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Offshore Code Comparison Collaboration within IEA Wind Annex XXIII: Phase II Results Regarding Monopile Foundation Modeling

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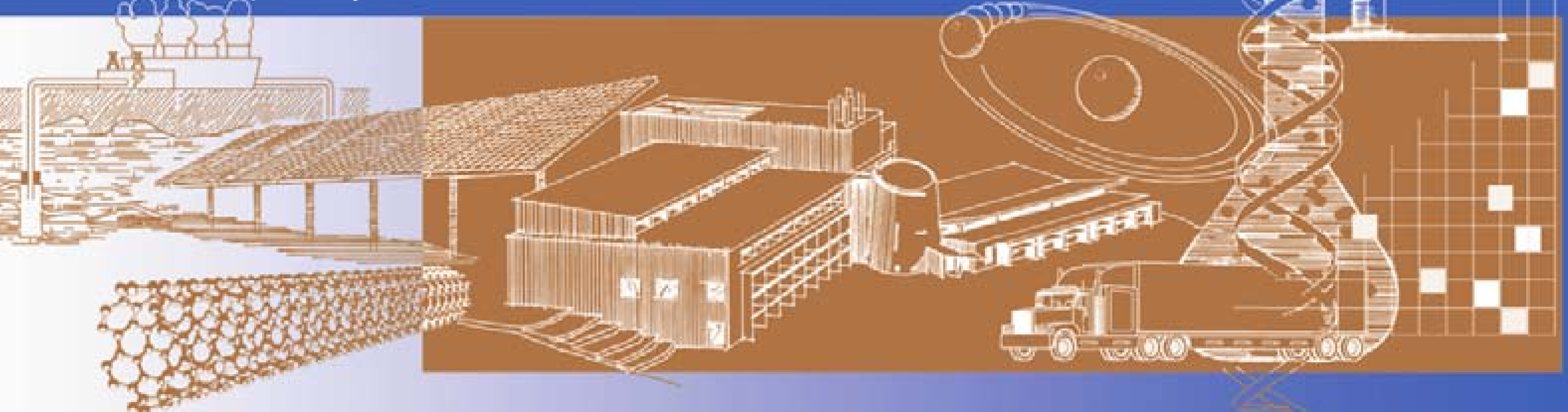

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Abstract

Offshore wind turbines are designed and analyzed using comprehensive simulation codes that account for the coupled dynamics of the wind inflow, aerodynamics, elasticity, and controls of the wind turbine, along with the incident waves, sea current, hydrodynamics, and foundation dynamics of the support structure. This paper presents an overview and describes the latest findings of the code-to-code verification activities of the Offshore Code Comparison Collaboration, which operates under Subtask 2 of the International Energy Agency Wind Annex XXIII. In the latest phase of the project, a variety of project participants using an assortment of codes have modeled the coupled dynamic response of a 5-MW wind turbine installed on a monopile with flexible foundation in 20 m of water. Foundation models included the simple apparent fixity model, a coupled springs model, and the more complicated distributed springs model, all of which were tuned to ensure that the overall response of the monopile above the mudline would be the same under a given set of loading conditions. The code predictions from a set of load-case simulations—each selected to test different features of the models—were compared. The comparisons, in general, agreed quite well. Differences that existed among the predictions were traced back to differences in the model fidelity, aerodynamic implementation, hydrodynamic load discretizations, and numerical difficulties within the codes.

1. Introduction

The vast offshore wind resource represents a potential to use wind turbines installed offshore to power much of the world. Design standardization is difficult, however, because offshore sites vary significantly through differences in water depth, soil type, and wind and wave severity. To ensure that offshore wind turbine 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.

Wind turbines are designed and analyzed using simulation tools (i.e., design codes) capable of predicting the coupled dynamic response and the extreme and fatigue loads of the system. Land-based wind turbine analysis relies on the use of aero-servo-elastic codes, which incorporate wind-inflow, aerodynamic, control system (servo), and structural-dynamic (elastic) models in the time domain in a coupled simulation environment. In recent years, a number 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 [1]. The sophistication of these aero-hydro-servo-elastic codes, and the limited data available with which to validate them, underscores the need to verify the codes to assess their accuracy and correctness. The Offshore Code Comparison Collaboration (OC3), which operates under Subtask 2 of the International Energy Agency (IEA) Wind Annex XXIII,* was established to meet this need.

2. Overview of the OC3 Project

To test the newly developed codes, the main activities of the OC3 project are (1) discussing modeling strategies, (2) developing a suite of benchmark models and simulations, (3) running the simulations and processing the simulation results, and (4) comparing the results. But these activities fall under the much broader objectives of

- Assessing the accuracy and reliability of results obtained by simulations to establish confidence in the predictive capabilities of the codes
- Training new analysts how 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 needs.

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 deficiencies in existing codes and needed improvements. These results are important because the advancement of the offshore wind industry is closely tied to the development and accuracy of dynamics models.

2.1. Participants and Codes

The OC3 project is performed through technical exchange among a group of international participants who come from universities, research institutions, and industry across the United States of America (U.S.), Germany, Denmark, the United Kingdom (UK), Spain, the Netherlands, Norway, Sweden, and Korea. In this paper, specifically, results are presented from participants who come from the National Renewable Energy Laboratory (NREL) of the U.S., the Endowed Chair of Wind Energy (SWE) at the University of Stuttgart in Germany, Risø National Laboratory of Denmark, Garrad Hassan & Partners Limited (GH) of the UK, and the National Renewable Energies Center (CENER) of Spain.

Most of the codes that have been developed for modeling the dynamic response of offshore wind turbines are tested within OC3. The existing modeling capabilities of the simulation tools used by (and for some, developed by) each participant are summarized in Table 1. Where Table 1 shows the same code being used by multiple OC3 participants, the model development, simulation runs, and data processing were done independently. Further enhancements of the modeling capabilities are planned within the course of the OC3 project.

2.2. Project Approach and Phases

The simulation of offshore wind turbines under combined stochastic aerodynamic and hydrodynamic loading is very complex. The benchmarking task, therefore, requires a sophisticated approach that facilitates the identification of sources of modeling discrepancies introduced by differing theories and / or 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 where model complexity is increased in each step.

The fundamental set of inputs to the codes controlled within OC3 relates to the specifications of the wind turbine. The OC3 project uses the publicly available specifications of the 5-MW baseline wind

* Web site: http://www.ieawind.org/Annex%20XXIII/Subtask2.html

Table 1. Overview of Aero-Hydro-Servo-Elastic Modeling Capabilities

	FAST	**Bladed**	**FLEX5**	**ADAMS**	**HAWC2**
Code Developer	NREL	GH	DTU / SWE	MSC / NREL	Risø
OC3 User	NREL, CENER	GH, CENER	SWE	NREL	Risø
Aerodynamics					
Loading Model	BEM, GDW	BEM, GDW	BEM	BEM, GDW	BEM, GDW
Hydrodynamics					
Wave Kinematics	$Airy^{+}$, UD	$Airy^{+}$, Stream	$Airy^{+}$, Stream, UD	$Airy^{+}$, UD	UD
Loading Model	$ME^{1,2,3}$, PF, UD	$ME^{1,2,3}$	$ME^{1,2,3,4}$	$ME^{1,2,3}$, PF, UD	$ME^{1,2,3}$
Control System (Servo)					
Implementation	DLL, UD, SM	DLL	DLL, UD	DLL, UD	DLL, UD
Structural Dynamics (Elastic)					
Analysis Method	Modal / MBS	Modal / FEM	Modal / FEM	MBS	MBS / FEM
Support Structure Types	GB, MP, $FL^{1,2,3,4}$	GB, MP, SF, FL^{1}	GB, MP, SF, FL^{1}	GB, MP, SF, $FL^{1,2,3,4}$	GB, MP, SF, FL^{1}
Foundation Models	AF, CS, DS, UD	AF, CS, DS	AF, CS, DS, UD	AF, CS, DS, UD	AF, CS, DS, UD

- AF – apparent fixity length (i.e., cantilevered beam)
- $Airy^{+}$ – Airy wave theory with free surface effect corrections
- BEM – blade-element / momentum
- CS – coupled springs at mudline
- DLL – external dynamic link library
- DS – distributed springs
- DTU – Technical University of Denmark
- GB – gravity base
- GDW – generalized dynamic wake
- FEM – finite-element method
- $FL^{1,\dots,n}$ – floating platform of type
  1) spar buoy
  2) tension leg platform
  3) barge
  4) hybrid concept
- MBS – multibody-dynamics formulation
- $ME^{1,\dots,n}$ – Morison equation for calculation of term
  1) viscous drag and inertia
  2) added mass
  3) relative kinematics
  4) slam
  5) slap
  6) breaking wave impact
  7) MacCumy-Fuchs
- MP – monopile
- MSC – MSC Software Corporation
- PF – linear potential flow with radiation and diffraction
- SF – arbitrary space frame
- SM – interface to Simulink® with MATLAB®
- UD – implementation through user-defined subroutine available

turbine developed by NREL, which is a representative utility-scale multimegawatt turbine that has also been adopted as the reference model for the integrated European Union UpWind research program.[†] This wind turbine is a conventional three-bladed upwind variable-speed blade-pitch-to-feather-controlled turbine. The specifications consist of detailed definitions of the 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 OC3 participants in the form of a dynamic link library (DLL). Reference [2] lists the specifications of the NREL offshore 5-MW baseline wind turbine in detail. The hydrodynamic and elastic properties of the varying offshore support structures used in the project are also controlled, and are discussed more in what follows. Furthermore, the turbulent full-field wind inflow and regular and irregular wave kinematics are model inputs controlled within the OC3 project. Risø generated the turbulent wind velocity datasets and GH generated the wave kinematics datasets; these datasets were then provided to all other participants. This approach reduces possible differences brought about by dissimilar turbulence models, wave theories, or stochastic realizations.

The key component of the stepwise procedure is the enabling and disabling of features of the model among different load-case simulations. Simulations are defined with and without aerodynamics and

† Web site: http://www.upwind.eu/default.aspx

hydrodynamics, with and without the control system enabled, and with individual subsystems both flexible and rigid. The structural dynamics are verified first without aerodynamics, hydrodynamics, or control system behavior by performing an eigenanalysis on a linearized model of the complete system, which gives the coupled system's natural frequencies and damping ratios. The aerodynamic and hydrodynamic models are then tested independently by running separate simulations with a completely rigid wind turbine structure. The aero-servo-elastic interaction is then verified by running simulations with a flexible—but an equivalent land-based—version of the wind turbine (with a rigid substructure). The hydro-elastic interaction is then verified by running simulations of the sea-based wind turbine with a flexible support structure, but a rigid rotor, drivetrain, and nacelle (i.e., an inverted pendulum). Finally, the fully coupled aero-hydro-servo-elastic response is tested by running simulations of the sea-based wind turbine with all features enabled. In addition, the environmental conditions in terms of the wind and wave input are varied. When deterministic wind and / or wave conditions are applied, the time series directly output from simulations are compared. When stochastic wind and / or wave conditions are applied, the statistics (minimum, mean, maximum, and standard deviation), damage-equivalent loads (DELs), and power spectra of the time series are compared. Each participant independently processed their time series to get the statistics, DELS, and power spectra, so the OC3 project compares not only the simulation tools, but also the processing algorithms.

Emphasis within the OC3 project is given to the verification of the offshore support structure dynamics as part of the dynamics of the complete system. This emphasis is a feature that distinguishes the OC3 projects from other wind turbine code-to-code verification exercises that have been performed in the past. Nevertheless, it was important to test the aerodynamic models separately so that modeling differences resulting from the aerodynamics could be identified. This identification is important because the aerodynamic models are known to be a routine source of differences in wind turbine code-to-code comparisons [3].

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) are investigated in separate phases of the OC3 project:

- In Phase I, the NREL offshore 5-MW wind turbine is installed on a monopile with a rigid foundation in 20 m of water.
- In Phase II, the foundation of the monopile from Phase I is made flexible by applying different models to represent the soil-pile interactions.
- In Phase III, the water depth is changed to 45 m and the monopile is swapped with a tripod substructure, which is one of the common space frame concepts proposed for offshore installations in water of intermediate depth.
- In Phase IV, the wind turbine is installed on a floating platform in deep water.

The OC3 project started in January of 2005 and is scheduled to be completed in the fall of 2008. During the time from the start of the project to now, the reference 5-MW wind turbine, including control system, was developed; the wind and wave datasets were generated; the simulations and code-to-code comparisons of Phases I and II have been completed; and Phase III has been initiated. A discussion of the wind and wave dataset generation and a description of Phase I and its results are presented in detail in Ref. [4]. This paper describes Phase II and discusses its results. Phases III and IV will be presented in future papers.

2.3. Review of Phase I Results

Before discussing Phase II, however, it is important to summarize the key findings from Phase I because many of the modeling differences that led to code-to-code discrepancies in Phase I led to similar differences in the model comparisons of Phase II. Though the code-to-code comparisons in Phase I agree very well, in general, the key reasons for the differences that remained were as follows [4]:

- The modal-based codes (FAST, Bladed, and FLEX5) predict slightly different 2nd and higher coupled eigenmodes than what are predicted by the higher fidelity multibody- and FEM-based codes (ADAMS and HAWC2). Differences in the dynamic response and energy content are, therefore, to be expected in the higher frequency range.
- The codes that rely on full-field wind that is supplied in polar coordinates (FLEX5) predict smoother aerodynamic loads (and thus smaller load deviations and smaller DELs) than codes that rely on rectangular coordinates (FAST, Bladed, ADAMS, and HAWC2). This follows from the method in which the wind datasets were generated. To ensure that all participants used the same wind inflow, the full-field wind datasets were generated in rectangular coordinates and subsequently interpolated to polar coordinates for the codes that needed it. This cause for differences was mitigated as much as possible by using a fine spatial resolution (32 × 32 points across the rotor disk).
- The differences among the codes relating to the implementation of aerodynamic induction, tower interference, hub and tip loss, and dynamic stall models—and whether or not the aerodynamic loads are applied in the deflected or undeflected blade state—attribute to variations in the mean values of several key wind turbine loads (e.g., blade-root bending moments, rotor torque, and rotor thrust).
- The blade-pitch controller compensates somewhat for variations that might have been caused between codes that do (ADAMS and HAWC2) and do not (FAST, Bladed, and FLEX5) have blade-twist degrees of freedom (DOFs).
- Differing model discretizations for the aerodynamic and hydrodynamic loads lead to differences among the code predictions. This is most apparent in the substructure loads that depend highly on the discretization of hydrodynamic loads near the free surface.
- Even though every effort has been made to standardize model inputs, user error still happens. It often takes several revisions before the model is developed and run as intended. It is also possible in some instances that errors still remain and account for otherwise unexplainable modeling differences.

3. Overview of Phase II

In Phase II, a set of three load-case simulations has been defined for the NREL offshore 5-MW wind turbine installed on a monopile substructure with flexible foundation in 20 m of water. The specifications of each load-case simulation are summarized in Table 2. Additionally, an eigenanalysis is used to verify the full-system structural dynamics. The load-case identifiers in Table 2 correspond to the identifiers used by the equivalent simulations from Phase I (see Ref. [4]), which employed a rigid foundation model. In Phase II, though, it was not necessary to independently test the aerodynamic, hydrodynamic, and aero-servo-elastic models—as was done in Phase I—because these models were identical between Phases I and II. Fewer combinations of wind and wave conditions were also needed to test the foundation models in Phase II.

Table 2. Summary Specifications for the Phase II Load-Case Simulations

Load Case	Flexible Subsystems	Wind Conditions	Wave Conditions
4.1	Foundation, Substructure, Tower	None: air density = 0	Regular Airy$^+$: H = 6 m, T = 10 s
4.2	Foundation, Substructure, Tower	None: air density = 0	Irregular Airy$^+$: H_s = 6 m, T_p = 10 s, Pierson-Mowskowitz wave spectrum
5.2	Foundation, Substructure, Tower, Drivetrain, Blades	Turbulent: V_{hub} = V_r (11.4 m/s), σ_1 = 1.981 m/s, Mann model	Irregular Airy$^+$: H_s = 6 m, T_p = 10 s, Pierson-Mowskowitz wave spectrum

H – individual wave height
H_s – significant wave height
T – individual wave period
T_p – peak spectral period
V_{hub} – hub-height wind speed averaged over 10 minutes
V_r – rated wind speed
σ_1 – longitudinal wind speed standard deviation

Consequently, the set of simulations from Phase II is much smaller than the set used in Phase I and the load-case identifiers are not sequential as a result.

For each load-case simulation, a total of 57 model outputs were analyzed. In addition to the 47 outputs analyzed in Phase I for the rotor, drivetrain, nacelle, tower, monopile, and environment (again, see Ref. [4]), 10 outputs were used in Phase II to analyze the loads and deformations within the now-flexible foundation.

3.1. Foundation Modeling

The monopile foundation was designed by SWE and its specifications were supplied to the OC3 participants. The intent of the design was to apply realistic soil properties and typical design procedures, and yet obtain a design that has a noticeable impact on the system's dynamic response to facilitate verification of the foundation models within the codes. Auxiliary effects such as axial displacement, torsion displacement, and scouring are neglected. The resulting design, consequently, is not an optimal—and may not even be a representative—design solution that is cost effective.

Pile foundations use lateral loading of the soil to withstand the loads induced in the supported structure. Under static lateral loading, typical soils, such as sand or clay, generally behave as a plastic material, which makes it necessary to nonlinearly relate soil resistance, *p*, to pile / soil deflection, *y*. The OC3 design uses the nonlinear *p*-*y* model for sand under cyclic loading conditions as defined by the American Petroleum Institute (API) [5]. This *p*-*y* model is dependent on the effective weight, *γ*, and angle of internal friction, *ø'*, of the sand—as well as on the pile diameter, *D*, and local soil depth, *z*. A layered soil profile is chosen with soil density (and *ø'*) increasing with depth. By this approach, a large participation of the soil-pile interactions in the dynamic response can be expected from the upper (less dense, less stiff) layer while the lower (denser, stiffer) layer ensures a sufficient bearing capacity of the soil. Figure 1 illustrates the soil profile and the properties of each soil layer.

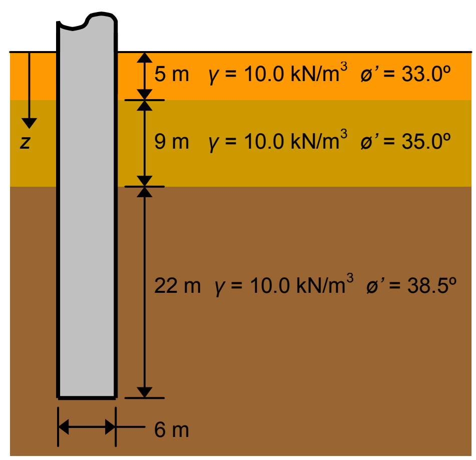


Figure 1. Soil profile

The subsoil portion of the monopile was designed to have the same properties (i.e., the same diameter, thickness, and material) as the portion above the soil for the monopile designed and used in Phase I. The pile penetration depth of 36 m was selected to minimize pile head deflections under ultimate loading conditions.

Most of the codes that have been developed for offshore wind turbines do not permit one to model the soil-pile interaction through detailed nonlinear and depth-dependent *p*-*y* models (e.g., see Table 1). Nor is it appropriate to assume that the API *p*-*y* model—which is normally intended for static analysis—is valid for transient dynamic analysis. Instead, most codes use one or more of a number of simplified linear foundation models suitable for dynamic analysis. SWE derived three such models for use in Phase II of the OC3 project. These models are illustrated in Figure 2 and are described below:

- The apparent (or effective) fixity length (AF) model idealizes the monopile with flexible foundation as a cantilever beam whose properties are different above and below the mudline. The beam above the mudline has the real properties (i.e., diameter, thickness, and material) of the monopile. The beam below the mudline has effective properties and a fictive length (i.e., the distance from the mudline to the cantilevered base) that are tuned to ensure that the overall response of the monopile above the mudline is the same as the response of the higher fidelity *p*-*y* model. The response can only be identical under a particular set of conditions, however, because the AF model is of lower fidelity. In the OC3

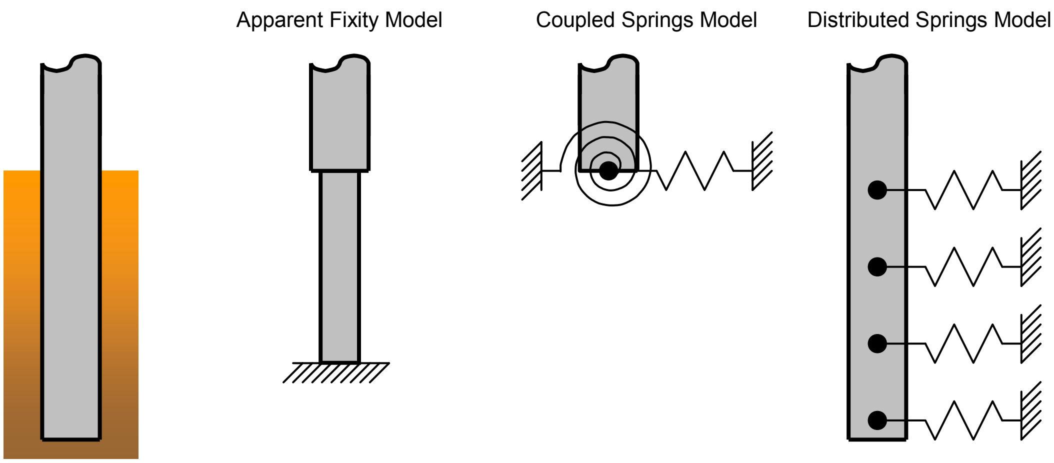


Figure 2. Simplified models of a monopile with flexible foundation

project, specifically, the properties of the fictive beam were tuned such that the mudline displacement and rotation for both models would be the same when loaded by a mudline shear force and bending moment that are representative of the loading that exists when the offshore wind turbine is operating under normal conditions.

- The coupled springs (CS) model idealizes the foundation compliance as a set of translational and rotational DOFs with coupled springs (i.e., a stiffness matrix) positioned at the mudline. Above the mudline, the monopile is modeled as a beam with the real properties of the monopile. The mudline spring stiffness constants were derived to give the same response as the AF model under the same loading conditions.
- The distributed springs (DS) model idealizes the monopile with flexible foundation as a free-free beam with lateral (Winkler-type) springs distributed along the subsoil portion of the monopile. The beam uses the real properties of the monopile both above and below the mudline—including the real penetration depth. The subsoil spring stiffness constants are depth-dependent and were calculated based on linearization of the *p*-*y* model under the same loading conditions chosen for the AF model.

3.2. Additional Phase II Analyses

In Phase II a separate set of load-case simulations was also run to verify the conclusion from Phase I that many of the code-to-code differences were the result of differing implementations of the aerodynamics models. A set of simulations was run by all OC3 participants with no aerodynamic induction, no tower interference, no hub and tip losses, and no dynamic stall (i.e., the aerodynamic loads that were computed within the simulations depended only on the geometric angle of attack, the dynamic pressure of the undisturbed inflow, and the given local force coefficients and chord length). The results of these simulations are not shown due to space limitations in this paper, however, the conclusion was verified because the results showed that the responses not influenced by model fidelity where much more similar among the codes.

4. Phase II Results and Discussion

The eigenanalysis and load-case simulations of Phase II were each run by every OC3 participant using all of the foundation models that were available in the codes they used. The legend in Figure 3

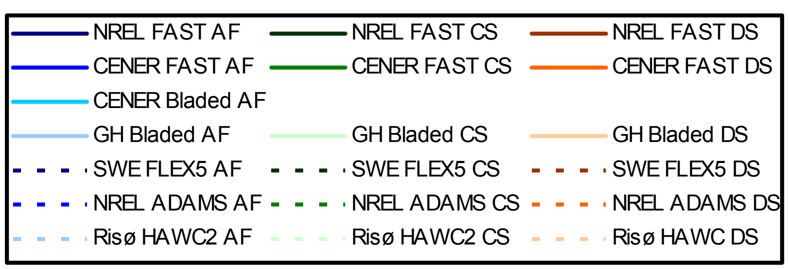
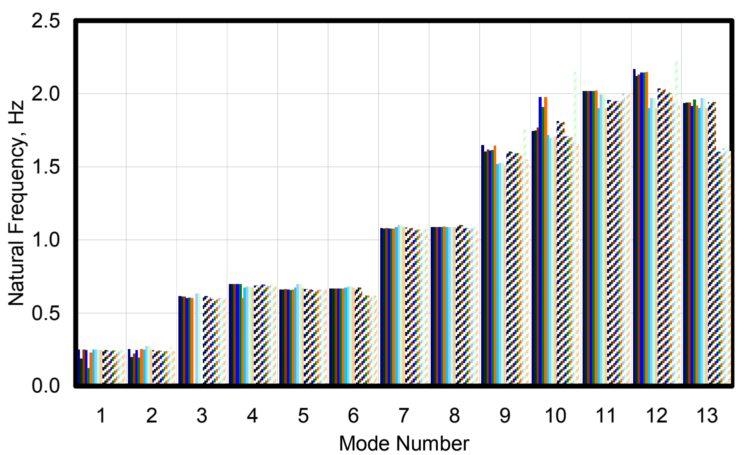


Figure 3. Legend for the Phase II simulation results

delineates how the results are presented in all of figures included in the subsections that follow. The results from the AF, CS, and DS foundation models are given in varying shades of blue, green, and orange, respectively. The color shade and line type distinguish the results from separate participants and codes. Only a small subset of the results is presented.

4.1. Full-System Eigenanalysis

Figure 4 gives the lowest 13 natural frequencies calculated for the stationary—but fully flexible—offshore wind turbine atop a monopile with flexible foundation. The designation of “pitch” and “yaw” in the asymmetric flapwise and edgewise blade modes identifies coupling of the blade motions with the nacelle-pitching and nacelle-yawing motions, respectively.



Mode	Description
1	1^{st} Support Structure Fore-Aft
2	1^{st} Support Structure Side-to-Side
3	1^{st} Drivetrain Torsion
4	1^{st} Blade Collective Flap
5	1^{st} Blade Asymmetric Flapwise Pitch
6	1^{st} Blade Asymmetric Flapwise Yaw
7	1^{st} Blade Asymmetric Edgewise Pitch
8	1^{st} Blade Asymmetric Edgewise Yaw
9	2^{nd} Support Structure Fore-Aft
10	2^{nd} Support Structure Side-to-Side
11	2^{nd} Blade Collective Flap
12	2^{nd} Blade Asymmetric Flapwise Pitch
13	2^{nd} Blade Asymmetric Flapwise Yaw

Figure 4. Full-system natural frequencies

The natural frequencies of the 1^{st} fore-aft and side-to-side modes of the support structure (Modes 1 and 2) with the CS foundation model are predicted lower by NREL and CENER with the FAST code. Additionally, the natural frequencies of the 1^{st} and 2^{nd} support structure fore-aft and side-to-side modes (Modes 1, 2, 9, and 10) and the 2^{nd} blade asymmetric flapwise pitch mode (Mode 12) with the CS foundation model are predicted higher by Risø with the HAWC2 code. These lower and higher predictions are both a result of numerical problems in solving the eigensolution for the CS foundation model systems. The numerical problems, in turn, are the result of ill conditioning of the linearized system matrices originating from numerical round-off error. The nonlinear time domain solutions in the FAST and HAWC2 codes, however, are not affected by these numerical problems; the time domain solutions have response frequencies that are consistent with the other foundation models.

The natural frequencies of the 2^{nd} support structure side-to-side mode (Mode 10) with all foundation models are predicted higher by CENER with the FAST code. NREL’s predictions from FAST of these frequencies, however, are similar to what were predicted by the other codes. These frequencies depend on the mode shapes of the support structure, which are inputs to FAST. CENER found these mode shapes by performing an eigenanalysis on a model of the support structure assembled within Nastran, while NREL found them independently using the results of their eigenanalysis from ADAMS. CENER is still investigating why Nastran predicts different mode shapes as compared to ADAMS and why these differences have a large effect on the prediction of the natural frequencies from FAST.

The addition of the flexible foundation in Phase II reduced the natural frequencies of the support structure by about 10% for the 1^{st} mode and 25% for the 2^{nd} mode when compared with the responses obtained in Phase I (see Ref. [4]), which employed a rigid foundation. The flexible foundation, however, had little effect on the natural frequencies of the drivetrain and blades, except for the 1st and 2nd blade asymmetric flapwise yaw modes (Modes 6 and 13) in the codes (ADAMS and HAWC2) that account for torsion within the support structure. In this mode, the vertically positioned blade remains stationary, while the two other blades flap out of phase with each other. These blade motions couple with torsion of the support structure in ADAMS and HAWC2, which drops the natural frequency when compared to the codes that do not account for support structure torsion (FAST, Bladed, and FLEX5). This coupling is more noticeable in Phase II because the support structure is longer, making its effective stiffness lower.

4.2. Hydro-Elastic Response of an Inverted Pendulum with Regular Waves

Figure 5 shows time histories of the bending moment within the monopile—both at the mudline (z = 0 m) and 7 m below the mudline (z = 7 m)—from load case 4.1, which models the offshore system as an inverted pendulum (i.e., the system has flexible foundation, substructure, and tower, but rigid rotor-nacelle assembly) excited by regular (i.e., periodic) waves. The responses are shown for one passage (i.e., period) of the wave after all start-up transients have died out. The instantaneous wave elevation at the tower centerline is highest at 50 s and lowest at 55 s. The hydrodynamic loading is dominated by inertia (not viscous drag) because the monopile bending moments are about 90º out-of-phase with the wave elevation.

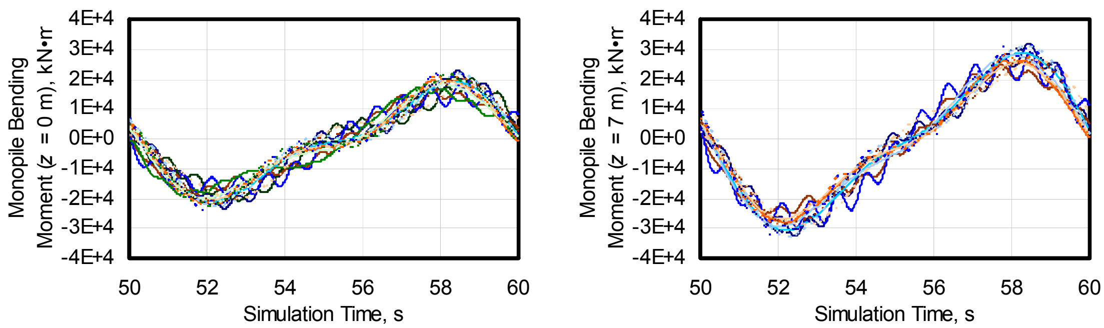


Figure 5. Time histories from load case 4.1

The mean values of the monopile bending moments are predicted very similarly between the codes. The 2nd mode of the support structure (indicated by the higher frequency oscillations), however, gets excited in some codes (FAST, ADAMS) but not the others (Bladed, FLEX5, HAWC2). This difference is more visible in the monopile loads than in the monopile deflections (not shown). The difference is the result of a numerical problem within FAST and ADAMS that exists when they read in externally generated wave data, as is done within the OC3 project. The problem is likely related to how the wave kinematics data are interpolated at the elements passing through the free surface, which might be causing a stepwise loading of these elements that tends to excite high frequencies within the model. The impact of the numerical problem can be mitigated by using a finer discretization of the hydrodynamic loads. Further study will be required, however, to isolate the exact problem and to identify a suitable correction.

The monopile bending moment 7 m below the mudline is slightly higher than the bending moment at the mudline. The location 7 m below the mudline is roughly the location within the foundation where the magnitude of the monopile bending moment reaches its maximum. Surprisingly, the bending moments at this location are predicted very similarly between the AF and DS models by all codes. (There is no output at this location for the CS model.) This similarity between the AF and DS models happens in this case because the soil is least dense (least stiff) in the upper layer and should not be expected between the models in general. (The AF model is of lower fidelity and should be less accurate than the DS model and should not be used, in general, to predict subsoil pile loads.)

4.3. Hydro-Elastic Response of an Inverted Pendulum with Irregular Waves

Figure 6 shows response statistics and DELs from load case 4.2, which tests the same model used in load case 4.1, but this time with excitation from irregular (stochastic) waves. The DELs were computed using two different values of the Wöhler material fatigue-strength exponent (*m*) as indicated. Responses of the monopile translational and rotational displacement, shear force, and bending moment at the mudline are presented. These responses were not processed by all of the OC3 participants, which is why some of the predictions are zero-valued.

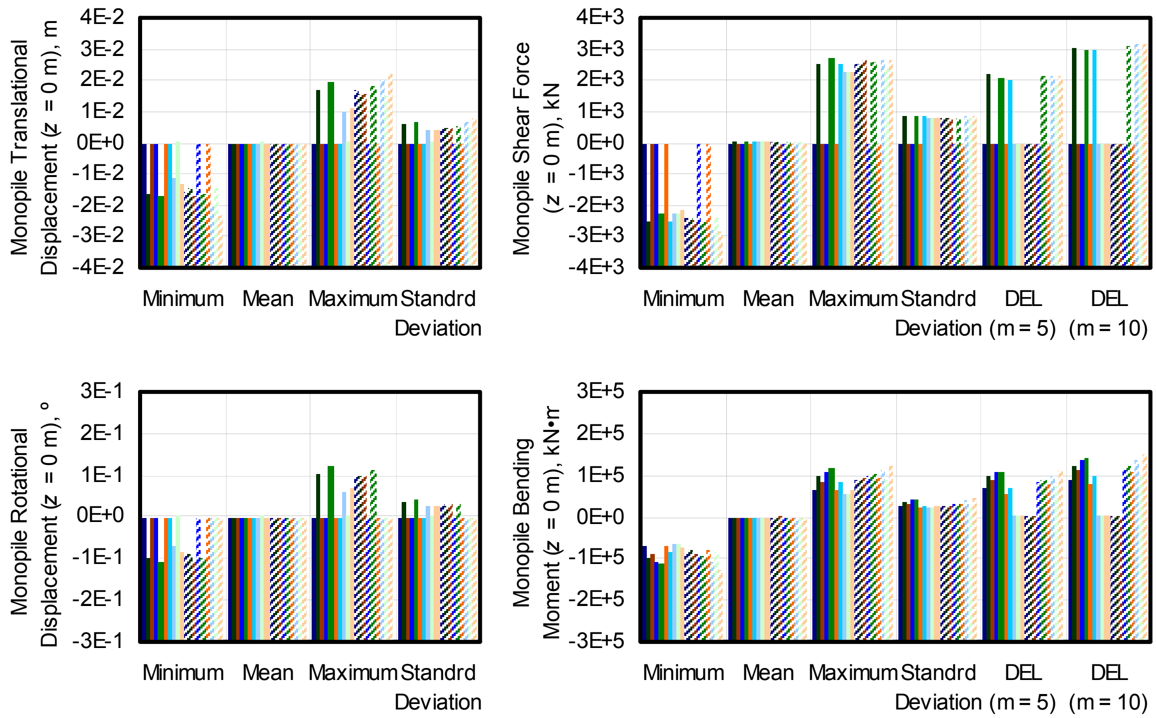


Figure 6. Statistics and DELs from load case 4.2

As in the results from load case 4.1, the mean values of all outputs are predicted very similarly between the codes in load case 4.2. There is some deviation, however, between the code predictions of the minimums, maximums, standard deviations, and DELs. The deviations between the code predictions are greater for the monopile bending moment at the mudline than for the shear force, which implies that the deviations are perhaps the result of the differing discretizations of the hydrodynamic loads near the free surface. (The discretization of hydrodynamic loads near the free surface has more of an effect on the bending moments than the shear forces because the hydrodynamic loads are weighted by the moment arm—which is largest for the loads at the free surface—in the bending moment calculation.)

The power spectra of the time series were also calculated for load case 4.2. The power spectra of the monopile shear force and bending moment at the mudline are shown in Figure 7. The predictions are very similar among all the codes at and below the 1st natural frequency of the support structure (about 0.25 Hz). HAWC2, however, predicts more excitation than FAST, Bladed, FLEX5, and ADAMS across all higher frequencies (except at 1.45 Hz). Risø is still investigating why these power spectra predictions are so different. Additionally, FAST and ADAMS, predict more excitation than do Bladed and FLEX5 at the 2nd natural frequency of the support structure (about 1.45 Hz). (The value of 1.45 Hz is lower than what is shown in Figure 4 because the rotor-nacelle assembly is rigid in load case 4.2, which removes any coupling with the blade motions and

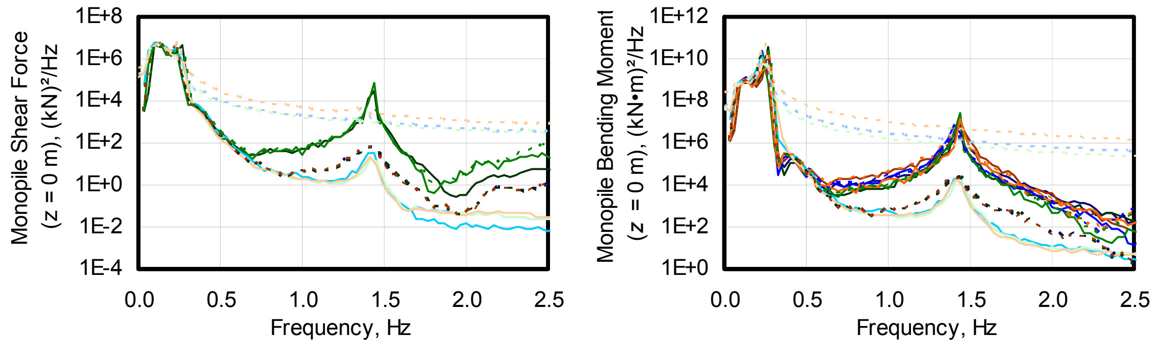


Figure 7. Power spectra from load case 4.2

increases the natural frequency.) This difference is consistent with the higher frequency oscillations predicted from FAST and ADAMS in load case 4.1 and is believed to be caused by the same numerical problem.

4.4. Fully Coupled Aero-Hydro-Servo-Elastic Response

Figure 8 shows the power spectra of the monopile shear force and bending moment at the mudline from load case 5.2, which models the full aero-hydro-servo-elastic response of the offshore wind turbine atop a monopile with flexible foundation subject to stochastic wind and wave loading.

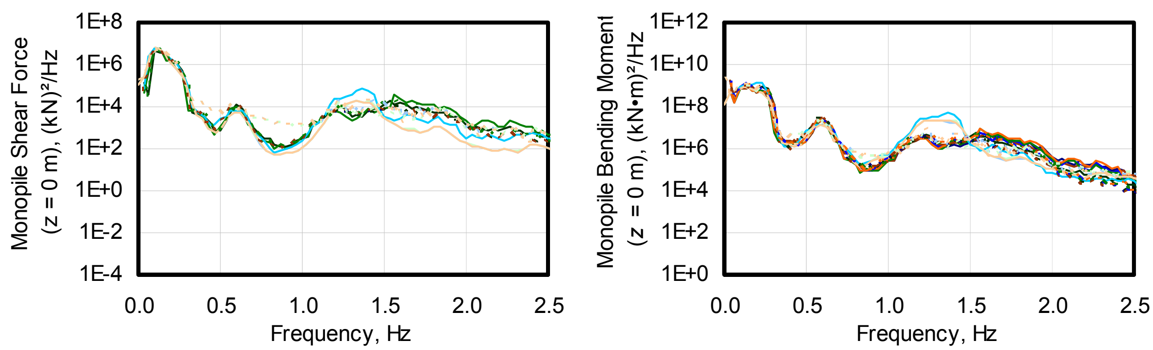


Figure 8. Power spectra from load case 5.2

The results compare very well among the codes, in general, especially in the frequency range encompassing the 1st natural frequencies of the support structure, drivetrain, and blades (up to about 1.1 Hz). The differences in the higher frequency range are influenced by differences among the codes in their predictions of the higher modes of the coupled system, as well as the other differences already described. What is perhaps surprising, however, is that the codes' predictions of the power spectra in the higher frequency range compare better in load case 5.2 than in load case 4.2. In particular, FAST and ADAMS in load case 5.2 no longer predict higher excitation than the other codes at the 2nd natural frequency of the support structure (they did in load case 4.2—see Figure 7). This improvement among the code predictions implies that the monopile loads at this frequency are heavily influenced (and perhaps being damped out) by the aerodynamic loading, which was absent in load case 4.2. The differing implementations of the aerodynamic models among the codes have more effect on the mean values of the wind turbine loads than on the power spectra.

5. Conclusions

Offshore wind turbines are designed and analyzed using comprehensive simulation codes that model the systems' coupled dynamic aero-hydro-servo-elastic response. The OC3 project, which operates under Subtask 2 of the IEA Wind Annex XXIII, has performed work to verify the codes to assess their accuracy and correctness.

In Phase II of the OC3 project, a variety of project participants using an assortment of codes have modeled the coupled dynamic response of the NREL 5-MW wind turbine installed on a monopile with flexible foundation in 20 m of water. Foundation models included the simple AF model, a CS model, and the more complicated DS model, all of which were tuned to ensure that the overall response of the monopile above the mudline would be the same under a given set of loading conditions. The code predictions from a set of load-case simulations—each selected to test different features of the models—were compared. The comparisons, in general, agreed quite well. Differences that existed among the predictions were traced back to differences in the model fidelity, aerodynamic implementation, hydrodynamic load discretizations, and numerical difficulties within the codes.

The verification activities performed in the OC3 project are 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 their predictions.

References

1. Passon P and Kühn M, "State-of-the-art and Development Needs of Simulation Codes for Offshore Wind Turbines," *Copenhagen Offshore Wind 2005 Conference and Expedition Proceedings, 26–28 October 2005, Copenhagen, Denmark* [CD-ROM], Copenhagen, Denmark: Danish Wind Energy Association, October 2005.

2. Jonkman J, Butterfield S, Musial W, and Scott G, *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*, NREL/TP-500-38060, Golden, CO: National Renewable Energy Laboratory, February 2007 (to be published).

3. Schepers JG, et al, *Verification of European Wind Turbine Design Codes, VEWTDC; Final Report*, ECN-C-01-055, Petten, The Netherlands: Energy Research Centre of The Netherlands, May 2002.

4. Passon P, Kühn M, Butterfield S, Jonkman J, Camp T, and Larsen TJ, "OC3—Benchmark Exercise of Aero-Elastic Offshore Wind Turbine Codes," *Journal of Physics: Conference Series, The Second Conference on The Science of Making Torque From Wind, Copenhagen, Denmark, 28–31 August 2007*, [online journal], Vol. 75, 2007, 012071, URL: http://www.iop.org/EJ/article/1742-6596/75/1/012071/jpconf7_75_012071.pdf?_request-id=8kI1Ig5u3BGgUobT2wi7Kg, [cited 28 August 2007].

5. American Petroleum Institute (API), *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms—Working Stress Design* (API RP 2A-WSD), 21st ed., December 2000.

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This paper presents an overview and describes the latest findings of the code-to-code verification activities of the Offshore Code Comparison Collaboration, which operates under Subtask 2 of the International Energy Agency Wind Annex XXIII.

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