration at 1P also has a predominant coupled effect on the tower-top bending moment.

Of course, it could be caused by experiment errors. For example, there may be an error with respect to the mass or the centroid in the model blade, which makes the mass center of the rotor not exactly at the hub center, resulting in an eccentric rotor rotation; or the rotor plane can not be arranged absolutely parallel to the outlet plane of the wind in the model test, which caused the 1P response; or the wind field can not meet the requirement of absolute uniform within the outlet plane in the basin test environment. However, it is worth noting that a real floating wind turbine will never be in an ideal environment condition like a numerical model being. Situations like the rotor eccentric spinning, the rotor plane unparallel to the outlet plane of the wind or the wind field nonuniform will surely happen. Therefore, the experimental characteristics of the yaw motion and the tower-top bending moment shown in Figure 7 will surely happen during a real FOWT operation, so the response characteristics of the yaw motion and the tower-top bending moment found in the test are well worth noting for reference.

## 4. Conclusions

A corresponding numerical model is established in the software FAST based on parameters of the published basin experiment [17]. The test data are referenced to validate the accuracy of the FAST simulation tool.

The accuracy of the mooring system numerical model in FAST was validated by the restoring stiffness tested results. Based on the combined wind and regular wave sea state, the accuracy of FAST simulation under constant environment loads is validated. Based on the combined wind and irregular wave sea state, it has been deeply analyzed with respect to the parts that perfectly matched, as well as some distinctions between test and simulated results. Such as the inaccurate simulation of surge, pitch and heave's responses at their natural frequencies, and the poor simulated 1P responses in yaw and tower-top bending moment, which providing a good reference for the further improvement of the floating wind turbine's numerical simulation and engineering design work in the future.

## References

[1] Stiesdal H 2009 Hywind: The world's first floating MW-scale wind turbine *Wind Directions* **13** 52-3
[2] Namik H and Stol K 2010 Individual blade pitch contorl of floating offshore wind turbines *Wind Energy* **13** 74-85
[3] Wang L and Sweetman B 2013 Multibody dynamics of floating wind turbines with large-amplitude motion *Applied Ocean Research* **43** 1-10
[4] Jeon M and Lee S 2014 Unsteady aerodynamics of offshore floating wind turbine in platform pitching motion using vortex lattice method *Renewable Energy* **65** 207-12
[5] Salehyar S and Zhu Q 2015 Aerodynamic dissipation effects on the rotating blades of floating wind turbines *Renewable Energy* **78** 119-27

[6] Nejad A R, Bachynski E E, Kvittem M I, Luan C Y, Gao Z and Moan T 2015 Stochastic dynamic load effect and fatigue damage analysis of drivetrains in land-based and TLP, spar and semi-submersible floating wind turbines *Marine Structures* **42** 137-53
[7] Karimirad M 2011 Stochastic dynamic response analysis of spar-type wind turbines with catenary or taut mooring systems (Ph.D. Thesis, Norwegian University of Science and Technology)
[8] Kvittema M I, Bachynski E E and Moan T 2012 Effects of hydrodynamic modeling in fully coupled simulations of a semisubmersible-submersible wind turbine *Energy Procedia* **24** 351-62
[9] Quallen S, Xing T, Carrica P, Li Y W and Xu J 2013 CFD simulation of a floating offshore wind turbine system using a quasi-static crowfoot mooring-line model *Proceedings of the Twenty-third (2013) International Offshore and Polar Engineering* (Anchorage, Alaska, USA) ISOPE 2013
[10] Bae Y H, Kim M H and Shin Y S 2010 Rotor-floater-mooring coupled analysis of mini-TLP-type offshore floating wind turbines *Proceedings of the ASME 2010, 29th International Conference on Ocean, Offshore and Arctic Engineering* (Shanghai, China) Paper no. OMAE2010-20555
[11] Gueydon S and Xu W 2011 Floating wind turbine motion assessment *Oceans 2011 Conference* (Kona, Hawaii, USA)
[12] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW reference wind turbine for offshore system development *Technical Report NREL/TP-500-38060 National Renewable Energy Laboratory (NREL)*
[13] Jonkman J 2010 Definition of the floating system for phase IV of OC3 *Technical Report NREL/TP-500-47535 National Renewable Energy Laboratory (NREL)*
[14] Jonkman J, Robertson A, Popko W, Vorpahl F, Zuga A, Kohlmeier M, Larsen T J, Yde A, Saetertro K, Okstad K M, Nichols J, Nygaard T A, Gao Z, Manolas D, Kim K, Yu Q, Shi W, Park H, Rojas A V, Dubois J, Kaufer D, Thomassen P, de Ruiter M J, Peeringa J M, Zhiwen H and Waaden H V 2012 Offshore code comparison collaboration continuation (OC4), phase I – results of coupled simulations of an offshore wind turbine with jacket support structure *Technical Report NREL/CP-5000-54124 National Renewable Energy Laboratory (NREL)*
[15] Robertson A, Jonkman J and Musial W 2013 Offshore code comparison collaboration, continuation: phase II results of a floating semisubmersible wind system *Technical Report NREL/CP-5000-60600 National Renewable Energy Laboratory (NREL)*
[16] Browning J, Jonkman J, Robertson A and Goupee A J 2014 Calibration and validation of a spar-type floating offshore wind turbine model using the FAST dynamic simulation tool *Journal of Physics Conference Series* **555** 012015. DOI: 10.1088/1742-6596/555/1/012015
[17] Duan F, Hu Z Q and Niedzwecki J M 2016 Model test investigation of a spar floating wind turbine *Marine Structures* **49** 76-96
[18] Koo B, Goupee A J, Lambrakos K and Kimball R W 2012 Model tests for a floating wind turbine on three different floaters *Proceedings of the ASME 2012, 31st International Conference on Ocean, Offshore and Arctic Engineering, OMAE2012-83642* (Rio de janeiro, Brazil)
[19] Duan F, Hu Z Q and Wang J 2015 Model tests of a spar-type floating wind turbine under wind/wave loads *Proceedings of the ASME 2015, 34th International Conference on Ocean, Offshore and Arctic Engineering, OMAE2015-41391* (St. John’s, NL, Canada)
[20] Alexander J C, Andrew J G, Amy N R, Jason M J and Habib J D 2013 Validation of a FAST semi-submersible floating wind turbine numerical model with DeepCwind test data *Journal of Renewable and Sustainabke Energy* **5** 023116