Final Technical Report,
April 21, 2014

IEA Wind Task 30

Offshore Code Comparison
Collaboration Continued
Final Technical Report

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Offshore Code Comparison
Collaboration Continued

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April 21, 2014
Executive Summary of IEA Wind Task 30

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 installations are cost effective, the use of a variety of support structure types is required. These types include fixed-bottom monopiles, gravity bases, and space-frames—such as tripods and lattice frames (“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 codes) capable of predicting the coupled dynamic loads and responses of the system. Land-based wind turbine analysis relies 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. In recent years, some of these codes have been expanded to include the additional dynamics pertinent to offshore installations, including the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. The sophistication of these aero-hydro-servo-elastic codes, and the limited data available with which to validate them, underscore the need to verify their accuracy and correctness. The Offshore Code Comparison Collaboration (OC3), which operated under Subtask 2 of the International Energy Agency (IEA) Wind agreement Task 23, was established to meet this need. OC3 ran from 2005-2009. The success of the project prompted a follow-on task, which is the one reviewed in this report. The OC3 Continued (OC4) project operated under IEA Wind Task 30 from 2010-2013.

As was true with OC3, the main activities of OC4 were to (1) discuss modeling strategies, (2) develop a suite of benchmark models and simulations, (3) run the simulations and process the simulation results, and (4) compare and discuss the results. These activities fell under broader objectives including:

- Assessing the accuracy and reliability of simulations to establish confidence in their predictive capabilities
- Training new analysts to run and apply the codes correctly
- Identifying and verifying the capabilities and limitations of implemented theories
- Investigating and refining applied analysis methodologies
- Identifying further research and development (R&D) needs.

Such verification work, in the past, led to dramatic improvements in model accuracy as the code-to-code comparisons and lessons learned 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 system-dynamics models. The OC4 project continued this work by examining additional offshore wind systems not examined during the OC3 project.

The OC4 project was 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. Moreover, most of the aero-hydro-servo-elastic codes developed for modeling the dynamic response of offshore wind turbines were tested within OC4.

The simulation of offshore wind turbines under combined stochastic aerodynamic and hydrodynamic loading is very complex. The benchmarking task, therefore, required a sophisticated approach that facilitated source identification of modeling discrepancies introduced by differing theories and model implementations in the various codes. This is possible only by (1) meticulously controlling all of the
inputs to the codes and (2) carefully applying a stepwise verification procedure in which model complexity is increased one step at a time.

The fundamental set of inputs to the codes controlled within OC4 relates to the specifications of the wind turbine. The OC4 project uses the publicly available specifications of the 5-MW baseline wind turbine developed by NREL, which is a representative utility-scale multi-megawatt turbine. This conventional three-bladed upwind variable-speed, variable-blade-pitch-to-feather controlled turbine is specified with detailed rotor aerodynamic properties; blade, drivetrain, nacelle, and tower structural properties; and generator-torque and blade-pitch control system properties, the latter of which were provided to all OC4 participants in the form of a dynamic link library (DLL). The hydrodynamic and elastic properties of the varying offshore support structures used in the project are also controlled. Furthermore, the turbulent full-field wind inflow and regular and irregular wave kinematics are model inputs controlled within OC4. This approach eliminated any possible differences brought about by dissimilar turbulence models, wave theories, or stochastic realizations.

An important part of the comparison was a stepwise process that allowed the origin of differences between code predictions to be discovered. Various combinations of wave and wind input were introduced with the rotor and tower being rigid or flexible, disentangling the contributions from wind- and wave-applied loads and dynamic response. Finally, the turbine was made operational so that the effect of the control system could be evaluated.

In OC4, emphasis is given to the verification of the offshore support structure dynamics as part of the dynamics of the complete system. To encompass the variety of support structures required for cost effectiveness at varying offshore sites, different support structures (for the same wind turbine) were investigated in separate phases of OC4:

- In Phase I, the NREL offshore 5-MW wind turbine was installed on a jacket support structure in 50 m of water.
- In Phase II, the wind turbine was installed on a floating semi-submersible in deep water (200 m).

The code-to-code comparisons in both phases have generally agreed very well. The key reasons for the differences that have remained and the other findings from Phases I and II are discussed below.

Phase I – Jacket:

- Only some codes account for gravity and damping terms in the eigenanalysis. These terms have a marginal influence on eigenfrequencies. A slight decrease of frequencies for global structural modes was observed in those codes that account for the gravity term.
- Overlapping members in the jacket sub-structure lead to increased material volume in the vicinity of joints. This resulted in overestimation of the structure weight, marine growth mass, buoyancy and hydrodynamic loads. The extent of the overestimation depends on a given jacket and varies due to the different topology, thicknesses and number of intersecting braces. Therefore, it is recommended to remove overlapping sections from models of jacket support structures in cases where very accurate results are required.
- The longest braces located in the lower bays of the jacket are subjected to local vibration phenomena. The result of the modal analysis showed that local vibrations include eigenmodes in the frequency range of 3.1 – 6.7 Hz.
- There is relation between rotor harmonic excitations and local vibration. Higher rotor harmonics were found in the vicinity of frequencies where local vibrations were present. Local vibrations are mostly induced above the rated wind speed where the rotor speed is relatively constant. In the partial loading region (below the rated wind speed), harmonic frequencies are smeared due to higher variation of the rotor speed.
• Increase of the structural mass due to marine growth affects dynamics of the jacket, which directly translates to significantly higher damage-equivalent loads of the lowest braces.

• Buoyancy forces can be calculated based on the pressure integration or displaced volume method. Many codes utilize the simpler displaced volume method, which does not account for the hydrodynamic pressure that is related to kinetic energy of water particles. The pressure integration method provides more accurate estimation of buoyancy as it can account for both hydrodynamic and hydrostatic pressures.

• Several improvements of the hydro load models were applied in diverse tools. For instance:
  o FEDEM WindPower improved interpolation of hydrodynamic forces applied on the beam elements;
  o 3DFloat code was extended with the following features: flooded members, irregular waves by the constant-energy method for discretization of the wave spectrum and stream function wave kinematics;
  o USFOS-vpOn code was corrected for the Froude-Krylov force, which had been accounted for twice;
  o an interface to WaveLoads for computation of the stream function and the Pierson-Moskowitz spectrum was verified in Poseidon;
  o In HAWC2 a bug in the stream function wave implementation was fixed.
  o The ability to model the hydro-elastic response of fixed-bottom multi-member offshore structures was added to FAST.

Phase II – Floating Semisubmersible:

• There is not a clear need for the inclusion of radiation/diffraction loads from a potential-flow theory type solution for this type of semisubmersible under the conditions examined. Morison-only solutions seem to yield similar results, though with more variation in the pitch response. These small differences, however, could be an issue for fatigue, which was not examined in this analysis.

• 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 (especially in the presence of large waves and current).

• Varying levels of mean drift resulting from wave excitation are seen among the different models, based on the inclusion of nonlinear hydrodynamics modeling theory. The modeling approaches that create a drift force include wave stretching in Morison’s equation, applying loads at the instantaneous position of the structure, including second-order terms in the potential-flow solution, or calculating the mean-drift force from the linear potential-flow solution. The drift force 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 base columns (or heave plates) of the semisubmersible to obtain accurate heave excitation in the system from waves. The need is significant for this structure because of its shallow draft.

• Mooring loads in frequencies above the linear wave range differ significantly between codes using a quasi-static model and 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 instead of the quasi-steady theory for the aerodynamic induction 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 (both without and with wind loading).

• 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 low.

The OC3 and OC4 projects have been extremely useful in showing the influence of different modeling approaches on the simulated response of an offshore wind system. Code-to-code comparisons, though, can only identify differences. They do not determine which solution is the most accurate. To address this limitation, Task 30 also held a topical experts meeting on “Offshore Wind Model Validation” in May, 2012. The meeting was attended by 60 international and domestic attendees from national labs, industry, and academia. Invited speakers gave 17 presentations and NREL moderated four discussions to address the following topics:

• What data is needed for validation?

• What data is currently available?

• What test methods and instrumentation should be used to gather useful data for validation?

• What are the trade-offs between tank testing (scale models) and field testing (full scale)?

• How should the data be post-processed?

• What is the validation process?

• What case studies of test data collection and validation are available to the Task 30 group?

From this meeting, participants gained a clearer understanding of the methods and practices used for validating offshore wind systems. Members from industry and research institutions spanning the fields of both offshore structures and wind turbines shared their experience and insight on the issues related to testing and model validation. Through a straw poll taken at the end of the workshop, 39 out of 60 participants expressed an interest in participating in a new IEA Wind Task focused on validating the codes used to model offshore wind systems. With this expressed level of interest, NREL agreed to develop a proposal for either a new IEA Wind Task devoted to validating offshore wind codes through code-to-data comparisons, or add a new component to the OC4 project devoted to this task.

In the fall of 2013, NREL requested and gained approval for the extension of Task 30 for a new project named the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5). This project will begin the validation of offshore wind modeling tools through the comparison of simulated responses to physical response data from actual measurements. It will start in 2014 and run for 4 years. The project will examine three structures using data from both floating and fixed-bottom systems, and from both scaled tank testing and full-scale, open-ocean testing.
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<tr>
<td>ABS</td>
<td>American Bureau of Shipping</td>
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<tr>
<td>BEM</td>
<td>Blade Element Momentum</td>
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<td>CENER</td>
<td>National Renewable Energy Centre</td>
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<tr>
<td>CENTEC</td>
<td>Centre for Marine Technology and Engineering</td>
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<td>CeSOS</td>
<td>Centre for Ships and Ocean Structures</td>
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<td>CGC</td>
<td>China General Certification</td>
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<tr>
<td>CM</td>
<td>center of mass</td>
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<td>CMS</td>
<td>component mode synthesis</td>
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<td>DEL</td>
<td>damage equivalent load</td>
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<tr>
<td>DHI</td>
<td>Danish Hydraulic Institute</td>
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<tr>
<td>DLL</td>
<td>dynamic link library</td>
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<tr>
<td>DOF</td>
<td>degree of freedom</td>
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<td>DS</td>
<td>dynamic stall</td>
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<td>Technical University of Denmark</td>
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<td>EU</td>
<td>European Union</td>
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<tr>
<td>FDT</td>
<td>filtered dynamic thrust</td>
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<tr>
<td>FEM</td>
<td>finite element method</td>
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<td>FWV</td>
<td>free-wake vortex</td>
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<td>GDW</td>
<td>generalized dynamic wake</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<td>Fraunhofer Institute for Wind Energy and Energy System Technology</td>
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<tr>
<td>IWL</td>
<td>instantaneous water level</td>
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<td>LC</td>
<td>load case</td>
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<tr>
<td>MBS</td>
<td>multibody-dynamics formulation</td>
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<td>MD</td>
<td>mean drift</td>
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<td>ME</td>
<td>Morison’s formula</td>
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<td>Abbreviation</td>
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<tr>
<td>MSL</td>
<td>mean sea level</td>
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<td>NOWITECH</td>
<td>Norwegian Research Centre for Offshore Wind Technology</td>
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<td>NREL</td>
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<tr>
<td>NTM</td>
<td>normal turbulence model</td>
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<td>OWT</td>
<td>offshore wind turbine</td>
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<tr>
<td>PDF</td>
<td>probability density function</td>
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<td>PF</td>
<td>potential flow theory</td>
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<td>PM</td>
<td>Pierson-Moskowitz wave spectrum</td>
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<tr>
<td>PSD</td>
<td>power-spectral density</td>
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<td>QS</td>
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<td>QTF</td>
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<td>RAO</td>
<td>response amplitude operator</td>
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<tr>
<td>RNA</td>
<td>rotor-nacelle assembly</td>
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<td>SWE</td>
<td>Stuttgart Wind Energy</td>
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<td>SWL</td>
<td>still water level</td>
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<td>TLP</td>
<td>tension leg platform</td>
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<td>UOU</td>
<td>University of Ulsan</td>
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IEA Wind Task 30

1. Background Information and Objectives

Authors: A. Robertson, J. Jonkman, and W. Musial (NREL, USA); W. Popko and F. Vorpahl (Fraunhofer IWES, Germany)

1.1 Overview of IEA Wind Task 30

Wind turbines are designed and analyzed using simulation tools (i.e., design codes) capable of predicting the coupled dynamic loads and responses of the system. Land-based wind turbine analysis relies 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. In recent years, some of these codes have been expanded to include the additional dynamics pertinent to offshore installations, including the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. The sophistication of these aero-hydro-servo-elastic codes, and the limited data available with which to validate them, underscores the need to verify their accuracy and correctness. First the OC3 and now the OC4 projects were established to meet this need.

The OC4 project benchmarked system-dynamics models used to estimate offshore wind turbine dynamic loads. Currently, conservative offshore design practices adopted from marine industries are enabling offshore wind development to proceed. But if offshore wind energy is to be economical, reserve margins must be quantified, and uncertainties in the design process must be reduced so that appropriate margins can be applied. Uncertainties associated with load prediction are usually the largest source and hence the largest risk. Model comparisons are the first step in quantifying and reducing load prediction uncertainties. Comparisons with test data would be the next step.

To test the offshore wind turbine system-dynamics models, the main activities of the OC4 project reported here were to (1) discuss modeling strategies, (2) develop a suite of benchmark models and simulations, (3) run the simulations and process the simulation results, and (4) compare and discuss the results. These activities fell under broader objectives including:

- Assessing the accuracy and reliability of simulations to establish confidence in their predictive capabilities
- Training new analysts to run and apply the codes correctly
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Such verification work, in the past 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 system-dynamics models.

The simulation of offshore wind turbines under combined stochastic aerodynamic and hydrodynamic loading is very complex. The benchmarking task, therefore, required a sophisticated approach that facilitated source identification of modeling discrepancies introduced by differing theories and/or model implementations in the various codes. This was possible only by (1) meticulously controlling all of the inputs to the codes and (2) carefully applying a stepwise verification procedure where model complexity was increased one step at a time.

The fundamental set of inputs to the codes controlled within OC4 related to the specifications of the wind turbine. The OC4 project used the publicly available specifications of the 5-MW baseline wind turbine
developed by NREL, which is a representative utility-scale multi-megawatt turbine that was also adopted as the reference model for the integrated European Union (EU) UpWind research program and OC3 project. This wind turbine is a conventional three-bladed, upwind, variable-speed, variable-blade-pitch-to-feather-controlled turbine. The specifications consisted of detailed rotor aerodynamic properties; blade, drivetrain, nacelle, and tower structural properties; and generator-torque and blade-pitch control system properties, the latter of which was provided to all OC4 participants in the form of a dynamic link library (DLL). The specifications of the NREL offshore 5-MW baseline wind turbine are summarized in Table 1 and available in detail [1]. The hydrodynamic and elastic properties of the varying offshore support structures used in the project were also controlled (and are described in the chapters that follow). Furthermore, the turbulent full-field wind inflow and regular and irregular wave kinematics were model inputs controlled in the OC4 project (and are described in the chapters that follow). This approach reduced possible differences brought about by dissimilar turbulence models, wave theories, or stochastic realizations.

### Table 1: Summary of properties for the NREL 5-MW baseline wind turbine

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>5 MW</td>
</tr>
<tr>
<td>Rotor orientation, configuration</td>
<td>Upwind, 3 blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable speed, collective pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High speed, multiple-stage gearbox</td>
</tr>
<tr>
<td>Rotor, hub diameter</td>
<td>126 m, 3 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-in, rated, cut-out wind speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-in, rated rotor speed</td>
<td>6.9 rpm, 12.1 rpm</td>
</tr>
<tr>
<td>Rated tip speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Overhang, shaft tilt, precone</td>
<td>5 m, 5°, 2.5°</td>
</tr>
<tr>
<td>Rotor mass</td>
<td>110,000 kg</td>
</tr>
<tr>
<td>Nacelle mass</td>
<td>240,000 kg</td>
</tr>
<tr>
<td>Tower mass</td>
<td>347,500 kg</td>
</tr>
<tr>
<td>Coordinate location of overall center of mass (CM)</td>
<td>(-0.2 m, 0.0 m, 64.0 m)</td>
</tr>
</tbody>
</table>

An important part of the comparison was a stepwise process that allowed the origin of differences between code predictions to be discovered. Various combinations of wave and wind input were introduced with the rotor and tower being rigid or flexible, disentangling the contributions from wind- and wave-applied loads and dynamic response. Finally, the turbine was made operational so that the effect of the control system could be evaluated.

In OC4, emphasis was given to the verification of the offshore support structure dynamics as part of the dynamics of the complete system. This emphasis distinguishes the OC4 project from past wind turbine code-to-code verification exercises. Less importance was placed on the testing of the aerodynamic models separately because this was addressed in the OC3 project.

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 installations are cost effective, the application of a variety of support-structure types is required. These types include fixed-bottom monopiles, gravity bases, and space-frames—such as tripods, quadpods, and lattice frames (e.g., “jackets”)—and floating structures. In this context, the offshore wind industry faces many new design challenges.
To encompass the variety of support structures required for cost-effectiveness at varying offshore sites, different types of support structures (for the same wind turbine) were investigated in separate phases of the OC3 and OC4 projects. For OC3, a monopile, tripod, and floating spar-buoy were analyzed. OC4 extended this work by looking at two new support structures (see Figure 1):

- In Phase I, the NREL offshore 5-MW wind turbine was installed on a jacket substructure in 50 m of water.
- In Phase II, the wind turbine was installed on a floating semisubmersible in deep water (200 m).

![OC4 Jacket](image1.jpg)

![OC4 DeepCwind Semisubmersible](image2.jpg)

**Figure 1: Support structure concepts investigated within the OC4 project**

During the OC4 project, the wind and wave data sets were generated; and the simulations and code-to-code comparisons of Phases I and II were completed. Four conference papers have been published and presented summarizing the findings, see references [2]-[5]. In addition, a journal article is under review, which summarizes the work of Phase I [6]. This report contains a complete review of all phases, with contributions from the conference papers and journal article.

Over the course of the OC4 project, internet meetings were held approximately every one to two months, which were productive and significantly reduced the need for physical meetings and travel. In addition, eight physical meetings were held at key points in the project:

- Bremerhaven, Germany – June, 2010
- Hamburg, Germany – October, 2010
- Maui, Hawaii, USA – June, 2011
- Amsterdam, the Netherlands – November, 2011
- Rhodes, Greece – June, 2012
Vienna, Austria – February, 2013
Nantes, France – June, 2013
Frankfurt, Germany – November, 2013

The verification activities performed in OC4 were important because the advancement of the offshore wind industry is closely tied to the development and accuracy of dynamics models. Not only have vital experiences and knowledge been exchanged among the project participants, but the lessons learned have helped identify deficiencies in existing codes and needed improvements, which will be used to improve the accuracy of future predictions.

Code-to-code comparisons, though, can only identify differences. They do not determine which solution is the most accurate. To address this limitation, Task 30 also held a topical experts meeting on “Offshore Wind Model Validation” in May, 2012. The conclusions drawn from this meeting were that participants were interested in forming a new IEA Wind project focused on validating the codes used to model offshore wind systems. Therefore, in the fall of 2013 an extension of the OC4 project was presented to and approved by the IEA Wind agreement for this purpose. The project is officially called the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5), and will begin the validation of offshore wind modeling tools through the comparison of simulated responses to physical response data from actual measurements. It will start in 2014 and run for 4 years and also operate under Task 30. The project will examine three structures using data from both floating and fixed-bottom systems, and from both scaled tank testing and full-scale, open-ocean testing.

1.2 References


2. Jacket Modeling of Phase I

Authors: Wojciech Popko, Fabian Vorpahl, Adam Zuga, Martin Kohlmeier (Fraunhofer IWES); Jason Jonkman, Amy Robertson (National Renewable Energy Laboratory); Torben J. Larsen, Anders Yde (Technical University of Denmark); Kristian Sætertrø, Knut M. Okstad (Fedem Technology AS); James Nichols (Garrad Hassan); Tor A. Nygaard (Institute for Energy Technology); Zhen Gao, Paul Thomassen (Norwegian University of Science and Technology); Dimitris Manolas (National Technical University of Athens); Kunho Kim, Qing Yu (American Bureau of Shipping); Wei Shi, Hyunchul Park (Pohang University of Science and Technology); Andrés Vásquez-Rojas, Jan Dubois (Institute of Steel Construction at the Leibniz Universität Hannover); Daniel Kaufer (Universität Stuttgart); Marten J. de Ruiter, Tjeerd van der Zee (Knowledge Centre WMC); Johan M. Peeringa (Energy Research Centre of the Netherlands); Huang Zhiwen (China General Certification); Heike von Waaden (REpower Systems SE)

2.1 Phase I Offshore Wind Turbine Model

In Phase I of the OC4 project an offshore wind turbine (OWT) consisting of the NREL 5-MW Offshore Baseline Turbine [1] and a jacket support structure was analyzed. The support structure, which was originally developed for the UpWind project by Vemula et al. [2] was adapted for the OC4 needs. Its detailed description is available in Vorpahl et al. [3].

The model consists of three main parts: a jacket sub-structure, a transition piece, and a tower. The entire structure is supported by four piles, which are modeled as cantilevered at the seabed. Four legs of the jacket are inclined from the vertical position resulting in a wider structural base. They are stiffened by four levels of X-braces. Additionally, four horizontal mudbraces are added above the mudline to reduce bending moments at the foundation. The jacket sub-structure and the tower are connected through a transition piece, which is modeled as rigid. The support structure is designed for 50 m water depth. The tower top elevation is 88.15 m above the mean sea level (MSL), whereas the hub height is located at 90.55 m above MSL. A schematic model of the analyzed jacket support structure is shown in Figure 2.

The definition of the support structure is kept as simple as possible to minimize the effort and modeling errors in its implementation in various simulation tools. However, its complexity is sufficient to mimic the structural behavior of a real OWT and to depict differences in results between the simulation tools. For simplification reasons, it is decided not to include appurtenances on the jacket structure, such as boat landings, J-tubes, anodes, cables, ladders etc. Also, joint cans are not accounted for in the model setup. At joints, the connecting nodes of elements are defined at the intersection points of the members’ centerlines. This leads to overlap of elements in the analyzed jacket model. Due to the overlapping members, the mass of the jacket is overestimated around 9.7%, though there is only a marginal influence coming from overlapping parts on eigenfrequencies and simulated loading as proved by Kaufer et al. [4]. The additional masses such as: hydrodynamic added mass, water in flooded legs and marine growth are included in the model description as they have a strong impact on the dynamic response of the structure. Marine growth mass and hydrodynamic added masses are overestimated around 9.2% and 4.6%, respectively, due to presence of overlapping members.
2.2 Phase I Participants and Codes

Multiple academic and industrial project partners from 10 countries participated in Phase I. Those actively involved who delivered the simulation results were: Fraunhofer Institute for Wind Energy and Energy System Technology IWES (Germany), the National Renewable Energy Laboratory (NREL) (USA), Technical University of Denmark, campus Risø, Roskilde, Denmark (Risø DTU) (Denmark), Fedem Technology AS (Norway), Garrad Hassan & Partners Ltd. (UK), Institute for Energy Technology (IFE) (Norway), Pohang University of Science and Technology (POSTECH) (Korea), Norwegian University of Science and Technology (NTNU) (Norway), National Technical University of Athens (NTUA) (Greece), Institute of Steel Construction at the Leibniz Universität Hannover (LUH) (Germany), the Endowed Chair of Wind Energy at the Institute of Aircraft Design at Universität Stuttgart (SWE) (Germany), Knowledge Centre WMC (The Netherlands), Energy Research Centre of the Netherlands (ECN) (The Netherlands), American Bureau of Shipping (ABS) (USA), REpower Systems SE (Germany) and China General Certification (CGC) (China). Each one of the participants has their own area of expertise, and therefore, their own unique contribution to the project.

A set of the state-of-the-art simulation codes for OWT modeling were represented in Phase I of the OC4 project. Table 2 shows these codes and summarizes some of their most important simulation capabilities.
Table 2: Overview of simulation capabilities of aero-hydro-servo-elastic codes used in Phase I

<table>
<thead>
<tr>
<th>Code</th>
<th>Developer</th>
<th>Aerodynamics (aero)</th>
<th>Hydrodynamics (hydro)</th>
<th>Control (servo)</th>
<th>Structural (elastic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DFloat</td>
<td>IFE + UMB</td>
<td>BEM or GDW</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME</td>
<td>UD</td>
<td>FEM</td>
</tr>
<tr>
<td>ADAMS + AeroDyn</td>
<td>MSC Software, LUH, NREL, IWES</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME</td>
<td>DLL or UD</td>
<td>MBS</td>
</tr>
<tr>
<td>ADCoS-Offshore</td>
<td>Aero Dynamik Consult + IWES</td>
<td>BEM + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME</td>
<td>DLL or UD</td>
<td>FEM</td>
</tr>
<tr>
<td>ASHES</td>
<td>NTNU</td>
<td>BEM + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; + ME</td>
<td>Internal control system</td>
<td>FEM</td>
</tr>
<tr>
<td>Bladed V3.8X</td>
<td>GLGH</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME</td>
<td>DLL or UD</td>
<td>FEM&lt;sup&gt;p&lt;/sup&gt; + Modal/MBS</td>
</tr>
<tr>
<td>Bladed V4 Multibod</td>
<td>GLGH</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME</td>
<td>DLL or UD</td>
<td>MBS</td>
</tr>
<tr>
<td>FAST-ANSYS</td>
<td>NREL, ANSYS, and ABS (AeroDyn)</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD + ME</td>
<td>DLL or UD or SM</td>
<td>Support structure: FEM; Turbine: FEM&lt;sup&gt;p&lt;/sup&gt; + Modal/MBS</td>
</tr>
<tr>
<td>FEDEM WindPower</td>
<td>Fedem Technology AS</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt;, Stream + ME</td>
<td>DLL or UD or Internal control system</td>
<td>MBS/FEM Modal (CMS)</td>
</tr>
<tr>
<td>FAST v8.00.03</td>
<td>NREL</td>
<td>BEM or GDW + DS</td>
<td>Airy + ME</td>
<td>DLL or UD</td>
<td>Substructure: FEM + Craig Bampton; Turbine: FEMP + Modal/MBS</td>
</tr>
<tr>
<td>Flex-ASAS</td>
<td>Stig Øye + ANSYS</td>
<td>BEM or DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD + ME</td>
<td>DLL</td>
<td>Modal, FEM</td>
</tr>
<tr>
<td>Flex5-Poseidon</td>
<td>DTU + SWE + LUH</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD or Stream + ME, Interface to WaveLoads</td>
<td>DLL or UD</td>
<td>FEM + Modal</td>
</tr>
<tr>
<td>GAST</td>
<td>NTUA</td>
<td>BEM or 3DFW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; + PF or Stream + ME</td>
<td>DLL or UD</td>
<td>MBS/FEM</td>
</tr>
<tr>
<td>HAWC2</td>
<td>DTU</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or Stream or UD + ME</td>
<td>DLL or UD or SM</td>
<td>MBS/FEM</td>
</tr>
<tr>
<td>OneWind</td>
<td>IWES</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or UD + ME</td>
<td>DLL or UD</td>
<td>MBS/FEM</td>
</tr>
<tr>
<td>Phatas-WMCfem</td>
<td>ECN + WMC</td>
<td>BEM or GDW + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or Stream + ME</td>
<td>DLL or Internal modeling</td>
<td>Rotor-FD, Tower: FEM + Craig Bampton</td>
</tr>
<tr>
<td>USFOS-vpOne</td>
<td>SINTEF + NTNU + Virtual Prototyping</td>
<td>BEM + DS</td>
<td>Airy&lt;sup&gt;str&lt;/sup&gt; or Stokes’ 5&lt;sup&gt;th&lt;/sup&gt; order or Stream + ME</td>
<td>DLL or UD</td>
<td>FEM</td>
</tr>
</tbody>
</table>

AIRY<sup>str</sup> – Airy theory with stretching method  
BEM – Blade Element Momentum Theory  
CMS – Component Mode Synthesis  
DLL – External dynamic link library  
DS – Dynamic Stall Implementation  
FEM – Finite-element method  
FEMP<sup>p</sup> – Finite-element method for mode pre-processing only  
PF – Linear potential flow with radiation and diffraction  

GDW – Generalized Dynamic Wake Theory, there are different formulations of these models that account for dynamic wake, but these differences are not discriminated here.  
MBS – Multibody-dynamics formulation  
ME – Morison’s Formula  
Modal – Modal reduced system  
Rotor-FD – Nonlinear partial differential equations of the rotating and elastically deforming rotor (slender beams) solved by finite difference method and cubic spline for deformation field.  
SM – interface to Simulink with Matlab  
Stream – Dean’s stream function
2.3 Phase I Load Cases and Outputs

A set of 17 load cases of increasing complexity was defined to allow for a stepwise comparison of results and to enable the OC4 participants to trace back possible errors coming from different models and methods used among the simulation tools. The load-case sets are specified in Table 3 and briefly discussed within this section. A detailed description of these load cases, including a precise definition of environmental conditions, simulation setup and output sensors can be found in Vorpahl and Popko [5].

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Enabled DOF</th>
<th>Wind Conditions</th>
<th>Wave Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0x¹</td>
<td>Support structure or all</td>
<td>No air</td>
<td>No water</td>
</tr>
<tr>
<td>2.1</td>
<td>None</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>2.2</td>
<td>None, Rotor speed and blade pitch via controller</td>
<td>Steady, uniform, no shear:  ( V_{hub} = 8 \text{ m/s} )</td>
<td>No water</td>
</tr>
<tr>
<td>2.3a</td>
<td>None</td>
<td>No air</td>
<td>Regular Airy: ( H = 6 \text{ m}, T = 10 \text{ s} )</td>
</tr>
<tr>
<td>2.3b</td>
<td>None</td>
<td>No air</td>
<td>Stream function: ( H = 8 \text{ m}, T = 10 \text{ s} )</td>
</tr>
<tr>
<td>2.4a</td>
<td>None, Rotor speed and blade pitch via controller</td>
<td>NTM (Kaimal):  ( V_{hub, avg} = 11.4 \text{ m/s} )</td>
<td>No water</td>
</tr>
<tr>
<td>2.4b</td>
<td>None, Rotor speed and blade pitch via controller</td>
<td>NTM (Kaimal):  ( V_{hub, avg} = 18 \text{ m/s} )</td>
<td>No water</td>
</tr>
<tr>
<td>2.4</td>
<td>None</td>
<td>No air</td>
<td>Irregular Airy with PM: ( H_s = 6 \text{ m}, T_p = 10 \text{ s} )</td>
</tr>
<tr>
<td>3.2</td>
<td>All, Rotor speed and blade pitch via controller</td>
<td>Steady, uniform, no shear:  ( V_{hub} = 8 \text{ m/s} )</td>
<td>No water</td>
</tr>
<tr>
<td>3.4a</td>
<td>All, Rotor speed and blade pitch via controller</td>
<td>NTM (Kaimal):  ( V_{hub, avg} = 11.4 \text{ m/s} )</td>
<td>No water</td>
</tr>
<tr>
<td>4.3b</td>
<td>Support structure</td>
<td>No air</td>
<td>Stream function: ( H = 8 \text{ m}, T = 10 \text{ s} )</td>
</tr>
<tr>
<td>4.5</td>
<td>Support structure</td>
<td>No air</td>
<td>Irregular Airy with PM: ( H_s = 6 \text{ m}, T_p = 10 \text{ s} )</td>
</tr>
<tr>
<td>5.6</td>
<td>All, Rotor speed and blade pitch via controller</td>
<td>Steady, uniform, no shear:  ( V_{hub} = 8 \text{ m/s} )</td>
<td>Stream function: ( H = 8 \text{ m}, T = 10 \text{ s} )</td>
</tr>
<tr>
<td>5.7</td>
<td>All, Rotor speed and blade pitch via controller</td>
<td>NTM (Kaimal):  ( V_{hub, avg} = 18 \text{ m/s} )</td>
<td>Irregular Airy with PM: ( H_s = 6 \text{ m}, T_p = 10 \text{ s} )</td>
</tr>
</tbody>
</table>

NTM – Normal turbulence model  
PM – Pierson-Moskowitz wave spectrum  
\( H \) – wave height  
\( H_s \) – significant wave height  
\( T \) – wave period  
\( V_{hub} \) – average wind speed at the hub height  
\( V_{hub, avg} \) – average wind speed at the hub height  
\( T_p \) – peak-spectral wave period  
\( x^1 \) – a and b cases without gravity and damping, c and d cases with gravity and damping, a and c cases only support structure  
DOF enabled, b and d cases all DOF enabled

Load-case set 2 dealt with a completely rigid OWT. Different load sources were enabled dependent on the individual load case. In LC 2.1, gravity and buoyancy were checked in still water environment without aerodynamic loads. LC 2.2 allowed for comparison of basic aerodynamic loading. Here, the wind field was as simple as possible and water was not included. In LC 2.4a and 2.4b, loads resulting from stochastic winds were simulated for rated and over-rated wind speeds. LC 2.3a, 2.3b and 2.5 were meant to verify wave load calculations for a linear and a nonlinear regular wave and an irregular linear train, respectively.

In load-case set 3, a land based turbine under deterministic and stochastic wind loads was investigated. No water effects were included herein. The jacket support structure was replaced with a land based tower as defined in [1]. The tower was placed on the top of a rigid, cylindrical element characterized by the following dimensions: 0.55 m height, 6 m diameter and 0.1 m thickness. This was required in order to
compensate the hub height difference between the jacket support structure and the land based tower. The entire turbine was simulated as fully-flexible.

Load-case set 4 dealt with a model of a flexible offshore structure and a rigid RNA. Herein, only two hydrodynamic loads, regular wave and irregular sea state, were analyzed.

The fully-flexible OWT was analyzed in load-case set 5 where both aerodynamic and hydrodynamic loads were enabled in one deterministic and one stochastic load case.

Turbulent wind fields were provided by DTU [6] according to the specification from [5]. The wind data could also be generated individually by each project partner, based on the delivered specification. The alternative was given for those participants, whose codes are not able to utilize the provided wind fields due to a different grid format (i.e. Phatas and Flex5 utilize polar grid) or limitations imposed on the grid resolution (i.e. ADCoS-Offshore). Wave loads were generated individually by each project participant based on the spectral input or the exact time history. For the latter possibility, 50 wavelets with predefined wave number, amplitude, phase angles and angular frequencies are specified in [5].

The simulation time for the deterministic load cases was 30 s. All stochastic cases were executed with one seed of 3600 s length to get statistically comparable results. Load cases with deterministic environmental loads (e.g. constant wind, regular wave) were directly compared in terms of time-series outputs, whereas those with stochastic environmental loads (e.g. turbulent wind, irregular sea state) were compared in terms of probability density functions (PDFs), power spectral densities (PSDs), and damage-equivalent loads (DELs).

Simulation outputs were recorded at multiple nodal points (sensors), located on the jacket support structure and the RNA as depicted in Figure 3. The position of sensors was chosen to provide maximum information regarding the OWT behavior with the minimal effort necessary for data acquisition and post-processing. Sensors located on the RNA captured aerelastic response of a turbine and its power production. The support structure sensors provided information concerning global and local dynamics of the jacket. For example, local vibrations of the structure were investigated at the lowest braces, whereas global bending moments and forces were calculated at the very bottom of the structure. Besides that, there were four additional sensors monitoring the wind speed at the hub height and the sea elevation at the center of the structure.

2.4 Phase I Simulation Results

The most interesting load cases and output sensors, according to the authors, are presented herein. Chosen results are meant to give a general overview of code-to-code differences and diverse approaches in modeling, that influence estimation of loads. The results obtained are the outcome of several revisions,
which were necessary due to the complexity of models, errors caused by human factor, the ongoing
development of some of the codes etc. These accounted for corrections at all stages of OWT modeling, its
simulation and post-processing of the data. Project participants put some effort into ensuring that their
models: (1) were implemented according to the provided specification of the OWT, (2) fulfilled initial
conditions of the simulations and start-up transients were eliminated, (3) used proper coordinate systems
for the data outputs. However, some errors caused by a human factor may persist in the results.

2.4.1 Comparison of Mass

Prior to the simulation of the prescribed load cases, a verification of the different implementations of the
OWT was conducted in terms of structural and additional masses. The comparison of masses is important,
as they are directly related to the structural dynamics. Structural masses encompass the jacket, transition
piece, tower and RNA. Additional masses include marine growth, water in flooded legs and the
hydrodynamic added mass imposed by water surrounding the structure. The results, obtained from 19
different models, are compared against each other in Figure 4 and Figure 5, respectively.

![Figure 4: Structural masses](image)

In general, a very good agreement between the implemented models is observed. The achievement of
such results involved a widespread discussion about modeling strategies and implementation methods.
The differences in RNA masses are mainly a result of discretization of the blade and its mass integration.
Dissimilarities in the tower masses are attributed to the discretization of the tower. Some codes could not
model it as conical; therefore a set of stepped cylindrical elements was utilized for its implementation.
Standard deviations of blade and tower masses coming from different codes are 0.2 t and 0.4 t,
respectively. Discrepancies in the jacket masses are the result of slightly different modeling of the
structure in diverse tools, though the standard deviation of 2.3 t is also very small. The transition piece
was defined as a point mass of 666 t by most of the participants. Small discrepancies should not have a
profound influence on the eigenfrequencies of the OWT. Water added mass and water in the flooded legs
were defined from the MSL to the seabed at -50 m. Marine growth was only implemented within the
range of -40 m to -2 m. The discrepancies in masses mainly arise from the discretization of these
threshold regions in the support structure. In fluid mechanics, water added mass is defined as the inertia
added to a system due to the movement of accelerating or decelerating structure that displaces some
volume of surrounding water. Herein, water added mass is calculated from the Morison’s equation
hydrodynamic mass force term without the acceleration component:

$$\rho_w (C_m - 1) D^2 \pi L$$

where:

$\rho_w$ – water density [kg/m$^3$]; $C_m$– inertia coefficient [-]; $D$ – diameter [m]; $L$ – member length [m].
2.4.2 Eigenanalysis

Four load cases are defined for eigenmodes analysis. The exemplary results from LC 1.0b are shown in Figure 6.

Eigenmodes were identified based on their visualization. Another approach would be to compare the energy contribution from different modal components. However, such information could only be extracted from a limited number of codes making the comparison rather difficult.

Values of the very first eigenmodes are in a very good agreement. Discrepancies increase for higher modes. This is expected, as different codes incorporate a different number of degrees of freedom (DOF) and somewhat dissimilar ways of structural modeling. Besides that, energy of higher modes usually originates from several different DOF, from which it is supplied in a different percentage. Consequently, it is difficult to clearly assess which coupled vibration mode is induced, for the high frequency modes,
based on the mode visualization. Furthermore, some of the codes used different reduction methods for solving the eigenvalue problem. While the impact of these differences is not directly visible in the eigenanalysis, it is worth mentioning their existence. Flex5-Poseidon calculated frequencies based on a “partly” reduced approach. Flex5 reduced the flexible beam elements of a tower and blades by Modal Decoupling, whereas no reduction of the substructure was performed by Poseidon. Then, both parts were coupled on the synthesis of the equations of motion. In general, modal-based codes predict slightly higher frequencies compared to multibody- or FEM-based tools, which indicates a stiffer behavior of a structure. Multibody and FEM codes accommodate more DOF and thus allow for more vibrational modes. This results in reduced stiffness of the structure, which should better mimic reality. This is well observed in the case of HAWC2, which predicted slightly lower frequencies than the modal-based Bladed V3.8X. The natural frequency for the fore-aft mode is slightly higher than for the side-to-side mode of the same order. The support structure is symmetric with respect to these modes. The RNA should be the only source of difference in the natural frequencies, as for instance, there are different moments of inertia of the nacelle, hub and rotor around two horizontal axes of symmetry. A number of codes had difficulty in detecting the 1st edgewise collective mode. Those that were able to capture it, show quite distinct frequencies due to the couplings with other modes. Bladed may overestimate the frequency, as the rotor inertia had to be artificially increased during the eigenanalysis to prevent the rotor from idling. This mode is close to the uncoupled edgewise vibration of the rotor. 3DFloat, Flex5 and USFOS-vpOne show significant coupling of the collective edgewise blade motion with the 1st drivetrain mode, while in ADCoS-Offshore, the coupling with the 2nd side-to-side mode is present.

**Figure 7: Influence of gravity and damping terms, percentage difference between LC 1.0b and 1.0d**

The influence of gravity and damping on the eigenanalysis of the fully flexible OWT was analyzed in LC 1.0d. Gravity and damping terms were accounted for in Bladed, GAST, FEDEM WindPower and ANSYS-BModes. Whereas, HAWC2 and Phatas-WMCfem accounted only for the damping term. The remaining codes neglected the influence of these two terms. The results are shown in Figure 7. A very low influence of gravity and damping on the eigenvalues is observed; in general, much less than 1.5%. In most of the cases, a slight decrease of frequency occurs. The highest, relative reduction is visible for the global modes such as side-to-side and the fore-aft. This is expected as gravity tends to reduce the bending stiffness of a vertical beam. A very small increase of frequencies for asymmetric flapwise and edgewise modes is observed. In general, the multibody code HAWC2 is expected to match GAST, Bladed V4.0 and
FEDEM WindPower results. However, a much smaller change in the frequencies of global modes is observed, as only the damping term was used in the analysis.

FEM- and multibody-based codes can be used to study higher local vibrational modes of the jacket. Those vibrations are mainly present in the lower bays of the sub-structure where the braces are longest. Mode-shape based tools might not accurately predict these vibrations due to the limited number of mode shapes used for the model. Local dynamics in the jacket were observed at higher frequencies, where diverse couplings with the RNA and the global structural modes were found by many multibody and FEM tools. Exemplary results are shown in Figure 8. There is a distinct range of frequencies, where the lowest modes of the local jacket vibrations were detected by different tools. Local vibration issue was more deeply studied by Popko et al. [7] within the OC4 project where it was confirmed that there is a relation between rotor harmonic excitations and local vibration phenomena. Higher rotor harmonics were found in the vicinity of frequencies where local vibrations were present. It was also found out that the increase of the structural mass due to marine growth affects dynamics of the jacket, which directly translates to significantly higher DEL of the lowest braces. On the other hand, the influence of the increased hydrodynamic load on fatigue loads of brace was found to be marginal.

2.4.3 Rigid OWT

In the load-case set 2.X, special attention was given to proper calculation of buoyancy. There was a wide discussion within the OC4 project concerning the modeling strategy for buoyancy and its physical correctness. Buoyancy can be accounted for based on the displaced volume method or the pressure integration method. The former estimates weight of water displaced by submerged elements of the structure. The latter integrates the external pressure acting on the surface of a structure, accounting for all pressure forces imposed on individual members. The pressure integration method provides more accurate estimation of buoyancy and should be used in the analysis of jackets. This method accounts for hydrodynamic and hydrostatic pressures. The hydrostatic pressure is associated with pressure exerted by a column of water due to the gravity force. The hydrodynamic pressure refers to kinetic energy of water particles.

The structure modeled within the OC4 project was cut and cantilevered at the mudline (see Figure 9). In such a case, there was no upward buoyant force acting on the bottom, cross-sectional area of a pile that is in contact with the seabed, as described by Clauss et al. [8]. As the piles were modeled as cut at the mudline (they did not penetrate the seabed), the pore water pressure in the seabed was also ignored in the modeling. The resulting vertical forces at the base of the structure for LC 2.1 and LC 2.3a are shown in Figure 10 and Figure 11, respectively. The shifts in the mean values of force are due to the diverse

Figure 8: Exemplary eigenmodes including local jacket vibrations and couplings detected by various codes

(a) ADCoS-Offshore 2.67 Hz.  
(b) USFOS-VPOne 5.40 Hz.  
(c) 3DPout 6.29 Hz.  
(d) Fedem WindPower 4.67 Hz.  
(e) GAST 5.59 Hz.
modeling approaches in accounting for buoyancy. Those project participants that considered in their modeling strategies that the structure was cantilevered at the seabed ended up with a mean force at about -16600 kN (a force directed upward) at the mudline. Other participants that did not adapt this approach ended up with about -15800 kN. In those cases, a buoyancy force was exerted at the bottom surfaces of piles. In Bladed V4.0, there was an additional pressure force applied on the top of the grouted piles that leads to about -17150 kN. In Flex5-Poseidon utilized by SWE, buoyancy of legs was ignored, as the code could not handle hollow tubes at the time this report was written. Pressure integration was only applied on the surface of sealed braces, which led to the mudline vertical force of about -17100 kN.

![Figure 9: Pile modeled as cut and cantilevered at the mudline; arrows indicate the areas where pressure is integrated](image)

![Figure 10: Vertical force at mudline, LC 2.1 – still water](chart)

Differences in the peak-to-peak amplitude of the vertical forces at the mudline, as shown in Figure 11, are mainly based on whether the displaced volume or the pressure integration method was used for calculation of buoyancy. The integration of the hydrodynamic pressure results in a reduced buoyancy effect seen at the mudline during the wave crest (higher upward buoyancy force at the wave crest), while it is increased during the wave trough (lower upward buoyancy force at the wave trough), compared to the displaced volume method. This is observed as smaller peak-to-peak amplitudes of the vertical force at the mudline. In reality, at the relatively deep position, the hydrostatic pressure does not change that much due to the changing water surface elevation. The influence of the hydrodynamic pressure is also small. Therefore, the variation in the vertical force at the mudline should also be small. This is observed in the results obtained with the pressure integration method. Summing up, the difference between the two furthest outliers is about 9%. This is acceptable, especially as different modeling assumptions for buoyancy were applied. Also, different masses of marine growth and the jacket substructure contributed to discrepancies.
A very good match of the rotor speed and the generator power was achieved in LC 2.2 for the majority of codes, as shown in Figure 12 and Figure 13, respectively. The tower blockage effect is captured by most of the tools as small fluctuations of the generator power and the rotor speed.

Upward and downward peaks in the low-speed shaft torque are present in the results of Flex5, utilized by LUH, SWE and REpower. Differences in the implementation of the tower blockage model are indicated as possible sources of those discrepancies. However, this issue has to be investigated further. The low-speed shaft torque was indirectly calculated in ADCoS-Offshore, through which a smoothing effect of the signal was introduced. High oscillations of the Flex5 (REpower) signals are due to the flexible model of the RNA used in the simulation, instead of the rigid one defined in the load-case set 2.X. The model setup
in ASHES still needs some refinements. The results for the remaining codes match very closely. They differ by less than 1% for the rotor speed, generator power and low-speed shaft.

Figure 13: Generator power, LC 2.2 – deterministic wind $V_{hub} = 8$ m/s

Figure 14: Low-speed shaft torque, LC 2.2 – deterministic wind $V_{hub} = 8$ m/s

Figure 15 shows the fore-aft force at the base of the structure for LC 2.3a. Some small differences in the peak-to-peak amplitude are caused, e.g., by dissimilarities in implementations of wave kinematics. The simulation results are also affected by differences originating in the modeling of the support structure. Flex5-Poseidon, utilized by SWE, gave the largest amplitude of the fore-aft base shear force, whereas a lower amplitude was calculated by the same code used at LUH. To sum up, a good agreement is observed for most of the codes. The maximum difference in the peak-to-peak amplitudes is less than 11% (for the majority of codes, it is much less).
The PDF of the tower-top and base fore-aft shear forces for LC 2.4b, as shown in Figure 16 and Figure 17, respectively, are expected to be very similar. Results from FAST-ANSYS and GAST differ in the mean value, which is about 10% higher at the mudline. Such a shift is caused by the additional wind loads applied on the tower, which should not have been accounted for, according to the definition of LC 2.4b. The mean fore-aft shear forces calculated in 3DFloat are higher than in other codes. 3DFloat had rigid blades, which were pitched according to the defined control system. One possible source of differences in the mean shear forces was the lack of the tower shadow model.

The explanation for the higher mean of the Flex5-Poseidon (LUH) signal is not that straightforward. The mean value of the generator power is higher than expected, but the mean pitch angle is lower. These facts may indicate wrong settings for the control system of the turbine. The utilization of different stochastic wind files is also a source of discrepancy, as already mentioned. HAWC2, FAST-ANSYS, FEDEM WindPower, 3DFloat and GAST utilized the same stochastic wind files as an input, whereas Bladed V3.85, ADCoS-Offshore, OneWind and Flex5-Poseidon used their own wind files. For example, there is less fluctuation in the longitudinal component of the wind speed in ADCoS-Offshore, which is reflected...
in the narrower PDF of the shear force. In general, a very good agreement of presented PDF results is observed.

Figure 17: PDF – fore-aft shear force at mudline, LC 2.4b – stochastic wind $V_{hub, \text{avg}} = 18$ m/s

DEL values of the mudline shear forces in LC 2.4b diverge a lot, as shown in Figure 18. The biggest outliers are GAST and ADCoS-Offshore. The energy content of the mudline signal of ADCoS-Offshore is of an order less than other codes, and its distribution is narrower, resulting in the lowest DEL value. The opposite behavior is observed for GAST (the PSD results are not shown herein). Apart from the outliers, the maximum difference between the other tools is less than 20%, which is a good result, considering all the mentioned differences in the setup of LC 2.4b.

Figure 18: DEL – fore-aft shear force at mudline, LC 2.4b – stochastic wind $V_{hub, \text{avg}} = 18$ m/s

2.4.4 Flexible Onshore Turbine

In Figure 19, tip twist of Blade 1 for LC 3.2 is zero in FAST, Flex5 and Bladed V3.85 outputs, as these codes did not consider torsion of the blade. USFOS-vpOne considered the torsional degree of freedom for the blade, but there was no output providing a time history of the tip angle. The blade torsion was included in the multibody release of Bladed V4.0 (no results presented herein) and should be soon
implemented in FAST. The results of FEDEM WindPower and GAST match closely. The biggest outlier, with the highest peak-to-peak oscillation, is ADCoS-Offshore. This has to be investigated further.

Figure 19: Blade 1 deflection at tip, LC 3.2 – deterministic wind $V_{hub} = 8$ m/s

The fluctuations of the low-speed shaft torque in LC 3.2 are mainly caused by the tower blockage effect, pronounced as 3P frequency at about 0.46 Hz and its higher harmonics, as shown in Figure 20. Only the first 10 s of the time series are shown for better clarity. In ADCoS-Offshore, the low-speed shaft torque was calculated indirectly, through which a smoothing effect was introduced. The shift of HAWC2 signal corresponds to higher rotational speed of the rotor, achieved by this tool in LC 3.2. The low-speed shaft torque of Flex5, utilized by REpower, is not shown herein due to excessive oscillations of the signal. Further refinements of the model are necessary. In general, mean values of the low-speed shaft torque are close for all the tools.

Figure 20: Low-speed shaft torque, LC 3.2 – deterministic wind $V_{hub} = 8$ m/s

A very good agreement in the distribution of flapwise and edgewise shear forces at the blade root is observed among the codes in LC 3.4a, as shown in Figure 21 and Figure 22, respectively. Minor shifts in
the mean values of the flapwise force distributions are caused by differences in the thrust force. For the spinning rotor cases, rigid blades were used in 3DFloat. Nevertheless, the distributions of the blade root forces closely match other codes where a flexible rotor was defined.

**Figure 21:** PDF – flapwise shear force at blade root, LC 3.4a – stochastic wind $V_{hub, avg} = 11.4$ m/s

**Figure 22:** PDF – edgewise shear force at blade root, LC 3.4a – stochastic wind $V_{hub, avg} = 11.4$ m/s

The PDF of the pitching moment at the blade root are shown in Figure 23. The discrepancies originate from the rate and magnitude of the pitching action, dependent on whether or not a rated speed of the rotor was achieved. HAWC2, FAST, FEDEM WindPower, 3DFloat and GAST utilized the same stochastic wind files as input; only Bladed V3.85 used its own wind files. Thus, the sources of discrepancies in the pitching moment at the blade root should mainly originate from the implementation of the blade model in various tools. For example, a shift of the blade mass center could affect the distribution of these values. Bladed V3.85 is the biggest outlier. However, such a difference is not caused by the utilization of different stochastic wind files, as the PDF of the longitudinal wind component match very well the same component in the wind files prepared by Risø DTU. The shift of the PDF of the pitching moment suggests incorrect setup of the model. For example, the aerodynamic center, relative to the pitch axis, could be specified incorrectly. However, in other stochastic LCs 2.4a, 2.4b and 5.7, PDF of the pitching moment of
Bladed V3.85 match other tools. Summing up, a good agreement of the PDF is observed for the majority of codes.

Figure 23: PDF – pitching moment at blade root, LC 3.4a – stochastic wind $V_{hub, avg} = 11.4$ m/s

2.4.5 Flexible Support Structure

The out-of-plane displacement in the fore-aft direction of the central joint X2S2 of X-brace (see Figure 3) is shown in Figure 24 for LC 4.3b. The OWT was excited with a deterministic wave, described by the 9th order stream function wave. The agreement of signal trends is remarkably good, although the peak-to-peak amplitude is very small. A frequency shift in the output of Flex5-Poseidon, utilized by SWE, is caused by a bug in the stream function wave. LUH also used Flex5-Poseidon. However, in their case, the WaveLoads tool was utilized to compute the stream function wave and then linked to Flex5-Poseidon by a DLL library. The relatively highest oscillation amplitude of 3DFloat requires further attention.

Figure 24: Out-of-plane deflection at center of X-joint at level 2 on side 2, LC 4.3b – stream function
In LC 4.5, the OWT was excited with a stochastic irregular wave. The axial force of the member B59 at the lowest X-brace (location presented in Figure 3) is shown in Figure 25. Frequency peaks at about 0.3 Hz and in ranges of 1.1 to 1.2 Hz and 2.6 to 2.8 Hz correspond to the 1st and 2nd global fore-aft modes and torsion, respectively, as detected in LC 1.0a and LC 1.0c. The results of the distribution of the axial member forces, shown in Figure 26, differ in the mean values mainly due to the differences in buoyancy modeling, discretization of the member and, therefore, slight offsets in placement of the output sensors. However, the widths and heights of most PDF are similar, indicating a good agreement in the fluctuation rate of the member axial force.

2.4.6 Flexible OWT

The DEL of the axial forces for LC 5.7, from sensors K1L2 and mudbraceL2 (see Figure 3) from Leg 2, are shown in Figure 27 and Figure 28, respectively. The biggest outlier in the DEL of the axial force at K1L2 located in the splash zone is Flex5-Poseidon, utilized by SWE. This is due to the incorrect
implementation of the stochastic wave, which is observed in the case of the code used at SWE. The remaining codes ended up with relatively small differences. The discrepancies at mudbraceL2 are relatively high, as many diverse modeling strategies influenced it.

Figure 27: DEL – axial force in Leg 2 at K1L2, LC 5.7 – stochastic wind $V_{hub, avg} = 18$ m/s and irregular Airy with PM

Figure 28: DEL – axial force in Leg 2 at mudbrace level, LC 5.7 – stochastic wind $V_{hub, avg} = 18$ m/s and irregular Airy with PM

Shifts in the mean values of the PDF of the axial force at the mudbrace shown in Figure 29 are caused by different approaches in modeling of buoyancy, as previously explained.

2.5 Phase I Conclusions

Results of Phase I are published in two conference papers [9] and [7]. Journal versions of these papers ([10] and [11]) are published in the Journal of Ocean and Wind Energy. Two technical reports are prepared by Fraunhofer IWES — one with detailed description of the support structure model [3] and another one with description of the load cases [5].

The load cases with deterministic inputs were compared in terms of time-series output, and the stochastic cases were compared in terms of probability density functions, power spectral densities, and damage
equivalent loads. Exemplary results of the simulations were presented in this report. The exemplary discrepancies between the codes were shown and sources of differences were discussed.

Figure 29: PDF – axial force in Leg 2 at mudbrace level, LC 5.7 – stochastic wind $V_{hub, avg} = 18$ m/s and irregular Airy with PM

The setup of coupled OWT simulations is an elaborated and difficult process, involving multidisciplinary engineering knowledge within the fields of structural engineering, control, hydrodynamics, aerodynamics, aeroelasticity, data pre- and post-processing etc. Thus, some of the obtained results are not free from the human-inherited errors. Furthermore, differences in the implemented theories and diverse modeling strategies contributed to the discrepancies in the presented results. In the light of these facts, a very good agreement in the obtained results has been achieved.

Through the participation in Phase I of the OC4 project, many of the participants have been able to verify their codes and methodologies developed for the dynamic analysis of a wind turbine supported with a jacket. Some inconsistencies and errors in models were detected in a direct code-to-code comparison of the results. Furthermore, the comparison with other codes has provided first sanity checks for the newly developed tools, i.e. 3DFloat, OneWind and ASHES. Some examples of improvements, corrections and bugs present in the tools and models are briefly mentioned herein.

Several improvements of the hydrodynamic load models were applied in FEDEM WindPower. For example, the mudline response from wave loads was smoothed out due to improved interpolation of forces applied on the beam elements. Also, the integration of AeroDyn with FEDEM WindPower was verified. The tower shadow effects in ADCoS-Offshore and FAST-ANSYS were improved. A bug in the implementation of the stream function in Poseidon was discovered.

Furthermore, an extended implementation of buoyancy, an interface to WaveLoads for computation of the stream function and the Pierson-Moskowitz spectrum were verified in Poseidon. The development of 3DFloat was accelerated by the participation in the project. It resulted in the implementation of i.e. models for marine growth, flooded members, irregular waves by the constant-energy method for discretization of the wave spectrum, and stream function wave kinematics.

In HAWC2, the position of the pitch axis in a blade model was corrected and a bug in the Stream function wave theory implementation was fixed. For calculation of the wave loads, the pressure integration method in USFOS-vpOne estimates the Froude-Krylov force by direct pressure integration using the incident wave velocity potential. During the modeling, it was found out that this requires a correction on the mass coefficient so that the Froude-Krylov force was not accounted for twice. Then, it was checked that the
wave loads obtained by the pressure integration method agree well with those obtained by the Morison equation in the USFOS-vpOne tool. This was mathematically confirmed by Chung [12].

Overlapping members lead to increased material volume in the vicinity of joints. This leads to the overestimation of the structure weight, marine growth mass, buoyancy and hydrodynamic loads. The extent of the overestimation depends on a given jacket and varies due to the different topology, thicknesses and number of intersecting braces. Therefore, it is recommended to remove overlapping sections from models of jacket support structures, even though the OC4 project chose to use a simpler model, due to the setup simplicity, in which members overlap at the joints.

Only some codes accounted for gravity and damping terms in the eigenanalysis. It was shown that these terms have a marginal influence on eigenfrequencies.

Local out-of-plane vibrational modes of lower X-braces in the jacket were detected by FEM- and multibody-based codes. Local vibrations were studied in more detail in [7].

Buoyancy should be calculated with the integrated pressure method, as this approach ensures correct results for multibraced structures like jackets. The jacket modeled within the OC4 project was cut and clamped fixed at the mudline, through which there was no upward buoyant force acting on the bottom, cross sectional area of a pile. This modeling approach was not physically correct for the jacket with piles penetrating the seabed, though it was used for the simplification of the model setup. The negligence of the upward buoyant force at the base of the structure, which is in contact with the mudline, is physically correct for structures with i.e. gravity-based foundations.

### 2.6 Phase I References


[7] Popko, W.; Antonakas, P.; and Vorpahl, F. "Investigation of Local Vibration Phenomena of a


3. Floating Semi-submersible Modeling of Phase II

Authors: Amy Robertson and Jason Jonkman (NREL), Fabian Vorpahl and Wojciech Popko (Fraunhofer IWES), Jacob Qvist and Lars Frøyd (4Subsea), Xiaohong Chen (American Bureau of Shipping), Jose’ Azcona (National Renewable Energy Centre), Emre Uzunoglu and Carlos Guedes Soares (CENTEC, Instituto Superior Técnico Universidade de Lisboa), Chenyu Luan (CeSOS and NOWITECH), Huang Yutong and Fu Pengcheng (China General Certification Center), Anders Yde and Torben Larsen (Technical University of Denmark), James Nichols and Ricard Buils (DNV GL), Liu Lei (Goldwind), Tor Anders Nygaard (Institute for Energy Technology), Dimitris Manolas (National Technical University of Athens), Andreas Heege (SAMTECH s.a.), Sigrid Ringdalene Vatne and Harald Ormberg (MARINTEK), Tiago Duarte and Cyril Godreau (Instituto Superior Técnico, Universidade de Lisboa), Hans Fabricius Hansen and Anders Wedel Nielsen (DHI), Hans Riber and Cédric Le Cunff (PRINCIPIA NORTH), Friedemann Beyer (University of Stuttgart), Atsushi Yamaguchi (University of Tokyo), Kwang Jin Jung and Hyunkyoung Shin (University of Ulsan), Wei Shi and Hyunchul Park (POSTECH), Marco Alves and Matthieu Guérinel (WavEC – Offshore Renewables)

3.1 Phase II Model

Phase II of the OC4 project involved the modeling of a semisubmersible floating offshore wind system developed for the DeepCwind project [1] as shown in Figure 30. 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 [2]. 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 [1]. The semisubmersible sub-structure design examined in this phase is based on the as-built configuration used in the DeepCwind tests. The as-built tower and turbine from these tests, however, was not be used. Instead, the turbine specification for OC4 Phase II is the NREL offshore 5-MW baseline wind turbine [4], which is a representative utility-scale, multi-MW turbine. This turbine was used in the OC3 project and is being used in all phases of OC4 as well. The tower supporting the wind turbine changes slightly between the different phases, and for this phase, the same tower and control system that were used for the OC3 Hywind spar are used. The new system is referred to as the OC4-DeepCwind semisubmersible, to distinguish it from the original DeepCwind design. Analyzing the DeepCwind semisubmersible design in the OC4 project creates the opportunity for a
follow-on project related to validation of the simulated dynamics of the system through comparison to the wave-tank data.

The geometry of the support structure and the labeling of the individual components is provided in Figure 31 and Figure 32, and the overall properties are summarized in Table 4. One nuance of the model is that it is ballasted with water in the offset columns. The water is compartmentalized and is not allowed to move or slosh.

![Figure 31: OC4-DeepCwind floating wind system design](image)

Figure 31: OC4-DeepCwind floating wind system design
Table 4: Summary of OC4 DeepCwind semi properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of platform base below SWL (total draft)</td>
<td>20 m</td>
</tr>
<tr>
<td>Platform roll inertia about CM</td>
<td>6.827E+9 kg-m²</td>
</tr>
<tr>
<td>Elevation of main column (tower base) above SWL</td>
<td>10 m</td>
</tr>
<tr>
<td>Platform pitch inertia about CM</td>
<td>6.827E+9 kg-m²</td>
</tr>
<tr>
<td>Elevation of offset columns above SWL</td>
<td>12 m</td>
</tr>
<tr>
<td>Platform yaw inertia about CM</td>
<td>1.226E+10 kg-m²</td>
</tr>
<tr>
<td>Spacing between offset columns</td>
<td>50 m</td>
</tr>
<tr>
<td>Number of Mooring Lines</td>
<td>3</td>
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<tr>
<td>Length of upper columns</td>
<td>26 m</td>
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<tr>
<td>Angle Between Adjacent Lines</td>
<td>120°</td>
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<tr>
<td>Length of base columns</td>
<td>6 m</td>
</tr>
<tr>
<td>Depth to Anchors Below SWL (Water Depth)</td>
<td>200 m</td>
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<tr>
<td>Depth to top of base columns below SWL</td>
<td>14 m</td>
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<tr>
<td>Radius to Anchors from Platform Centerline</td>
<td>837.6 m</td>
</tr>
<tr>
<td>Diameter of main column</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Diameter of offset (upper) columns</td>
<td>12 m</td>
</tr>
<tr>
<td>Radius to Fairleads from Platform Centerline</td>
<td>40.868 m</td>
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<tr>
<td>Diameter of base columns</td>
<td>24 m</td>
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<tr>
<td>Unstretched Mooring Line Length</td>
<td>835.5 m</td>
</tr>
<tr>
<td>Diameter of pontoons and cross braces</td>
<td>1.6 m</td>
</tr>
<tr>
<td>Mooring Line Diameter</td>
<td>0.0766 m</td>
</tr>
<tr>
<td>Platform mass, including ballast</td>
<td>1.3473E+7 kg</td>
</tr>
<tr>
<td>Equivalent Mooring Line Mass Density</td>
<td>113.35 kg/m</td>
</tr>
<tr>
<td>CM location below SWL</td>
<td>13.46 m</td>
</tr>
<tr>
<td>Equivalent Mooring Line Mass in Water</td>
<td>108.63 kg/m</td>
</tr>
</tbody>
</table>

3.2 Phase II Simulations

A set of 21 different load cases (simulations) were specified to analyze the OC4-DeepCwind semi, encompassing varying levels of model complexity and a variety of metocean conditions. Table 5 summarizes these load cases. The cases are ordered in increasing complexity, with three distinct groupings.
Table 5: Load cases run in OC4 Phase II

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Description</th>
<th>Enabled DOFs</th>
<th>Wind Condition</th>
<th>Wave Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Eigenanalysis</td>
<td>All</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>1.2</td>
<td>Static equilibrium</td>
<td>All</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>1.3a</td>
<td>Free decay, surge</td>
<td>Platform and moorings</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>1.3b</td>
<td>Free decay, heave</td>
<td>Platform and moorings</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>1.3c</td>
<td>Free decay, pitch</td>
<td>Platform and moorings</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>1.3d</td>
<td>Free decay, yaw</td>
<td>Platform and moorings</td>
<td>No air</td>
<td>Still water</td>
</tr>
<tr>
<td>2.1</td>
<td>Regular waves</td>
<td>Support structure</td>
<td>No air</td>
<td>Regular airy: H = 6 m, T = 10 s</td>
</tr>
<tr>
<td>2.2</td>
<td>Irregular waves</td>
<td>Support structure</td>
<td>No air</td>
<td>Irregular airy: Hs = 6 m, Tp = 10 s, γ=2.87, JONSWAP spectrum</td>
</tr>
<tr>
<td>2.3</td>
<td>Current only</td>
<td>Support structure</td>
<td>No air</td>
<td>Regular airy: H = 6 m, T = 10 s; current at surface = 0.5 m/s, 1/7th power law</td>
</tr>
<tr>
<td>2.4</td>
<td>Current and regular waves</td>
<td>Support structure</td>
<td>No air</td>
<td>Regular airy: H = 6 m, T = 10 s; current at surface = 0.5 m/s, 1/7th power law</td>
</tr>
<tr>
<td>2.5</td>
<td>50-year extreme wave</td>
<td>Support structure</td>
<td>No air</td>
<td>Irregular airy: Hs = 15.0 m, Tp = 19.2 s, γ=1.05, JONSWAP spectrum</td>
</tr>
<tr>
<td>2.6</td>
<td>RAO estimation, no wind</td>
<td>Support structure</td>
<td>No air</td>
<td>Banded white noise, PSD =1 m²/Hz for 0.05-0.25 Hz</td>
</tr>
<tr>
<td>3.1</td>
<td>Deterministic, below rated</td>
<td>All</td>
<td>Steady, uniform, no shear: $V_{hub} = 8$ m/s</td>
<td>Regular airy: H = 6 m, T = 10 s</td>
</tr>
<tr>
<td>3.2</td>
<td>Stochastic, at rated</td>
<td>All</td>
<td>Turbulent (Mann model): $V_{hub} = V_r (11.4$ m/s)</td>
<td>Irregular airy: H = 6 m, Tp = 10 s, γ=2.87, JONSWAP spectrum</td>
</tr>
<tr>
<td>3.3</td>
<td>Stochastic, above rated</td>
<td>All</td>
<td>Turbulent (Mann model): $V_{hub} = 18$ m/s</td>
<td>Irregular airy: H = 6 m, Tp = 10 s, γ=2.87, JONSWAP spectrum</td>
</tr>
<tr>
<td>3.4</td>
<td>Wind/wave/current</td>
<td>All</td>
<td>Steady, uniform, no shear: $V_{hub} = 8$ m/s</td>
<td>Regular airy: H = 6 m, T = 10 s; current at surface = 0.5 m/s, 1/7th power law</td>
</tr>
<tr>
<td>3.5</td>
<td>50-year extreme wind/wave</td>
<td>All</td>
<td>Turbulent (Mann model): $V_{hub} = 47.5$ m/s</td>
<td>Irregular airy: Hs = 15.0 m, Tp = 19.2 s, γ=1.05, JONSWAP spectrum</td>
</tr>
<tr>
<td>3.6</td>
<td>Wind/wave misalignment</td>
<td>All</td>
<td>Steady, uniform, no shear: $V_{hub} = 8$ m/s</td>
<td>Regular airy: H = 6 m, T = 10 s, direction = 30°</td>
</tr>
<tr>
<td>3.7</td>
<td>RAO estimation, with wind</td>
<td>All</td>
<td>Steady, uniform, no shear: $V_{hub} = 8$ m/s</td>
<td>Banded white noise, PSD =1 m²/Hz for 0.05-0.25 Hz</td>
</tr>
<tr>
<td>3.8</td>
<td>Mooring line loss</td>
<td>All</td>
<td>Steady, uniform, no shear: $V_{hub} = 18$ m/s</td>
<td>Regular airy: H = 6 m, T = 10 s</td>
</tr>
<tr>
<td>3.9</td>
<td>Flooded column</td>
<td>All</td>
<td>Turbulent (Mann model): $V_{hub} = 8$ m/s</td>
<td>Irregular airy: H = 6 m, Tp = 10 s, γ=2.87, JONSWAP spectrum</td>
</tr>
</tbody>
</table>

Group 1.X encompasses a set of simulations focused on system identification, including an eigenanalysis, a static equilibrium simulation, and a series of free-decay simulations. All simulations are run in the absence of air, with still water, and with the generator locked (a brake is applied).

Group 2.X focuses on the interaction of the waves with the platform in the absence of wind. For these simulations, the platform, moorings, and tower are flexible, but the nacelle, drivetrain, and rotor are rigid and the generator is locked. The simulations include regular waves, irregular waves, and current.

The last group, 3.X, examines the system with all degrees of freedom (DOFs) enabled, and with combined wind and wave excitation. A variety of conditions are examined including both regular and irregular waves, steady and turbulent wind, current, and some damage scenarios. The two damage scenarios involve the investigation of the dynamic response of the system after the sudden loss of a
mooring line, and after the flooding of a compartment in one of the offset columns. (Wind-only simulations with the NREL 5-MW turbine were compared within the OC3 project and were not repeated in OC4 Phase II.) In addition to traditional wind/wave load cases, this group included the computation of response amplitude operators (RAOs), which are 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.

In all load cases, the turbine is initially facing perfectly upwind (no yaw error), and in all but one load case, the direction of the waves is aligned with the wind. The only exception to this is load case 3.6, in which the waves are offset from the wind by 30 deg. Turbulent wind and irregular wave time histories were provided to the group, but some participants generated their own files based on the parameters provided.

For each load case simulation, a total of 62 outputs were analyzed. These included the environmental conditions, motion response behavior, and loads in the structure, including the substructure and the mooring lines.

### 3.3 Phase II Participants and Codes

The OC4 project was performed through technical exchange among a group of international participants from universities, research institutions, and industry across the United States, Germany, Denmark, the United Kingdom, Spain, the Netherlands, Norway, Sweden, Korea, Japan, Portugal, Greece, and China. The participants that contributed results for Phase II included:

- The National Renewable Energy Laboratory (NREL)
- The Centre For Marine Technology And Engineering (CENTEC)
- Instituto Superior Tecnico (IST)
- Goldwind
- The American Bureau Of Shipping (ABS)
- The National Renewable Energy Centre (CENER)
- The University Of Ulsan (UOU)
- Garrad Hassan (GH)
- The China General Certification Center (CGC)
- Pohang University Of Science And Technology (POSTECH)
- 4Subsea
- The Technical University Of Denmark (DTU)
- The National Technical University Of Athens (NTUA)
- The Centre For Ships And Ocean Structures (Cesos)
- Norwegian Marine Technology Research Institute (MARINTEK)
- The Institute For Energy Technology (IFE)
- SAMTECH S.A. With The Catalonia Institute For Energy Research (IREC)
- PRINCIPIA With IFP Energies Nouvelles (IFPEN)
- The University Of Stuttgart’s Endowed Chair Of Wind Energy At The Institute Of Aircraft Design (SWE)
- The University Of Tokyo
- Wavec Offshore Renewables
- Chonqing Haizhung Windpower Equipment Co., LTD (CSIC)
- DHI
Most of the aero-hydro-servo-elastic codes that have been developed for modeling the dynamic response of offshore wind turbines were tested within OC4. Table 6 summarizes the existing modeling capabilities of the simulation tools used by (and in some cases, developed by) each participant for Phase II. In the cases where Table 6 shows the same code being used by multiple OC4 participants, the model development, simulation runs, and data processing were done independently.

Table 6: Overview of offshore wind modeling tool capabilities

<table>
<thead>
<tr>
<th>Code</th>
<th>Code Developer</th>
<th>OC4 Participant</th>
<th>Structural Dynamics</th>
<th>Aerodynamics</th>
<th>Hydrodynamics</th>
<th>Mooring Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST</td>
<td>NREL</td>
<td>NREL, CENTEC, IST, Goldwind, CSIC</td>
<td>T: Mod/MB P: Rigid</td>
<td>(BEM or GDW)+DS</td>
<td>PF + QD + (QTF)</td>
<td>QS</td>
</tr>
<tr>
<td>FAST v8</td>
<td>NREL</td>
<td>NREL</td>
<td>T: Mod/MB P: Rigid</td>
<td>(BEM or GDW)+DS</td>
<td>PF + ME</td>
<td>QS</td>
</tr>
<tr>
<td>CHARM3D</td>
<td>TAMU+ NREL</td>
<td>ABS</td>
<td>T: Mod/MB P: Rigid</td>
<td>(BEM or GDW)+DS</td>
<td>PF + ME + (MD + NA) + (IP + IWL)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>FAST+</td>
<td>CENER+ NREL</td>
<td>CENER</td>
<td>T: Mod/MB P: Rigid</td>
<td>(BEM or GDW)+DS</td>
<td>PF + ME</td>
<td>LM/Dyn</td>
</tr>
<tr>
<td>UOU+FAS</td>
<td>University of Ulsan</td>
<td>T: Mod/MB P: MB</td>
<td>(BEM or GDW)+DS</td>
<td>PF + QD</td>
<td>QS</td>
<td></td>
</tr>
<tr>
<td>Bladed</td>
<td>GH, GH, CGC, POSTECH</td>
<td>T: Mod/MB P: MB</td>
<td>(BEM or GDW)+DS</td>
<td>PF + ME + (IWL)</td>
<td>QS</td>
<td></td>
</tr>
<tr>
<td>Bladed Advanced Hydro Beta</td>
<td>GH</td>
<td>GH</td>
<td>T: Mod/MB P: MB</td>
<td>(BEM or GDW)+DS</td>
<td>PF + ME + (IWL)</td>
<td>QS</td>
</tr>
<tr>
<td>OrcaFlex</td>
<td>Orca</td>
<td>4Subsea</td>
<td>T: FE P: Rigid</td>
<td>BEM, GDW, or FDT</td>
<td>PF + ME</td>
<td>LM/Dyn</td>
</tr>
<tr>
<td>HAWC2</td>
<td>DTU</td>
<td>DTU</td>
<td>T: MB/FE P: MB/FE</td>
<td>(BEM or GDW)+DS</td>
<td>ME</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>hydro-GAST</td>
<td>NTUA</td>
<td>NTUA</td>
<td>T: MB/FE P: MB/FE</td>
<td>BEM or FWV</td>
<td>PF + ME + (IP)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>Simo+Rifle+ AeroDyn</td>
<td>MARINTEK+ NREL</td>
<td>CeSOS</td>
<td>T: FE P: FE</td>
<td>(BEM or GDW)+DS</td>
<td>PF+ME</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>Riflex-Coupled</td>
<td>MARINTEK</td>
<td>MARINTEK</td>
<td>T: FE P: Rigid</td>
<td>BEM+FDT</td>
<td>PF + ME + (IWL)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>3Dfloat</td>
<td>IFE-UMB</td>
<td>IFE</td>
<td>T: FE (co-rotated) P: FE</td>
<td>BEM+FDT</td>
<td>ME + (IWL)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>SWAT</td>
<td>SAMTECH+ IREC</td>
<td>SAMTECH &amp; IREC</td>
<td>T: FE+Mod/MB P:FE+Mod/MB</td>
<td>BEM or GDW</td>
<td>ME + (IWL)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>DeepLines</td>
<td>PRINCIPIA-IFPEN</td>
<td>PRINCIPIA</td>
<td>T: FE P: FE</td>
<td>BEM+DS</td>
<td>PF + ME + (MD + QTF/NA) + (IP + IWL)</td>
<td>FE/Dyn</td>
</tr>
<tr>
<td>SIMPACK+ HydroDyn</td>
<td>SIMPACK</td>
<td>SWE</td>
<td>T: Mod/MB P: Rigid</td>
<td>BEM or GDW</td>
<td>PF + QD</td>
<td>QS</td>
</tr>
<tr>
<td>CASt</td>
<td>University of Tokyo</td>
<td>University of Tokyo</td>
<td>T: FE W: FE</td>
<td>BEM</td>
<td>ME</td>
<td>QS</td>
</tr>
<tr>
<td>Wavec2Wi re</td>
<td>WavEC</td>
<td>WavEC</td>
<td>T: N/A P: Rigid</td>
<td>N/A</td>
<td>PF + QD</td>
<td>QS</td>
</tr>
<tr>
<td>WAMSIM</td>
<td>DHI</td>
<td>DHI</td>
<td>T: N/A P: Rigid</td>
<td>N/A</td>
<td>PF + QD</td>
<td>QS</td>
</tr>
</tbody>
</table>

T = turbine  
P = platform  
Mod = modal  
MB = multi-body  
FE = finite element  
N/A = not applicable  
BEM = blade-element/momentum  
GDW = generalized dynamic wake  
DS = dynamic stall  
FDT = filtered dynamic stall  
FWV = free-wake vortex  
PF = potential flow theory  
ME = Morison eq.  
MD = mean drift  
QTF = quadratic transfer function  
NA = Newman’s approximation  
IP = instantaneous position  
IW = instantaneous water level  
QD = quadratic damping  
QS = quasi-static  
Dyn = dynamic  
LM = lumped mass
3.4 Phase II Results

Each of the participants ran the prescribed load cases using the models they had built in their modeling tool of choice. The simulated response behavior (loads/motions) was then compared between the various codes at multiple points throughout the system. A subset of these results is summarized in the plots in this section (full results are available in [5]). In these plots, a unique color is assigned to the result from a given participant, as shown in the legend in Figure 33. In the bar plots, the results are presented as a solid color, but in the line plots, the results use either a solid, dotted, or dash-dot line, based on the type of hydrodynamic model being used in the tool. A solid line represents a code that uses a potential-flow theory approach, dotted is for Morison-only, and dash-dot is for codes that use a combination of the two. Some tools have the option of using different theories, so some participants have supplied two different results from the same code with differing hydrodynamic models.

For the free-decay and deterministic wind/wave simulations, time series were compared. For the stochastic wind/wave simulations, the results were compared using PSDs of the responses (with the application of some smoothing functions). In addition, this project included the computation of response amplitude operators (RAOs) both in wave-only and combined wind/wave conditions.

The delineation of the responses in the plots based on the hydrodynamic model used suggests the importance of the model on the results seen in the simulations. The large motion of floating structures and the complexity of this floating design create a complex hydrodynamics problem. In the simulations it was found that the differences in the hydrodynamic theories were more significant among the modeling tools than the aerodynamic or structural theories. Therefore, the results presented in this section largely focus on the system response due to wave loads. Some wind cases are covered, especially in terms of how adding wind affects the response of the system when compared to a wave-only simulation.

3.4.1 Full-System Eigenanalysis (Load Case 1.1)

Figure 33 shows a selection of the lowest natural frequencies of the OC4 DeepCwind semisubmersible in still water and no wind (load case 1.1). The rigid-body frequencies of the system (upper plot of Figure 33) are fairly consistent, with the exception of the roll and pitch motions for POSTECH and the University of Tokyo. The University of Tokyo investigators have identified an issue with modeling the pitch moment of inertia in their code, which also affects the blade’s natural frequencies.

Larger differences are seen in the tower and turbine flexible frequencies, with some codes not capturing all of the flexible modes requested. Very few codes identify the tower torsion DOF, and there is little consistency between the results provided. PRINCIPIA and IFE’s values show the coupling between the tower torsion and the blade asymmetric flapwise yaw mode. The largest variability in identified mode values is for the second bending modes of the tower. These modes are most likely more sensitive to the various methods being used to model the flexibility of the structure.
3.4.2 Free Decay (Load Case 1.3)

Four different free-decay simulations were run in load case 1.3, in which the system was offset by a prescribed amount, and then released to return to its equilibrium position. The simulations investigated included separate offsets for surge, heave, pitch, and yaw; however, each simulation has all platform and mooring DOFs enabled. These simulations are useful in demonstrating the rigid-body natural frequencies of the system, and their associated damping.
Figure 34: Free decay plots: Left column: LC 1.3a, surge free decay; Right column: LC 1.3b, heave free decay

Figure 34 shows the surge, pitch, and heave motion results of the surge free-decay and heave free-decay simulations, respectively. The differences between the results are caused by two main factors, the hydrodynamic modeling approach used and the mooring line modeling approach used. These influences are most easily seen in the damping behavior of the results. The damping of the larger-motion response of the structure is more strongly influenced by the (quadratic) viscous loads on the structure, whereas the smaller amplitude motion is more governed by (linear) radiation damping.

Generally, for the surge free-decay results, the results are very similar between the codes, with the exception of POSTECH and WavEC for the coupled responses in heave and pitch. There is no significant grouping of the responses because of the modeling approaches used.
For the heave free-decay simulations, the heave response itself is very similar, with the exception of PRINCIPIA, which employed a different radiation damping value. Larger differences are seen in the coupled responses to surge and pitch. For pitch, a very distinct grouping is seen for codes using Morison’s equation for calculating the viscous drag (dotted or dash-dotted results) versus those using a quadratic drag matrix (solid line results). The different levels of damping most likely result from a lack of off-diagonal terms in the quadratic damping matrix. Potential-only solutions do not model the coupled pitch damping during heave motion.

In general, one can see that the differing modeling theories for hydrodynamics and mooring loads do not strongly influence the free-decay responses.

3.4.3 Regular Waves (Load Case 2.1)

Load case 2.1 examines the response of the semisubmersible when excited by regular (periodic) waves with a height of 6 m and a period of 10 s. No wind was used in this simulation, and the turbine DOFs were turned off. Therefore, the modeling components of importance are once again the hydrodynamic and mooring models.

Figure 35 shows the surge, heave, and pitch responses of the semisubmersible for load case 2.1, as well as the tension of the second mooring line at the fairlead, which is the upwind mooring line oriented along zero-degree wind/waves. The surge response shows large differences between the different codes, based on whether drift forces are being accounted for in the hydrodynamic modeling approach. The surge response for simulations using first-order potential flow-theory and/or Morison’s equation calculated at the undisplaced position of the body without wave stretching will oscillate about a zero-mean position. Realistically, however, the system will drift slightly, a nonlinear phenomenon that is captured through one of the following modeling approaches:

- Inclusion of second-order terms in the potential-flow theory solution
- Approximation of difference-frequency terms through Newman’s approximation
- Application of a mean-drift force derived from first-order potential-flow theory
- Application of Morison’s equation, both at the mean or instantaneous position of the body
- Integration of Morison’s equation up to the instantaneous elevation of the wave using a stretching technique

Only codes that include one of these components have a non-zero mean value for the surge displacement. Two codes have much larger offsets than the others, ABS and GH. ABS includes every one of the methods described previously for accounting for drift forces, with the exception of the direct inclusion of second-order terms in the potential-flow solution. Most other codes include only the second-order difference terms in the potential-flow solution (IST2), Newman’s approximation, or the application of ME at the instantaneous position and wave elevation.

The heave response to regular waves is more consistent, with only a couple of Morison-only codes, POSTECH and University of Tokyo, showing distinctly different results. This difference is assumed to be caused by incorrectly accounting for the variation in dynamic pressure on the base columns of the semi. This problem was encountered early in the project when many more of the Morison-only codes were under-predicting the heave response of the system in regular waves.

The fairlead tension for this load case demonstrates the differences between the mooring model used, whether a quasi-static solution is employed or one that considers the dynamics of the line as well as the excitation of the line from the waves. This differentiation is seen in the two distinct groupings of the response, as indicated by the circles in the figure. Those codes using a dynamic solution are out of phase with the quasi-static solutions, and include more frequencies in the response behavior beyond the wave frequency. Although 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.
3.4.4 Stochastic Wind/Waves (Load Case 3.2)

To this point, the description of the results has focused on the global response of the structure, and has not covered the loads and motion of the turbine itself. This is because the turbine response is more similar between the codes than these global motions. But for completeness, this section shows a sample of wind turbine response behavior for a load case (3.2) in which the turbine is excited by irregular waves ($H_s = 6 m$, $T_p = 10 s$) and stochastic wind ($V = 11.4 m/s$).

Figure 36 shows the PSD of the out-of-plane deflection of blade 1. The results are fairly similar between the codes, but the different solutions deviate more as frequency increases. The higher responses come from those codes that use a quasi-steady BEM approach for their aerodynamic induction model, while the lower responses are those that use a form of dynamic wake theory. This is to be expected because the dynamic wake theory delays the response of the turbine to sudden changes in the wind, effectively damping the higher frequency response. Similar results are seen for the in-plane bending of the blade in Figure 36.
3.4.5 Irregular Waves (Load Cases 2.2 and 3.2)

The next set of simulations examined involves irregular waves, both with and without wind. Figure 37 shows the mean value of select responses (surge, pitch, and tower bending in the fore/aft direction) to an irregular wave modeled using a JONSWAP spectrum with a significant wave height ($H_s$) of 6 m, and a peak-spectral period ($T_p$) of 10 s. Figure 38 then shows the same results, but with turbulent wind present for the operating turbine at rated wind speed (11.4 m/s).

In these figures, note that when wind is included, the offsets and loads increase significantly because of the thrust force of the wind on the turbine. The wind also equalizes the results among the participants, masking the differences seen when only waves are present (because the thrust force is much higher than the mean-drift force). The case without wind shows larger differences between the codes. The outliers from DTU probably result from an incorrectly prescribed axis definition for the output, and those in the surge response are largely caused by the drift effects discussed for the regular wave results.

Figure 39 and Figure 40 then show the variance (square of the standard deviation) of the system responses for these two simulations, which is an indicator of fatigue loading. A larger variance is seen in the response with wind present, especially for the surge motion, and there is more discrepancy among the different codes. These differences could be caused by variations in the underlying aerodynamic theories or by not eliminating all start-up transients in some results. The significant differences between the results for both the mean value and variance of the tower bending are concerning because this is a major component in the design of an offshore wind system.
3.4.6 Response Amplitude Operators (Load Cases 2.6 and 3.7)

RAOs are the ratio of system response to wave amplitude (resulting from wave excitation) and are commonly used during the design process in the offshore oil and gas industry to assess the linear wave-body response of floating platforms in the frequency domain. For this project, the RAOs were produced through the excitation of the system using a banded white-noise spectrum between 0.05 and 0.25 Hz (see wave height PSD in Figure 13). Further information on how the RAOs were calculated can be found in [6].

Figure 41 and Figure 42 show the computed RAOs for the semisubmersible both with and without wind (steady, 8 m/s) for a selection of output responses. Only the frequency band that was excited by the waves is shown in these plots. The information outside this band is meaningless since it would require a division by zero (or almost zero) to achieve.
In general, the wind excitation used here has very little effect on the RAOs, with the most significant change being seen in the mooring response for those using a dynamic model. There is a clear grouping in the mooring tension results for codes using dynamic versus quasi-static mooring models. The most significant difference is in the higher frequency region around 0.17 Hz, where the quasi-static results greatly underpredict the mooring loads in the system. This result suggests the need for a dynamic mooring model to accurately capture both the extreme and fatigue loads in the moorings. The surge and heave responses show some variation between the different codes, but the pitch and tower-bending moment are much more varied.

Significant variation is not expected in these RAOs because the focus has been only on the wave-excitation region where linear wave loads dominate the response. This is well covered by all modeling approaches. Examining the response of the semisubmersible outside the wave-excitation region reveals more differences in the response of the structure based on the modeling approach employed. In Figure 43 and Figure 44, the PSDs of the outputs examined in the RAO plots are shown for the frequency band from 0 to 0.5 Hz. The wave-excitation region (0.05 – 0.25 Hz) can be clearly seen in drop-offs in the response for the surge and mooring tension PSDs.

The surge and pitch natural frequencies are seen in their respective PSDs at 0.01 and 0.04 Hz, which are outside the wave-excitation region and are therefore excited by some form of nonlinear effect. One source is nonlinear hydrodynamic wave loads produced from Morison’s equation or from higher-order terms in the potential-flow solution. In addition, it was found that codes using a Morison-only approach for calculating the hydrodynamic forces had an overall increased level of response in the pitch motion at frequencies outside the wave-excitation region, and to a lesser degree the surge.

The heave PSD, on the other hand, shows very little difference between the simulated responses because the heave natural frequency lies within the linear wave-excitation region at 0.058 Hz. The mooring tension PSD again clearly shows groupings in the higher frequencies based on whether a dynamic model is used (the two circles in Figure 43 show quasi-static and dynamic groupings), but the response in the low-frequency region is dominated by the surge/pitch behavior of the structure. The PSD of the tower-bending moment in the fore/aft direction, which is largely dictated by the pitching motion of the structure and therefore has similar behavior to that PSD, is also shown in the figure. More noticeable here, though, is the first bending natural frequency of the tower around 0.43 Hz. This frequency peak is also outside the wave-excitation region, and its magnitude is extremely varied between the different codes. Consistent with the pitch PSD, those codes using a Morison approach and/or some form of nonlinear hydrodynamic loading have an increased response. The solution from Marintek is an exception, showing no peak for the tower-bending moment natural frequency.

The PSD results outside the wave-excitation region are much more heavily affected by wind than the RAOs. This is especially true for the pitch response and the tower bending.
Figure 41: RAO comparisons without wind (top row – load case 2.6) and with wind (bottom row – load case 3.7) for select outputs

Figure 42: RAO comparisons without wind (top row – load case 2.6) and with wind (bottom row – load case 3.7) for platform motion
Figure 43: RAO comparisons without wind (top row – load case 2.6) and with wind (bottom row – load case 3.7) for platform motion

Figure 44: PSD comparisons without wind (top row – load case 2.6) and with wind (bottom row – load case 3.7) for platform motion

3.4.7 Damage Case (Load Case 3.8)

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.

Figure 45 and Figure 46 show some exemplary results from load case 3.8, which entailed the sudden loss of mooring line 1 60 s after the start of the simulation, and included excitation from both steady wind (8 m/s) and regular waves (H = 6 m, T = 10 s). (Mooring line 1 is downwind and to the left when looking downwind.) The roll response of the structure (Figure 45) has an initial transient just after the loss of the
mooring, but the large response quickly dies out for most codes. Only for results from the FAST simulation code does the roll response begin to grow again – at around 300 s. This instability appears to be tied to the use of the quadratic drag matrix and disappears when Morison drag is used instead.

Figure 46 shows the path the semisubmersible takes in the water plane after the failure. There is concern that after such an event the system would become twisted and tangled among the remaining lines, but these simulations show the system floating away from the lost mooring line with minimal rotational motion.

The other damage load case (3.9) simulated in this project examined the response of the semisubmersible during a scenario where water has flooded a compartment within one of the offset columns. Additional water was added to the already ballasted column, but the column was not assumed to be entirely flooded because of compartmentalization within that member. The results of this load case did not show significant effects from the flooding, and in hind-sight, the flooding level may have been too low.

3.5 Phase II Conclusions

The comparisons performed in Phase II of OC4 and throughout the OC3 and OC4 projects have resulted in a greater understanding of offshore wind turbine dynamics and modeling techniques, and in 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.

Two conference papers have been published summarizing the findings from Phase II, see [7] and [8]. The following is a list of the main technical findings drawn from Phase II of OC4:

- There is not a clear need for the inclusion of radiation/diffraction loads from a potential-flow theory type solution for this type of semisubmersible under the conditions examined. Morison-only solutions seem to yield similar results, though with more variation in the pitch response. These small differences, however, could be an issue for fatigue, which was not examined in this analysis.
- 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 (especially in the presence of large waves and current).
- Varying levels of mean drift resulting from wave excitation are seen among the different models, based on the inclusion of nonlinear hydrodynamics modeling theory. The modeling approaches that create a drift force include wave stretching in Morison’s equation, applying loads at the instantaneous position of the structure, including second-order terms in the potential-flow solution, or calculating the mean drift force from the linear potential-flow solution. The drift force 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 base columns (or heave plates) of the semisubmersible to obtain accurate heave excitation in the system from waves. The need is significant for this structure because of its shallow draft.
- Mooring loads in frequencies above the linear wave range differ significantly between codes using a quasi-static model and 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 instead of the quasi-steady theory for the aerodynamic induction 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 (both without and with wind loading).
- 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 low.

### 3.6 Phase II References

4. Jonkman, J.; Butterfield, S.; Musial W.; and Scott, G. "Definition of a 5-MW Reference Wind Turbine for Offshore System Development" National Renewable Energy Laboratory , Golden, CO,
Website for OC4 project: [http://oc4.collaborationhost.net](http://oc4.collaborationhost.net). An anonymous login may be used to view results from the project on this site:

- login: anonymous@oc4.collaborationhost.net
- password: changeit2


4. Validation Workshop

Authors: A. Robertson, J. Jonkman, and W. Musial (NREL, USA); W. Popko and F. Vorpahl (Fraunhofer IWES, Germany)

4.1 Introduction

As part of the IEA Wind Task 30, a topical experts meeting was held on “Offshore Wind Model Validation” at the Millennium Harvest House in Boulder, CO on May 15–16, 2012. The purpose of the meeting was to begin development of a plan for international collaboration on validating the codes used for modeling and designing offshore wind turbines. The meeting was attended by 60 international and domestic attendees from national labs, industry, and academia. Invited speakers gave 17 presentations and NREL moderated four discussions to address the following topics:

- What data is needed for validation?
- What data is currently available?
- What test methods and instrumentation should be used to gather useful data for validation?
- What are the trade-offs between tank testing (scale models) and field testing (full scale)?
- How should the data be post-processed?
- What is the validation process?
- What case studies of test data collection and validation are available to the Task 30 group?

4.2 Background

The objective of IEA Wind Task 30 is to ensure the accuracy of the codes used for designing offshore wind turbines through cooperative activities and information exchange on R&D topics of common interest. The topical experts meeting described herein helps achieve this objective and was a major part of the total Task 30 work plan.

Both the OC3 and OC4 projects thus far have been focused on the verification of offshore wind modeling tools through code-to-code comparisons. Verification of the modeling tools is just one step towards ensuring the accuracy of the results that these tools provide. Another step is validation, which involves the comparison of simulated results to measured data from a physical test. This experts’ meeting was focused on understanding how we in the international offshore wind community can collaborate to validate the modeling tools used to analyze offshore wind systems, with the goal of increasing the accuracy of the design tools worldwide.

In addition to expertise with modeling tools, validation requires test data, with good documentation of its quality and the methods used to acquire it. High quality data is useful whether it comes from tests in a wave or wind basin, or from open-ocean deployment, but the method of validation may vary depending on the source. The system being analyzed can be a scaled model for demonstration purposes, or a full-scale system. There are currently a variety of offshore wind turbine tests being performed worldwide, and potentially a variety of datasets which can be used for validation.

Researchers associated with code development alone cannot achieve a successful validation campaign. Industry members with direct knowledge and experience in the testing of offshore structures must be involved. This meeting brought together both modelers and testers to understand the methods needed to achieve the goal of validating our offshore wind simulation tools. In the end, the verification and validation efforts of this group will provide industry with reliable tools with which to analyze and evolve offshore wind system designs.
4.3 Meeting Summary

The meeting was organized into three sessions. During each session, a series of presentations were given by experts in the field. Following the presentations, a group discussion was held on the session topic. The following sections summarize the presentations given in each session and the subsequent discussions.

4.3.1 Data and Testing

The first session was focused on understanding the test procedures and data collection methods used to validate an offshore wind system design. The following presentations were given:

<table>
<thead>
<tr>
<th>Presenter</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jacob Tornfeldt-Sørensen (DHI)</td>
<td>Wave Induced Force Validation For Irregular Seas</td>
</tr>
<tr>
<td>Kevin Maki (University of Michigan)</td>
<td>Accuracy, Efficiency, and the Quest of Code Validation</td>
</tr>
<tr>
<td>Andrew Goupee (University of Maine)</td>
<td>Model Testing of the Coupled Aero-Hydro-Elastic Response of Three Floating Wind Turbine Concepts</td>
</tr>
<tr>
<td>Arjan Voogt (MARIN)</td>
<td>Model Tests For Floating Offshore Wind Turbines</td>
</tr>
<tr>
<td>Jorgen Jorde (SWAY)</td>
<td>Sway Experiences In Large Scale Prototype Testing</td>
</tr>
</tbody>
</table>

Below are some of the observations made during the discussion contrasting the reasons for scaled tank testing versus full-scale, open-ocean testing.

Field Testing

- Full-scale field tests are best for examining the loads and performance of an integrated system design.
- In an open-water test, the conditions are limited to what occurs during a relatively short test window, which means that statistically rare events such as extreme events cannot usually be quantified by experiment alone.
- The influences of wind and waves are not easily separated in field testing.
- Metocean conditions at the turbine are not easily measured in field testing and better methods are needed.
- If an open-water test is to be performed, most agreed that it is best to test at full scale.
- If testing a scaled system in the open water, sheltered sites may be needed to provide scaled metocean conditions appropriate for the model being tested and that do not exceed the extreme limits of the design. This is not always easy to accomplish.
- Scaled open-ocean testing may be an economic way to approximate a full-scale system if protected waters are available. Extreme events may be easier to capture under these conditions.

Scale-Model Tank Testing

- Issues related to scaling, such as conflicts between Froude and Reynolds number scaling, are relatively well understood.
- Tank testing is limited to the range of conditions available in the facility, which may not always be sufficient to characterize the desired conditions.
- Testing performed in a tank using a scaled model is better than open-water testing for confirming system behavior, estimating extreme responses, and evaluating non-linear phenomenon.
- Metocean conditions can be controlled in a tank, allowing testing under a wide range of conditions (including extremes).
• Tank testing can isolate wind and wave excitation individually. Because the metocean conditions are prescribed, they are better understood.
• A big disadvantage to tank testing is the need to scale the model to fit in the tank environment, which can induce inconsistencies in scaling some parameters such as drag forces.
• Technically, there is not much difference between a 1:30 and 1:50 scale test. Scale is usually driven by the limits of the test facility. Scaling issues become less important as the scaling value approaches full scale. The largest scale model that a wave basin allows should be used.
• The instrumentation can induce measurement errors in the mass and response of the structure for small-scale tests.

4.3.2 Procedures
The second session focused on the methods used for calibrating and validating a model of a floating offshore wind system. The following presentations were given:

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Presentation Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonjun Koo (Technip)</td>
<td>Floating Structure Model Test Data Analysis &amp; Correlation</td>
</tr>
<tr>
<td>Qing Yu (ABS)</td>
<td>Experience of Full-Scale Measurement &amp; Monitoring of Ship &amp; Offshore Structures</td>
</tr>
<tr>
<td>Cesar Vidal (University of Cantabria)</td>
<td>The IDERMAR Floating Met-Mast: Numerical Models Validation Campaign using Laboratory and Prototype Data</td>
</tr>
<tr>
<td>Finn Gunnar Nielsen (Hywind)</td>
<td>Experimental Validation Of Offshore Wind Foundations – Can We Learn From The Offshore Oil And Gas Experience?</td>
</tr>
<tr>
<td>Jan Muren (4SubSea)</td>
<td>Offshore SPAR Type Structure Model Development And Validation</td>
</tr>
</tbody>
</table>

Below are some of the observations made during the discussion.

To what extent is component-level versus system-level testing and validation needed?

• It was suggested that separate tests should be performed using wind-only and wave-only excitation before combined wind-wave testing is done as a way to build confidence in the methods.
• Current-only tests are one way to assess the drag of a structure, large-amplitude free-decay tests are used to measure viscous effects, and small-amplitude free-decay tests are used for understanding potential-flow effects.
• Wave radiation is measured from forced motion of the floater.
• It could be useful to examine the hydrodynamic behavior of some simple geometries before examining the full system, such as a single cylinder or the interaction of multiple cylinders.
• Individual components of a structure may change when integrated into the system. For instance, the bending frequency of the wind turbine tower will change whether it is fixed or integrated with the rest of a floating system, due to the change in boundary conditions of the component.

Issues related to validation procedures.

• It is difficult to accurately measure the wind and wave fields at the turbine location, due to interaction from the structure. It may be possible to calibrate the wind and wave fields without the system present, and use these measurements in the validation process. This method will not provide instantaneous measurements of the waves interacting with the structure. A major problem is assessing directionality.
• Most codes do not model the full 3D characteristics of the waves and are not good at modeling extreme waves.
• The inconsistencies between Froude scaling laws and Reynold’s number were discussed further. For the wind turbine blade shape, one must consider Reynold’s number as well, so that appropriate thrust values can be obtained in the test.
• Nonlinear effects can be more significant for offshore wind systems than in offshore oil and gas structures because of the smaller volume and larger motion of the structure.

The participants discussed how the approach for calibration differs from the approach for validation of a model of an offshore wind system.

• Calibration is the method of refining system parameters based on some of the information gained from the tests, and validation compares the results of the calibrated system response to the remainder of the test data.
• Calibration is needed to resolve parameter uncertainties, unmodeled physics in the codes, and testing issues. For example, the interaction of sensor wires that actually alter the dynamic response of the structure.

### 4.3.3 Case Studies

The final session examined some case studies of offshore wind system testing. The presentations given were as follows:

<table>
<thead>
<tr>
<th>Speaker</th>
<th>Presentation Title</th>
</tr>
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<tbody>
<tr>
<td>Lin Yifeng (Shanghai Investigation, Design &amp; Research Institute)</td>
<td>Simulation, Field Testing &amp; Scale Modeling Testing On WGT’s Substructure And Foundation Of Donghai Bridge Offshore Windfarm</td>
</tr>
<tr>
<td>Hyunkyoung Shin (University of Ulsan)</td>
<td>What Are The Benefits Of Tank Testing (Scale Models) Versus Full Scale Field Test Data?</td>
</tr>
<tr>
<td>Michael Muskulus (Norwegian Research Centre for Offshore Wind Technology)</td>
<td>Extreme Event Computations For Floating Wind Turbines, And The Need For Test Data</td>
</tr>
<tr>
<td>Torben Larsen (DTU Wind Energy)</td>
<td>Experiences With The Poseidon Measurement Campaign And More</td>
</tr>
<tr>
<td>Boris Fischer (Fraunhofer IWES)</td>
<td>HiPRWind: High Power, High Reliability offshore Wind technology</td>
</tr>
<tr>
<td>Antoine Peiffer (Principle Power)</td>
<td>Windfloat, Getting From Concept To Reality Code Validation For Offshore Wind System Modeling</td>
</tr>
</tbody>
</table>

The discussions in this section were a continuation of the discussions from the previous sections, but with more emphasis on the experience gained from individual projects. The additional observations are detailed below.

How should one determine the needed fidelity of the model to be built? What tests are needed?

• The answer is dictated by what one seeks to learn from the tests.
• The test objectives will dictate whether rigid or elastic components are used, whether inertial or viscous loads are important (and therefore what scaling law should be used), the importance of wind/waves/current, what type of control system is used (passive/manual/active), and what scale system will be tested.
4.3.4 Outcome of Meeting

From this meeting, participants gained a clearer understanding of the methods and practices used for validating offshore wind systems. Members from industry and research institutions spanning the fields of both offshore structures and wind turbines shared their experience and insight on the issues related to testing and model validation. Through a straw poll taken at the end of the workshop, 39 out of 60 participants expressed an interest in participating in a new IEA Wind Task focused on validating the codes used to model offshore wind systems. With this expressed level of interest, NREL agreed to develop a proposal for either a new IEA Wind Task devoted to validating offshore wind codes through code-to-data comparisons, or add a new component to the OC4 project devoted to this task.

Before a final decision was made, further discussions were had amongst the OC4 group to determine the best approach. One approach that was discussed was to use publicly available data (and design information) to perform the code-to-data comparisons. A number of datasets were identified as possible candidates for this work. Another approach would be to produce the data needed as part of the task (funded through the task dues or through national funding sources), by building and testing a scaled offshore wind system as a group. The scope of the project could vary from the analysis of one system to multiple systems (e.g., monopile, tripod, jacket, or various floaters).

In the fall of 2013, NREL requested and gained approval for the extension of Task 30 for a new project named the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5). This project will begin the validation of offshore wind modeling tools through the comparison of simulated responses to physical response data from actual measurements. It has started in 2014 and will run for 4 years. The project will examine three structures using existing data from both floating and fixed-bottom systems, and from both scaled tank testing and full-scale, open-ocean testing.