Offshore Code Comparison Collaboration, Continuation: Phase II Results of a Floating Semisubmersible Wind System

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"Offshore Code Comparison Collaboration, Continuation: Phase II Results of a Floating Semisubmersible Wind System"

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Summary

Offshore wind turbines are designed and analyzed using comprehensive simulation tools that account for the coupled dynamics of the wind inflow, aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. The Offshore Code Comparison Collaboration (OC3), which operated under the International Energy Agency (IEA) Wind Task 23, was established to verify the accuracy of these simulation tools [1]. This work was then extended under the Offshore Code Comparison Collaboration, Continuation (OC4) project under IEA Wind Task 30 [2]. Both of these projects sought to verify the accuracy of offshore wind turbine dynamics simulation tools (or codes) through code-to-code comparison of simulated responses of various offshore structures.

This paper describes the latest findings from Phase II of the OC4 project, which involved the analysis of a 5-MW turbine supported by a floating semisubmersible. Twenty-two different organizations from 11 different countries submitted results using 24 different simulation tools. The variety of organizations contributing to the project brought together expertise from both the offshore structure and wind energy communities.

Twenty-one different load cases were examined, encompassing varying levels of model complexity and a variety of metocean conditions. Differences in the results demonstrate the importance and accuracy of the various modeling approaches used. Significant findings include the importance of mooring dynamics to the mooring loads, the role nonlinear hydrodynamic terms play in calculating drift forces for the platform motions, and the difference between global (at the platform level) and local (at the member level) modeling of viscous drag. The results from this project will help guide development and improvement efforts for these tools to ensure that they are providing the accurate information needed to support the design and analysis needs of the offshore wind community.

Introduction

The vast offshore wind resource represents a potential to use wind turbines installed offshore to power much of the world. Design standardization is difficult, however, because offshore sites vary significantly through differences in water depth, soil type, and wind and wave severity. To ensure that offshore wind turbine (OWT) installations minimize cost, the application of a variety of support structure types is required. These types include fixed-bottom monopiles, gravity bases, space-frames—such as tripods and lattice frames (e.g., "jackets")—and floating structures. In this context, the offshore wind industry faces many new design challenges.

Wind turbines are designed and analyzed using simulation tools (i.e., design computer codes) capable of predicting the coupled dynamic loads and responses of the system. The simulation tools that were developed to model land-based wind systems rely on the use of aero-servo-elastic codes, which incorporate wind-inflow, aerodynamic (aero), control system (servo), and structural-dynamic (elastic) models in the time domain in a coupled simulation environment. To accommodate the additional dynamics pertinent to offshore installations, these codes have been expanded to include the modeling of incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure (see Figure 1). The high complexity and sophistication of these simulation tools underscores the need to verify and validate their accuracy. Two research tasks were developed under the International Energy Agency (IEA) to address this need: the Offshore Code Comparison Collaboration (OC3)[1] and the Offshore Code Comparison Collaboration, Continuation (OC4) [2] projects.
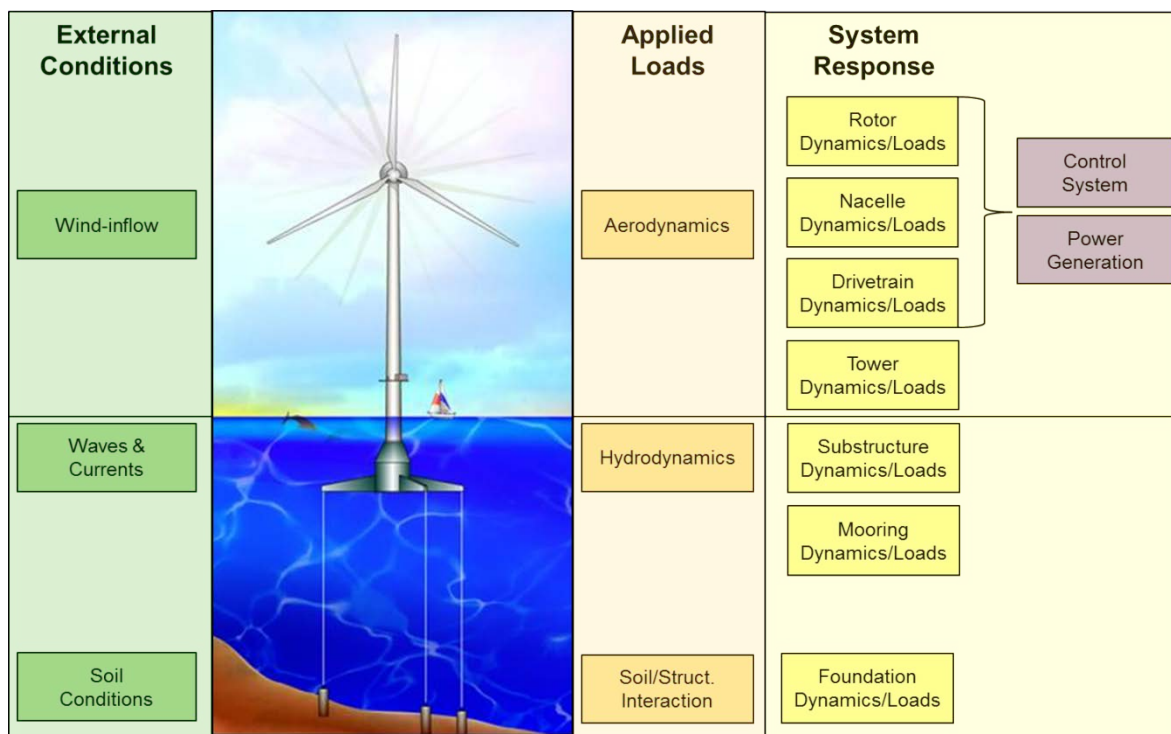

Figure 1: Diagram of the components of offshore wind modeling tools

Overview of the OC3 and OC4 Projects

The OC3 project was operated under the IEA Wind Task 23, Subtask 2, and was the first international project to address the need to verify OWT modeling tools. The OC4 project was an extension of the original project and has operated under IEA Wind Task 30. The approach used in these projects was to verify offshore wind modeling tools by comparing simulated results of offshore wind systems from the various tools available (code-to-code comparisons). Accuracy was assessed through the consistency of the results reported. Validation was not addressed in these tasks due to

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[1] www.ieawind.org/task_23.html
[2] www.ieawind.org/task_30/task30_Public.html

the importance of verification before validation and due to the limited availability of measurement data from actual offshore wind systems.

To test the newly developed codes, the main activities of OC3 and OC4 were to discuss modeling strategies, develop a suite of benchmark models and simulations, run the simulations and process the simulation results, and compare and discuss the results. These activities fell under broader objectives including:

- Assessing the accuracy and reliability of simulations to establish confidence in the predictive capabilities of the modeling tools
- Training new analysts on how to run and apply the tools correctly
- Investigating the capabilities and limitations of implemented theories
- Refining applied analysis methodologies
- Identifying further research and development needs.

Such verification work has led to dramatic improvements in model accuracy as the code-to-code comparisons and lessons learned have helped identify model deficiencies and needed improvements. These results are important because the advancement of the offshore wind industry is closely tied to the development and accuracy of dynamics models.

Project Approach and Phases

The theories used in offshore wind modeling tools are complex, and the diversity of the system designs means that a modeling theory that is applicable to one design may not be applicable to another. The approach of the OC3 and OC4 projects has therefore been to perform a very meticulous step-by-step methodology for examining the individual modeling components of the simulation tools, as well as their coupled behavior. The verification assessment has been performed for multiple architectures to ensure the applicability of the modeling approaches across the design space of offshore wind.

The code-to-code verification process is performed as follows. First, an offshore wind system design of interest is identified, and the information needed to model the system is developed and shared with the project partners. Second, a set of simulations (load cases) is defined to test the response behavior of the system. The simulations encompass system-identification tests and a stepped approach for examining the system response to wind, waves, and the combination of the two. Different components of the system are modeled as flexible or rigid within the load cases, to also examine the influence of system elasticity and its interaction with the offshore environment. Various environmental conditions are used to examine the response behavior in both benign and extreme conditions. Next, each of the participants builds a model of the given design in their respective modeling tools, and runs the prescribed load cases. The simulated response behavior (loads/motions) is then compared between the various codes at multiple points throughout the system, which results in the identification of mistakes in the modeling implementation or simulation settings, shows differences in the resulting loads/motions based on the modeling approach, and spurs discussion about the differences between and applicability of the various modeling theories. This procedure is repeated for multiple offshore wind system designs, and through this process an understanding of the applicability of modeling theories is developed, changes are made to the tools, and future tool improvement needs are identified.

The OC3 and OC4 projects ran from 2005 to 2013 and examined five different offshore wind systems. The same wind turbine, the National Renewable Energy Laboratory (NREL) 5-MW Offshore Baseline Turbine [3], was used for all three systems. Only the offshore support structure was varied. An image of the five designs modeled is provided in Figure 2 and includes:

- OC3 Phase I: Monopile with a rigid foundation, 20-m water depth
- OC3 Phase II: Monopile with a flexible foundation to examine soil/pile interaction, 20-m water depth
- OC3 Phase III: Tripod, 45-m water depth
- OC3 Phase IV: Floating spar buoy, 320-m water depth
- OC4 Phase I: Jacket, 50-m water depth
- OC4 Phase II: Floating semisubmersible, 200-m water depth
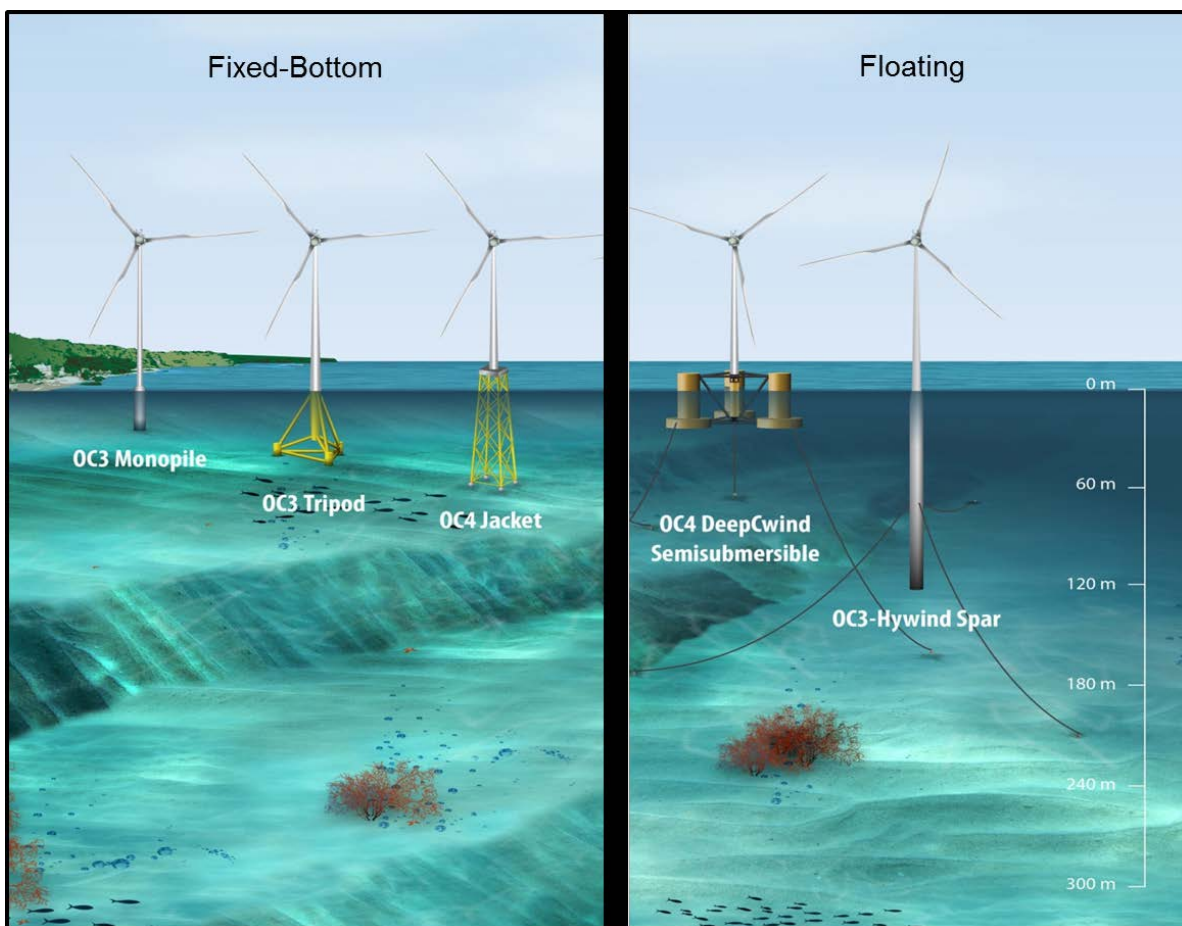

Figure 2: OC3 and OC4 offshore wind system designs modeled

The systems analyzed span the design space of offshore wind, including shallow-water systems (monopile), transition water-depth systems (tripod and jacket), and deep-water floating systems (spar and semisubmersible). See references [1] and [2] for more information about the previous phases of the OC3 and OC4 projects.

Participants and Codes

The OC3 and OC4 projects were performed through technical exchange among a group of international participants from universities, research institutions, and industry across the United States of America, Germany, Denmark, the United Kingdom, Spain, the Netherlands, Norway, Sweden, Korea, Japan, Portugal, Greece, and China. Each one of the participants has their own area of expertise, and therefore, their own unique contribution to the projects. Those who delivered simulation results for the most recent phase (Phase II of OC4) are summarized in Table 1.

Table 1: Active participants in OC4 Phase II

Country	Institution
China	Chinese General Certification Center (CGC), Goldwind
Denmark	Danish Hydraulic Institute (DHI), Technical University of Denmark (DTU), PRINCIPIA
Germany	Garad Hassan (GH), Endowed Chair of Wind Energy (SWE) at the University of Stuttgart
Greece	National Technical University of Athens (NTUA)
Japan	University of Tokyo
Korea	Pohang University of Science and Technology (POSTECH), University of Ulsan (UOU)
Norway	4subsea, Centre for Ships and Ocean Structures (CeSOS) at the National Technical University of Norway (NTNU), Institute for Energy Technology (IFE), MARINTEK
Portugal	Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico (IST), Wave Energy Center (WavEC)
Spain	National Renewable Energy Centre (CENER)
USA	American Bureau of Shipping (ABS), National Renewable Energy Laboratory (NREL)

Overview of OC4, Phase II

Phase II of the OC4 project involved the modeling of a semisubmersible floating offshore wind system developed for the DeepCwind project [4] as shown in Figure 3. This concept was chosen for its increased hydrodynamic complexity compared to the only other floating system analyzed in the OC3 and OC4 projects, the Hywind spar buoy [5]. Floating offshore wind designs are generally categorized into three groups: semis, spars, and tension leg platforms (TLPs). By analyzing the semi, the OC3 and OC4 projects have now examined two out of three of these categories.

DeepCwind is a U.S.-based project aimed at generating field-test data for use in validating floating OWT modeling tools. The semi and two other floating designs were tested by the DeepCwind project in a series of scaled tank tests at MARIN in 2011 [4]. The turbine modeled in this project is the NREL 5-MW Offshore Baseline Turbine [3], which differs slightly from the scaled one tested by DeepCwind. This turbine was used in all phases of the OC3 and OC4 projects, but the control system properties changed to accommodate the differences in system dynamics.

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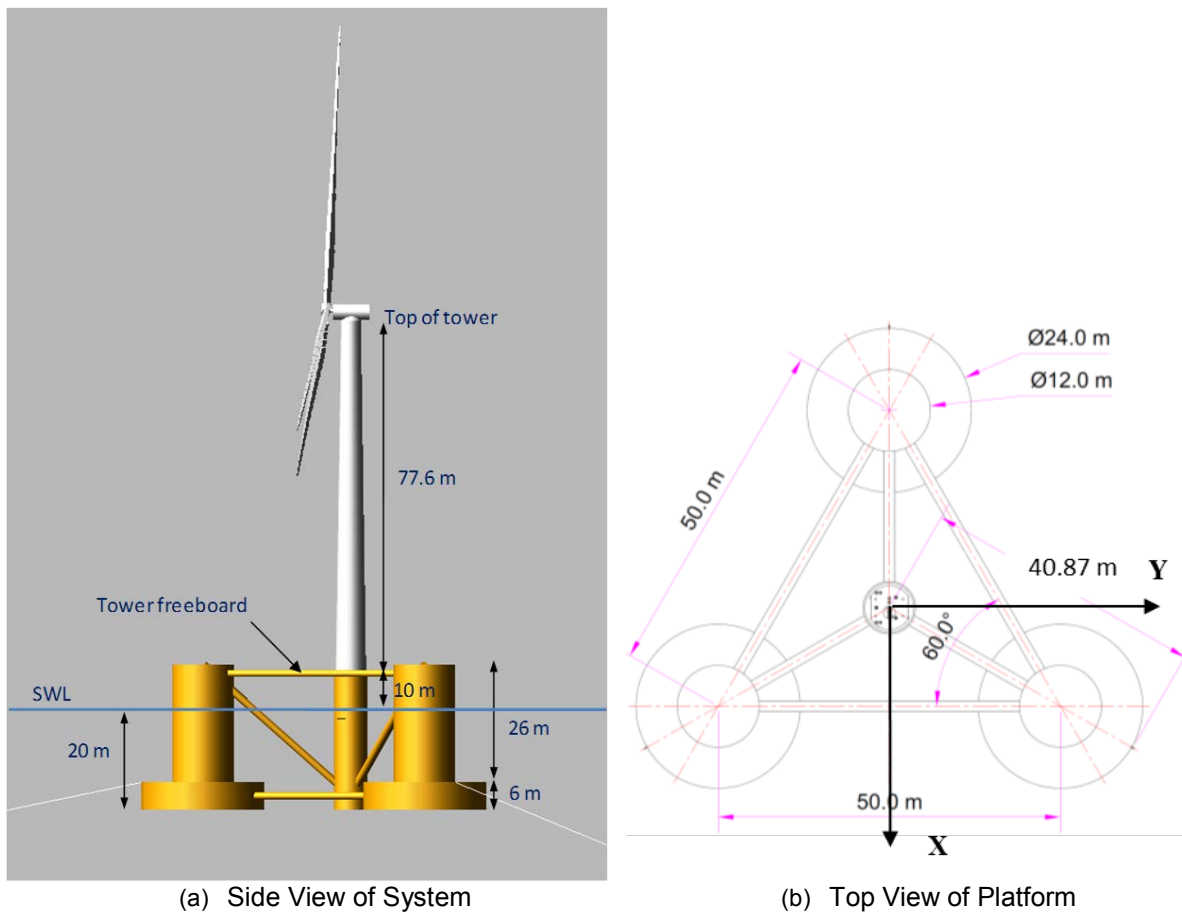| (a) Side View of System | (b) Top View of Platform |

Figure 3: OC4-DeepCwind floating wind system design

Twenty-one different organizations from 10 different countries submitted results using 24 different simulation tools for Phase II of the OC4 project. The variety of organizations contributing to the project brought together expertise from both the offshore structure and wind energy communities. Some institutions provided multiple results, examining the influence of varying modeling approaches within their tool. Multiple institutions also used the same tool, which provided insight into the differences that could be obtained from a given simulation tool based on the user's choice of modeling parameters.
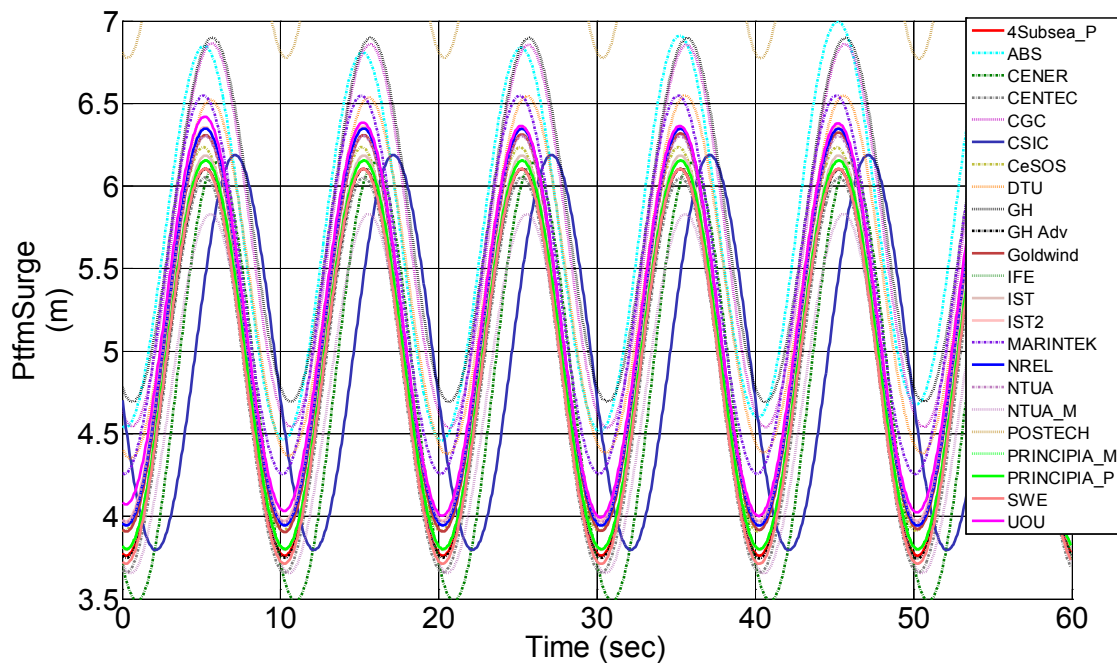
Results for OC4 Phase II

To compare the response behavior achieved by the different modeling approaches, twenty-one different load cases (simulations) were performed, encompassing varying levels of model complexity and a variety of metocean conditions. In addition to traditional wind/wave load cases, this phase included the computation of response amplitude operators (RAOs), which were shown to be a good way to examine offshore structure response characteristics across a range of wave conditions, an approach traditionally used in the offshore structural community, but new to the wind community. Damage cases were also modeled, which included the loss of a mooring line and the flooding of one column, to check the simulation tools' capabilities in assessing system behavior in a variety of design conditions. The results obtained are the outcome of several revisions, which were

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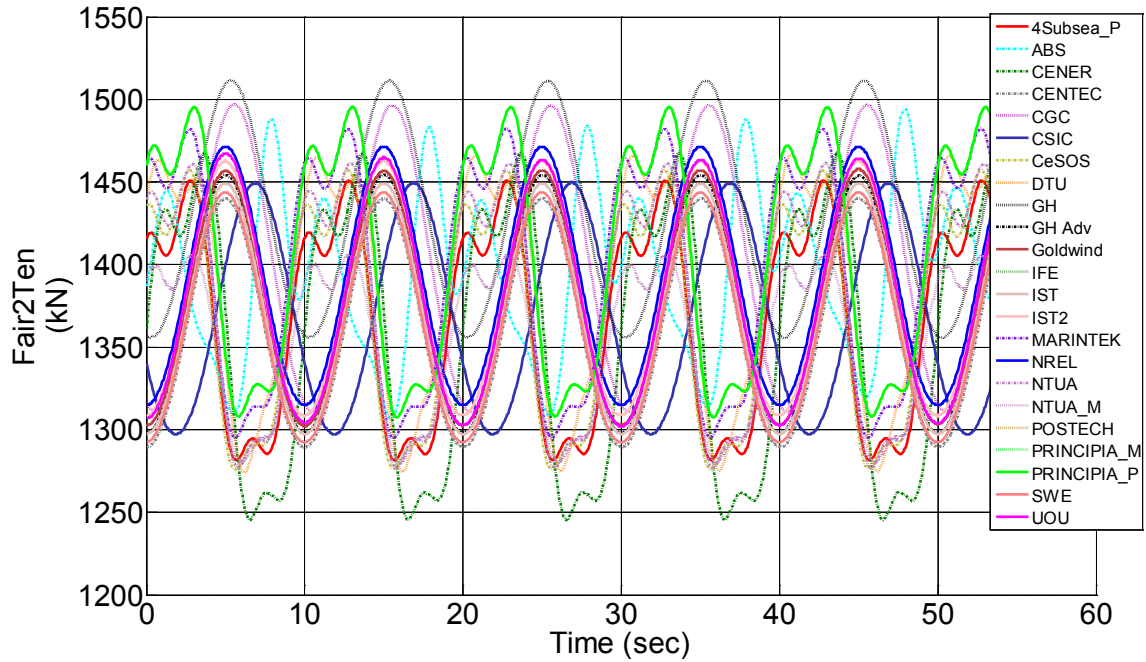at www.nrel.gov/publications.

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necessary due to the complexity of the model, code/user errors, the ongoing development of some of the codes, etc.
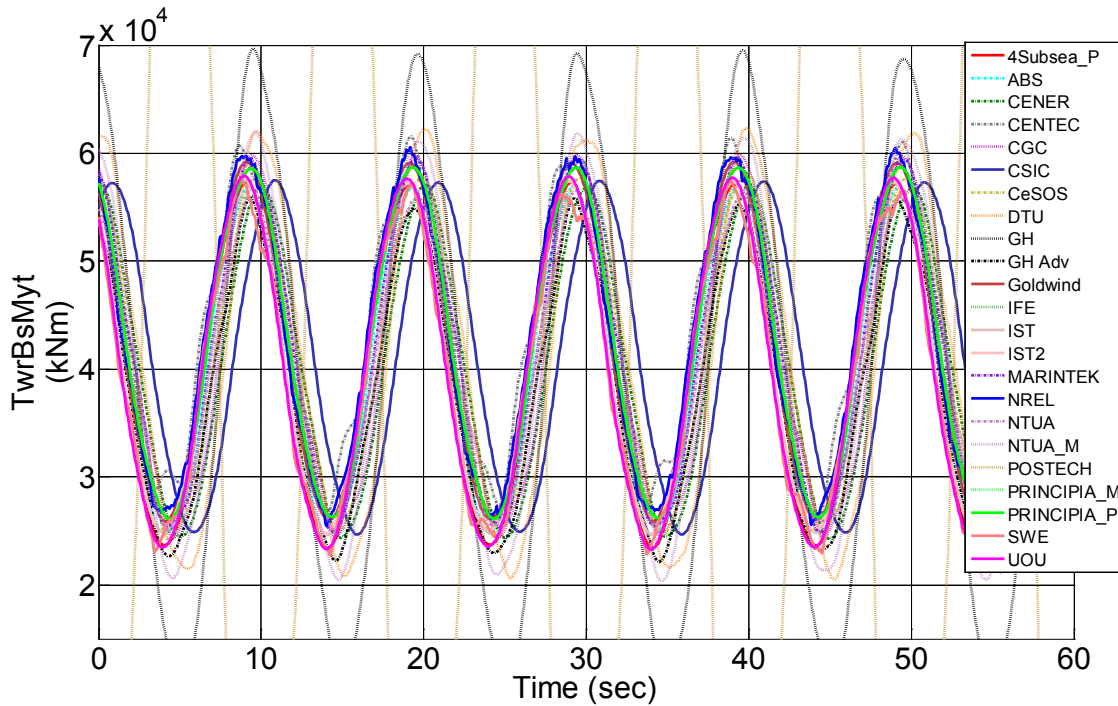
Some exemplary results for one of the load cases are shown in Figure 4. In this load case, the entire OWT is modeled as flexible and excited by steady wind and regular (periodic) waves that act on the system simultaneously. The outputs shown are the surge motion of the system, the mooring forces at the fairlead connection, and the resulting tower-base bending moment in the fore/aft direction. Differences in the results demonstrate the importance and accuracy of the various modeling approaches used. For the platform surge, a small difference is seen in the amount of mean displacement of the system, which can be attributed to differences in the aerodynamic rotor thrust calculations and the approach used for modeling the nonlinear hydrodynamics, which can create drift forces. The fairlead mooring loads show two distinct sets of results based on whether a dynamic or quasi-static mooring modeling approach is used. While the mooring loads may differ vastly between these two approaches, the mean values are similar and tend to have no significant effect on the overall dynamic response of the structure, but would be important in understanding the design loads for the mooring system. Finally, the tower bending moment shows the overall influence of the modeling approaches on the resulting loads in the system. The majority of simulation tools produce similar results, but overall there is an 18% difference in the spread, which is significant in the design of an offshore wind system.

(a) Platform surge response

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(b) Fairlead tension of line 2, which is upwind of the turbine, and in-line with the wind direction

(c) Tower-base bending moment

Figure 4: Exemplary results from load case 3.1:
Simulation of semi with deterministic wind (8 m/s) and waves (H = 6 m, T = 10 s)

This subset of results represents the type of comparisons performed during the OC4 Phase II project. Based on all the simulations run, a set of conclusions was drawn concerning the similarity in the predicted response of the semisubmersible based on the modeling approaches used. The following is a list of the main findings drawn from the project:

- There is not a clear need for the inclusion of radiation/diffraction loads from a potential-flow theory type solution for this type of system; strip-theory approaches are sufficient.
- Approximating the viscous-drag loads for the structure through a global drag matrix may not be sufficient as compared to calculating the member-level Morison drag terms.
- Varying levels of mean drift due to wave excitation are seen between the different models, based on the inclusion of nonlinear hydrodynamics modeling theory. The modeling approaches that create a drift force include wave stretching, applying loads at the instantaneous position of the structure, and including second-order terms in the potential-flow solution either directly or through Newman's approximation. The drift offset is masked by wind loads when the turbine is operating.
- Those codes using a Morison-only approach for modeling the hydrodynamic loads need to be augmented with calculations of the dynamic pressure on the heave plates of this semi to get accurate heave excitation in the system from waves. The need is significant for this structure due to its shallow draft.
- Mooring loads differ significantly between codes using a quasi-static model versus those using a dynamic model. These loads have not been seen to have a significant impact on the system dynamics, but they are important in assessing ultimate and fatigue loads in the mooring lines.
- The predicted out-of-plane motion of the blades is slightly smaller for codes using a dynamic wake approach rather than the blade element momentum theory for the wind inflow model, especially in the higher frequency range.
- RAOs are a good way of concisely examining the response characteristics of a floating wind system across a range of wave conditions and comparing the response characteristics between codes.
- The sudden loss of a mooring line for a semisubmersible system does not appear to result in significant loading to the system during the event.
- The partial flooding of one column was not seen to be very significant in the overall response of the system, but the level of flooding examined may have been too minimal.

Conclusions

The comparisons performed in Phase II of OC4 and throughout the OC3 and OC4 projects have resulted in a greater understanding of offshore floating wind turbine dynamics and modeling techniques, and better knowledge of the validity of various modeling approaches. The results from this project will help guide development and improvement efforts for these tools to ensure that they are providing accurate information to support the design and analysis needs of the offshore wind community.

This project is now planned to be extended for an additional four years, with an expanded focus on validating the tools through the comparison to data from actual physical systems. While the OC3 and OC4 tasks have shown the differences between the modeling approaches, ambiguity still

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remains as to which approach more accurately represents the true physical response; this new extension will begin to address this uncertainty.

Acknowledgments

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