Final report

1.1 Project details

Project title	IEA task 30 Offshore Code Comparison Collaboration, Continued, med Correlation (OC5)
Project identification (program abbrev. and file)	64014-0587
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Technical University of Denmark, DTU Wind Energy
Project partners	Danish Hydraulic Institute
CVR (central business register)	30 06 09 46
Date for submission	31-01-2019

1.2 Short description of project objective and results (max 800 characters each)

The main objective of the OC5 project is to advance the overall accuracy of the existing aero-hydro-servo-elastic analysis tools through comparing numerical results and measurements.
The overall project was performed as expected with minor delays, which was due to delays in sharing the measurement data from the Alpha Ventus wind farm.
The validation results reveal that the numerical tools developed by DTU and DHI are able to predict the dynamic responses very well compared to the measurement data. Moreover, the comparison facilitated the identification of areas for further improvement of the codes. This has ensured that the numerical models are useful tools of high fidelity for wind system global response and load prediction.
The engineering model for monopile loads developed at DHI showed good comparisons with experimental data and provides a design tool to be used in consultancy services for the industry.
The obtained results from this project are disseminated via 4 published conference papers and 2 paper will be presented in 2019. There were 9 physical meetings and 32 video conferences during the project.

Danish:
Hovedformålet i OC5 projektet var at øge nøjagtigheden af eksisterende aero-hydro-elastiske beregningskoder gennem sammenligning med numeriske resultater og målinger. Projektet er gennemført som planlagt bortset fra mindre forsinkelser i forbindelse med data-deling fra Alpha Ventus vind-farmen.
De udførte valideringer viser at de udviklede modeller på DTU og DHI er i stand til at forudsige det strukturelle dynamiske respons med god nøjagtighed. Sammenligningerne har ydermere gjort det muligt at identificere de områder, der kræver ydereligere forbedringer. Indsatsen har været vigtig i forhold til at sikre at HAWC2

er et brugbart og nøjagtigt værktøj til at bestemme laster og global respons for offshore vindsystemer.
Resultaterne fra projektet er publiceret i fire artikler. To artikler vil blive præsenteret i 2019. Der har været 9 fysiske projektmøder og 32 video-konferencemøder i projektets levetid.

1.3 Executive summary

This project enabled Danish participation in the International Energy Agency task 30 project named 'OC5'. The scope of this project is to establish a forum where newly developed aero-hydro-servo-elastic codes can be benchmarked. The unique thing about this project is that both experimental model data and full-scale measurements were used as the benchmark cases. This converts the project from being a verification project to a validation project. This is a significant extension compared to the two previous code-to-code comparison phases and has been requested in general by both industry and participants.

The project consists of three major work packages. WP1: Hydrodynamic loads on a flexible monopile. WP2: Floating wind turbine mounted on a semisubmersible platform. WP3: Open water bottom fixed offshore wind system with turbine.

In WP1, DTU successfully delivered and shared the DHI-measured data obtained in the previous ForskEL Wave Loads Project (ForskEL 10495; Bredmose *et al.*, 2013) with the full IEA consortium. DTU used three different models to verify the numerical results against the measurement data. Generally, the developed numerical models by DTU predicted very well compared to the measurement data and other numerical codes developed by other institutes. Full comparisons are reported in the paper of Robertson *et al.* (2016). DHI contributed to the work in this WP by developing an engineering model for estimating extreme wave induced loads on monopile foundations. The model is based on the usage of measured surface elevations that are scaled to a given sea state or input from the fully non-linear wave model MIKE3 Wave FM. The load calculation is based on a Morison's approach with an additional slamming load formulation and provides load data for a full sea states and thereby enabling prediction of probability for occurrence of the most extreme slamming events.

In WP2, DTU successfully developed numerical models for a semi-submersible floating wind turbine at model scale. Two modelling approaches were conducted in HAWC2 with different hydrodynamic models. Based on the defined the load cases, DTU performed very detailed load analysis and compared with the measurement data and other numerical results provided by other institutes. Generally, HAWC2 predict very well compared to other results. More details of the turbine and substructure definition and comparison results can be found in the published conference paper (Robertson *et al.* 2017).

From WP3 the numerical verification (code-to-code comparison) and experimental validation (code-to-filed data comparison) were performed. In order to perform the code-to-code verification four groups of verification load cases (LCs) of increasing complexity were defined. Detailed DTU results and comparisons with the other project participants have been published in Popko *et al.* (2018). Furthermore, the detailed results from the validation phase are being finalized and will be presented in a conference during 2019.

In this WP DHI investigated the usage of a CFD model to simulate wave interaction with a bottom fixed jacket structure. The model was tested with a regular wave based on stream function theory. The work provided a proof-of-concept and enables DHI to move this field forward in future projects.

The obtained results were published in 4 conference papers and 2 paper will be presented in 2019. During the project, total 32 times net meeting have taken place and 9 times physical meeing were held. DTU participated in all meetings and all publications.

1.4 Project objectives

The International Energy Agency (IEA) Task 30 was initiated with the OC3 project (2005-2009) and continued with the OC4 (2010-2014) project. In projects OC3 and OC4 the focus was the development and verification of existing aero-servo-elastic simulation tools for offshore wind turbines. The OC5 project, which is a follow-up project had as main objective the validation of the simulation tools through benchmarking with both experimental model data from basin and full-scale measurements (in-situ data) of offshore wind turbine substructure.

In other words, the scope was to assess the ability of the modelling tools to accurately predict real system responses, which is the intended use of the tools. This converted the project from being a verification project to a validation project, which was also a need for the offshore wind industry. The project was an international collaboration between research institutions and the offshore wind industry code developers and users.

The OC5 project was organised in three phases where the first two focused on benchmarking and validation of the physical response through basin tests, while the last phase contained full-scale measurements from the Alpha Ventus wind farm. More specifically phase II addressed the validation comparison of a scaled 5MW wind turbine mounted on a floating semi-submersible substructure. Phase III addressed the validation of a 5MW wind turbine on a jacket foundation operating at Alpha Ventus offshore wind farm.

Overall the project evolved as expected with minor delays. A delay on the delivery of the measurement data from the Alpha Ventus wind farm and detailed jacket structural data from the company OWEC, which were essential data for the entire WP3, resulted in extending the project studies until the beginning of December 2018. Moreover, IEA task 30 organizers discovered that the provided statistical data for the comparisons were not corresponding to the measurement time series. Therefore, the initially defined external conditions have been updated thus the simulation and analysis of the validation phase (WP3, task2) has been done twice.

Some small unforeseen issues appeared during the phase III simulations (HAWC2 code was crashing) thus extra time has been spent to update the coupling (wrapper DLL file) of the provided controller (BLADED style controller) with HAWC2. The updated wrapper DLL is a useful feature that will be used in other projects. Additionally, the simulation of the start-up load case was not performed as expected due to the provided controller. Extra time was also needed to modify the controller by adding a filter. All the mentioned unforeseen issues have been handled, resulting in a successful outcome.

An unforeseen positive outcome through this project was the testing of a new Beta HAWC2 time domain sparse solver. The solver considers the fact that the mass and stiffness matrices of the whole model are sparse due to many Timoshenko beam elements of the jacket substructure. The results were of the same accuracy as the original HAWC2 solver. However, the simulation time was reduced by more than 50% which is a huge improvement. Furthermore, the auto-generation of jacket sub-structures in HAWC2 format based on member properties (multi-member preprocessor) was updated including more properties to be automatically assigned in the generated jacket structure.

1.5 Project results and dissemination of results

This project contains three work packages. The main activities and technical results are addressed under each work package.

WP1: Hydrodynamic loads on a flexible monopile

WP1 focused on validation of numerical models for the loads and response of monopiles. The three tasks and their main results are reported in the following.

Task 1.1 Model development

In task 1.1, data measured at DHI in the previous ForskEL Wave Loads project (ForskEL 10495; Bredmose *et al.*, 2013) were shared with the full IEA consortium. The setup is shown in Figure 1 and consists of a flexible cylinder, representing a monopile substructure at scale 1:80. The full-scale diameter was 6 m, and two point masses were added, to match the first and second natural frequencies of the NREL 5MW reference wind turbine (Jonkman *et al.* 2009).

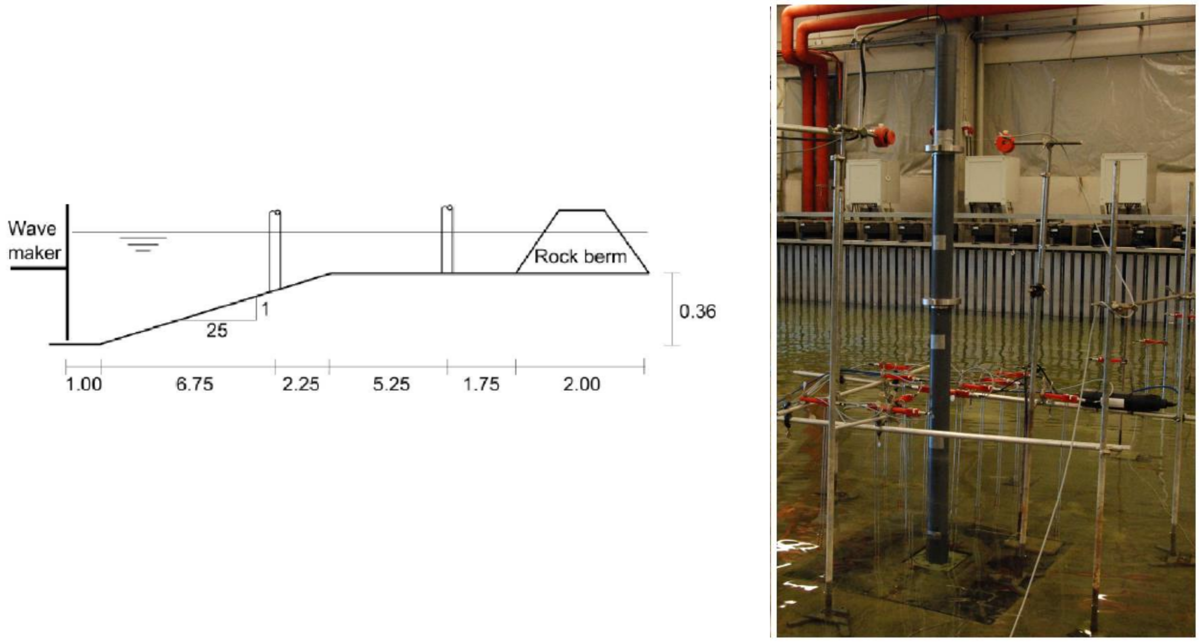

Figure 1: Test setup from the WaveLoads project at DHI. Left: Side view. Numbers show distances in lab scale in unit of meters. Right: Photo of the setup with the flexible monopile, point masses and the wave maker behind.

Information on the experimental setup and instrumentation was provided for NREL, which compiled a specification report (Robertson, 2015) for use in OC5. As part of this, DTU determined the damping ratio for the first and second mode from decay tests and hammer tests, see Figure 2. The damping ratios were used by the participants to set up their structural models.

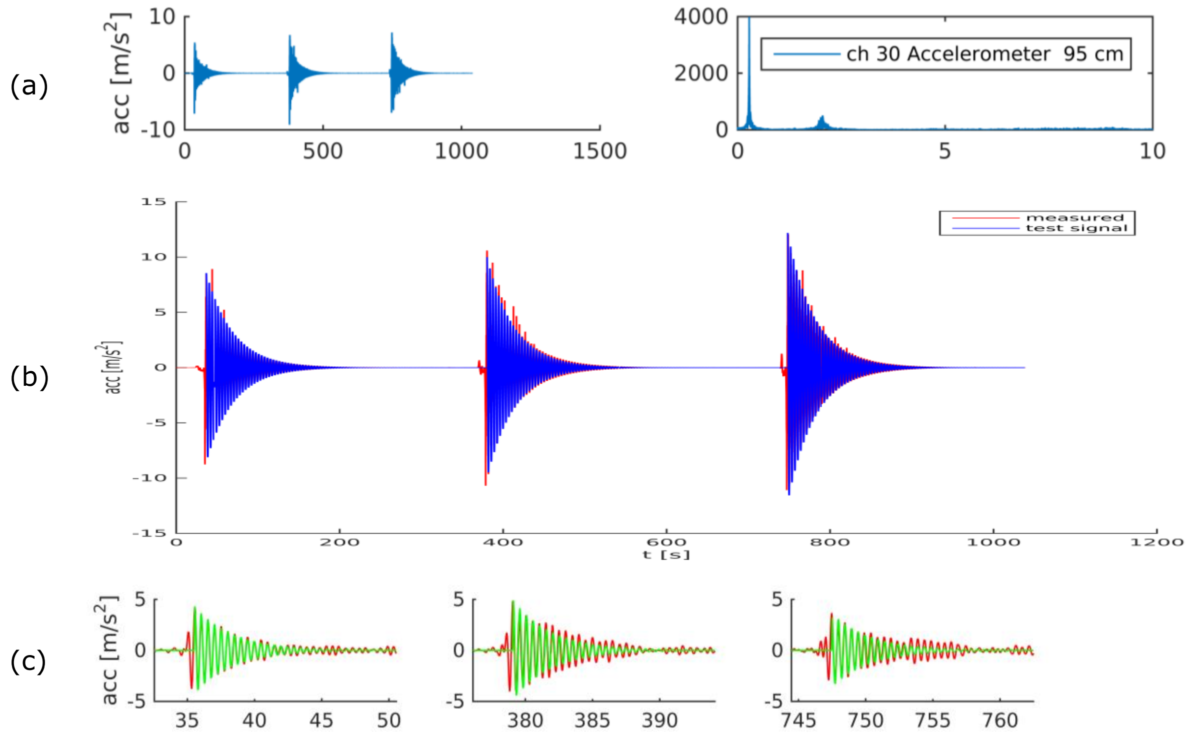

Figure 2: Determination of damping ratio by analysis of hammer tests. (a) Raw acceleration signal and power spectrum (Hz) for accelerometer 95cm above bed. (b) Filtered signal at first mode (0.28 Hz) and fitted decay curve. (c) Filtered signal at second mode (2.0 Hz) and fitted decay curve.

Following the specification for the experiments, seven experimental test cases for comparison were selected through interaction between DTU, DHI and NREL. The seven cases are stated in Table 1, and comprise 4 base cases of regular (periodic) waves and 3 cases of irregular waves of 3-hour duration (full scale).

Table 1: The seven test cases chosen for comparison.

Test #	**Wave Type**	**Water depth (m)**	**H or Hs (m)**	**T or Tp (s)**
1	Regular	0.51	0.090	1.5655
2	Regular	0.51	0.118	1.5655
3	Irregular	0.51	0.104	1.40
4	Irregular	0.51	0.140	1.55
5	Regular	0.26	0.086	1.565
6	Regular	0.26	0.121	1.565
7	Irregular	0.26	0.133	1.560

The regular wave cases were selected to support the interpretation of the more complex irregular cases. The selection of the irregular cases were aided by scatter plots of acceleration magnitude of the accelerometer 1.65m above the bed, see Figure 3. The scatter plots represent each wave with a dot, placed in a coordinate system of normalized depth (h/L_0) and deep water steepness (H/L_0). Here h is the depth and H is the trough-to-crest wave height. Further, L_0 is the deep water wave length, defined by $L_0=g/(2\pi)\ T^2$, where g is the acceleration of gravity and T is the period determined from zero-down-crossing analysis. The scatter plots show that I3 is the weakest sea state with no waves in the breaking regime (marked by the two lines). In case I4, the wave height is larger and more waves are close to breaking. Finally for sea state I5, the strongest sea state, the depth is smaller, the waves steeper and many waves are in the breaking region.

(I3) (I4) (I5)

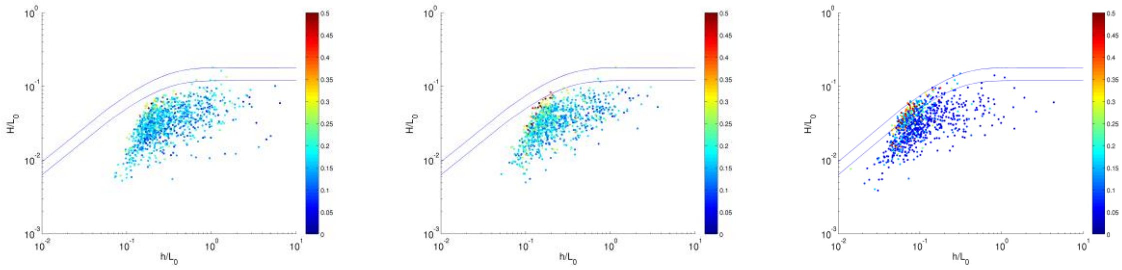

Figure 3: Scatter plot of normalized depth (h/L0) and deep water steepness (H/L0) for the three cases of irregular waves. The color of the dots represent the magnitude of acceleration.

For each wave case, wave kinematics were computed by DTU with the fully nonlinear potential flow solver OceanWave3D (Engsig-Karup, Bingham & Lindberg 2009). The numerical setup replicated the one of DHI and is shown in Figure 4.

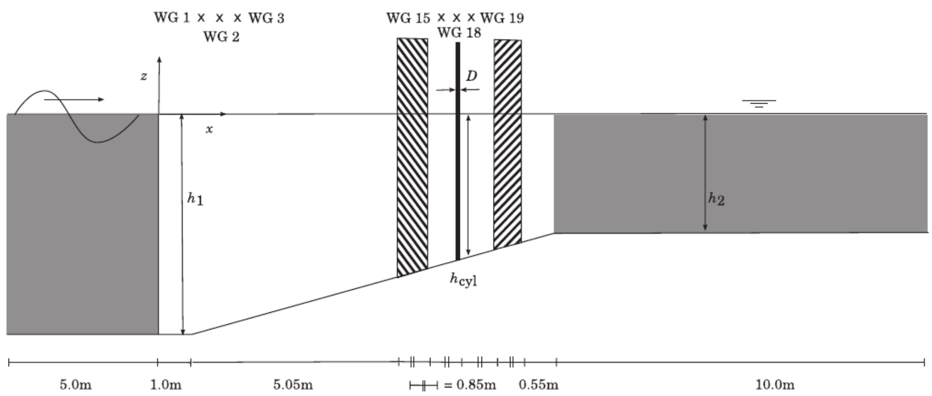

Figure 4: Principal sketch of the numerical setup in OceanWave3D with a generation zone, an absorption zone and wave gauge signals which are used to extract the linear wave field properties. Figure originates from Paulsen, Bredmose & Bingham (2014).

The procedure followed the methodology also used in Bredmose *et al.* (2013b). Wave signals from four wave gauges in the tank were used to extract the linear properties of the waves that propagated towards the structure (incident wave field). This wave field was applied as boundary condition in the deep-water wave generation zone and the waves next evolved through the domain and over the slope to reach the position of the structure. They eventually reached a wave absorption zone in the right extent of the domain. In previous studies, this approach has been found to provide a close reproduction of the waves in the tank, due to the consistency with the wave makers position in the test domain. It should be noted that the structure (monopile) is not part of the simulation, which is only made to extract the wave kinematics at the position where the pile was placed in the physical experiment.

Kinematics at the position of the monopile was computed for the full duration of the tests (3 hours, full scale) and provided to the other participants in the project. The data consisted of free surface elevation, the three velocity components and spatial derivatives of them and made it possible to apply the Morison equation or similar slender-body force models within a structural response model.

Task 1.2 Modeling by participants.

In task 1.2, the participants were to setup calculation models for local re-simulation of the measurements. DTU took part with three different models, namely a HAWC2 model with fully nonlinear kinematics; a HAWC2 model with linear wave theory and a Matlab-based Finite-element model (DTU-Beam). The models and their details are given in Table 2.

Table 2: The three codes used at DTU for phase 1b.

Code	Wave model	Wave elevation	Hydro model	Structual model	Number of DOFs
HAWC2	Linear Airy	OCW3D kinematics	Morison Stretching MacCamy-Fuchs	FEM (Timoshenko; Rayleigh daming)	126
HAWC2-PF	OCW3D kinematics	OCW3D kinematics	Morison	FEM (Timoshenko; Rayleigh daming)	192
DTU-Beam	OCW3D kinematics	OCW3D kinematics	Morison Rainey	FEM (Euler; Rayleigh damping)	160

The HAWC2 model with linear wave kinematics was used to benchmark whether a simple modelling approach was sufficient, given only fully nonlinear free surface elevation. This corresponds to the standard modelling method in HAWC2. For the HAWC2-PF model, a special kinematics import function was made to read the fully nonlinear wave kinematics and apply them within the Morison force model. The DTU-Beam model was tailored as an independent model in the previous Wave Loads project and included the Rainey (1989, 1995) additional terms for the Morison equation. These terms are higher-order corrections and have been derived to allow for application of fully nonlinear kinematics within the slender-body approximation.

The main results for regular waves and irregular waves are summarized. Figure 5 shows the peak force for the regular wave case of smallest nonlinearity (test 1) for all participants. The experimental result is shown in black as line 7 from the bottom, with the DTU models coming right below. A good match between the models and experiment is seen. The right panel shows the results of test case 6 which is the most nonlinear regular wave case. Here the DTU Beam model provides a fair match to the test results, while the kinematics-driven HAWC2 matches within 20%.

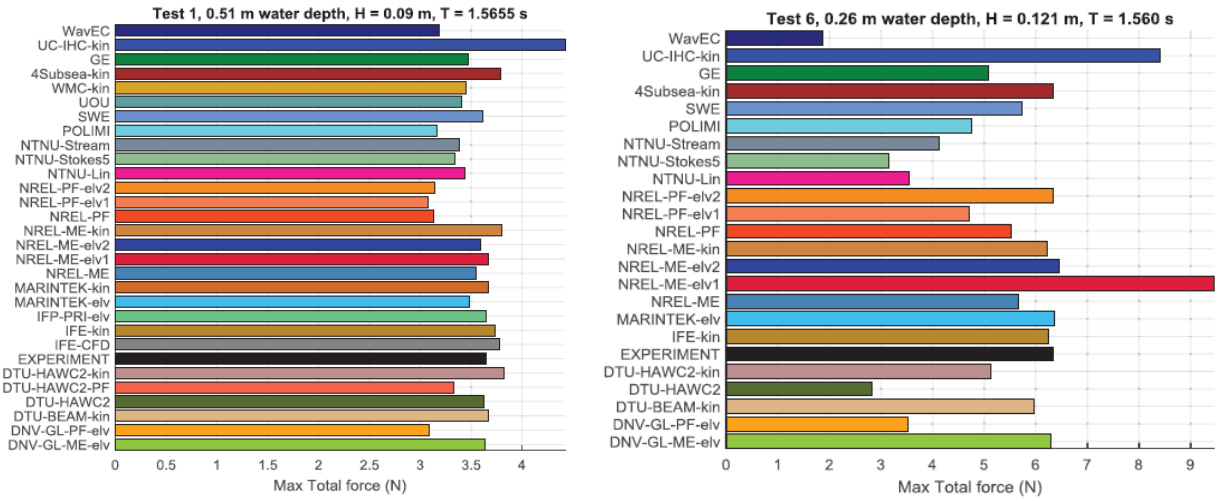

Figure 5: Peak force for regular waves. Left: Test case 1, a weakly nonlinear wave. Right: Test case 6, strongly nonlinear wave. From Robertson et al. (2016).

A further break-down of the force analysis for test case 6 is shown in Figure 6. Here the force time series is presented in terms of the magnitude of the first and second harmonic peaks in the power spectrum. HAWC2-kin shows an accurate match for both harmonics here, while the DTU Beam model shows a good match for the first harmonic and a 10% over-prediction for the second harmonic. It is interesting to see that the second harmonic force peak of the HAWC2 model with linear wave kinematics is under-predicting the second-harmonic force peak strongly. This is a clear sign of the limitation of linear wave theory for strongly nonlinear waves.

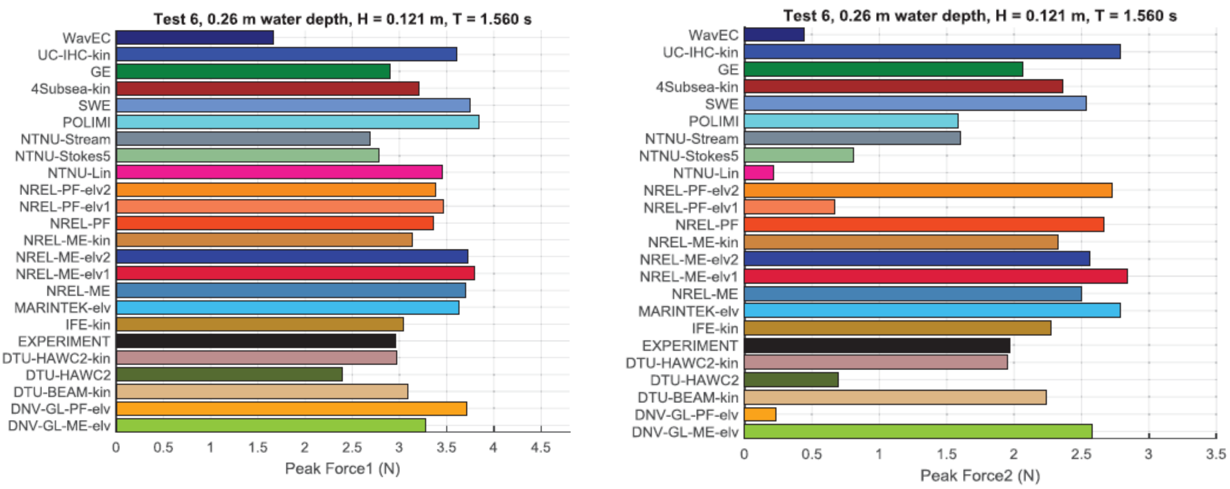

Figure 6: First (left) and second (right) force harmonic for test case 6, strongly nonlinear waves. From Robertson et al. (2016).

The dynamic response of the structure was quantified by comparison of the accelerations of the cylinder, measured 165*cm* above the bed. The comparison between experiments and models are shown in Figure 7 for test case 1 and 6. In both cases, the majority of the consortium models show an under-prediction of the acceleration. This is also the case for the DTU models for test 1. For test 6, the DTU Beam model shows the best match with an under-prediction of around 20%.

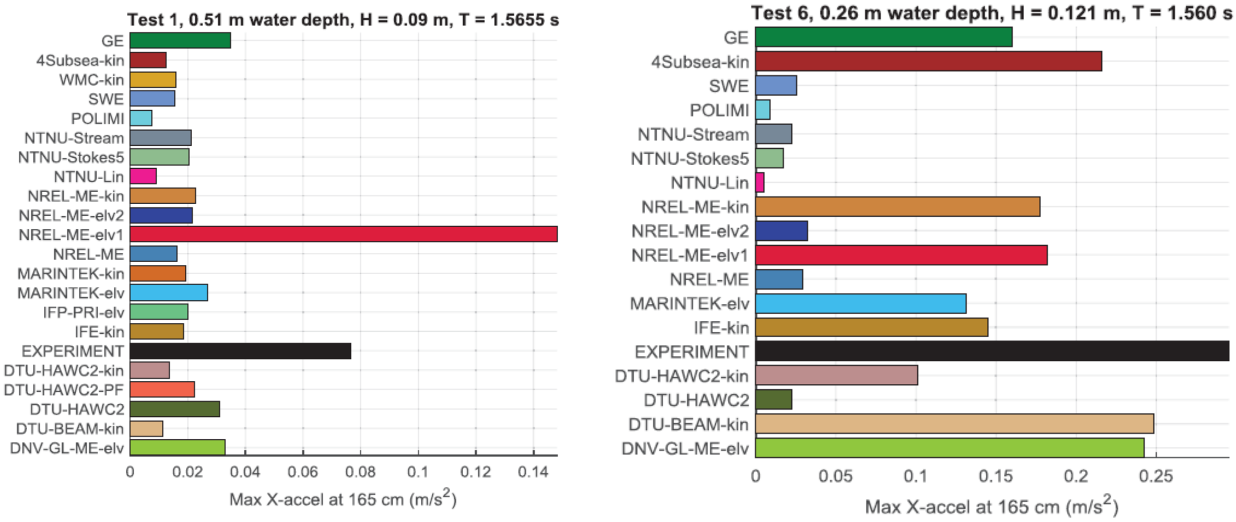

Figure 7: Maximum acceleration during regular wave forcing. Left: Test case 1, a weakly nonlinear wave. Right: Test case 6, strongly nonlinear wave. From Robertson et al. (2016).

The regular cases were used as base cases and helped to calibrate the numerical models. Further comparison was next done within the irregular wave cases. An example of time series are provided in Figure 8 for test case 3, the mildest case of irregular waves. The figure shows the free surface elevation (water level), the shear force at the bed and the acceleration 165*cm* above the sea bed. The total time series is 10800*s* long. An extreme event occurs at t=754*s*, where what looks like a breaking wave hits the structure and excites an impulsive response.

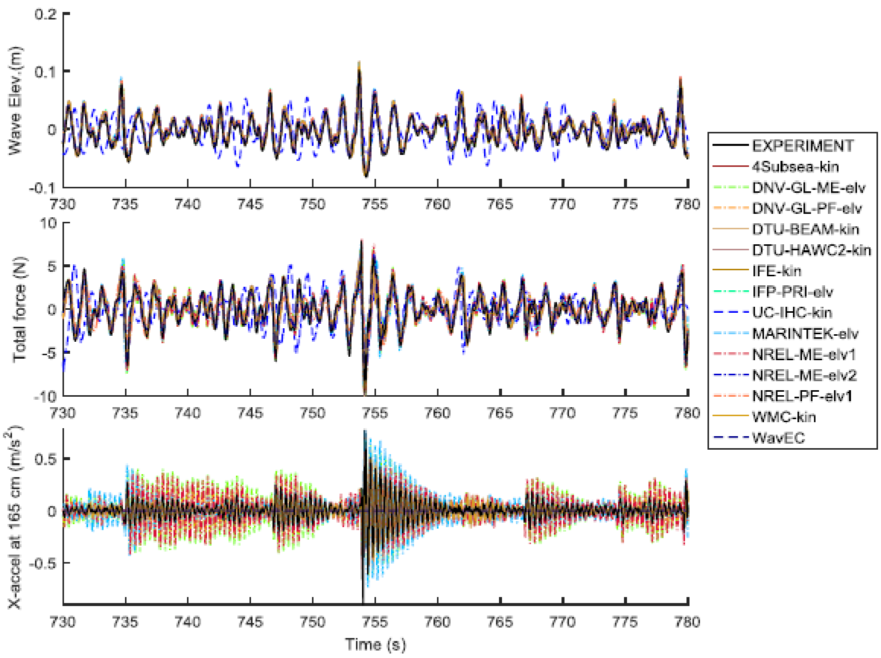

Figure 8: Example of an extreme event of test case 3 of nonlinear irregular waves. The top panel shows the free surface elevation, the middle panel shows the total shear force at the sea bed and the lower panel shows the structural acceleration 165cm above the bed. From Robertson et al. (2016).

While time series are good for interpretation of the physical processes, the stochastic nature of irregular waves requires a statistical approach to quantify the model accuracy. To this end, the method of exceedance probability plots was adopted, building on a method previously developed at DTU (Bredmose et al. 2013b). Here the measurement signals are divided into single wave episodes by zero-down-crossing analysis of the free surface elevation. Then, within each wave episode, the largest value of the signal of interest is registered.

Figure 9 shows exceedance probability plots for bed shear force for test case 7, the most nonlinear case of irregular waves. The measurements are shown in black. It can be seen that the DTU-Beam and kinematics-driven HAWC2 model follows the experimental results for force levels up to about 6*N* (lab units). Then for larger force levels, the DTU-Beam results strongly over-predict the force levels while the kinematics-driven HAWC2 results over-predict by around 13%, which is quite good in comparison to the other consortium models. Results for structural acceleration are shown in the lower panel. Here the DTU-Beam model follows the trend of the measurement, although with a maintained over-prediction of up to a force level of 0.6m/s^2. For larger acceleration levels, a strong over-prediction is seen again. The kinematics-driven HAWC2 model follows the data with fair agreement up to accelerations of 0.3m/s^2. After that an under-prediction occur, followed by over-prediction for the largest accelerations. The HAWC2 model with linear wave theory under-predicts the forces and accelerations in call cases.

The example illustrates the difficulties in modelling breaking waves and their response. A better match between models and experiments where seen in the weaker cases (test case 3 and 4), where the wave nonlinearity is less strong. These cases are reported in the paper of Robertson *et al.* (2016), which provides a summary of the flexible monopile comparisons for the full consortium.

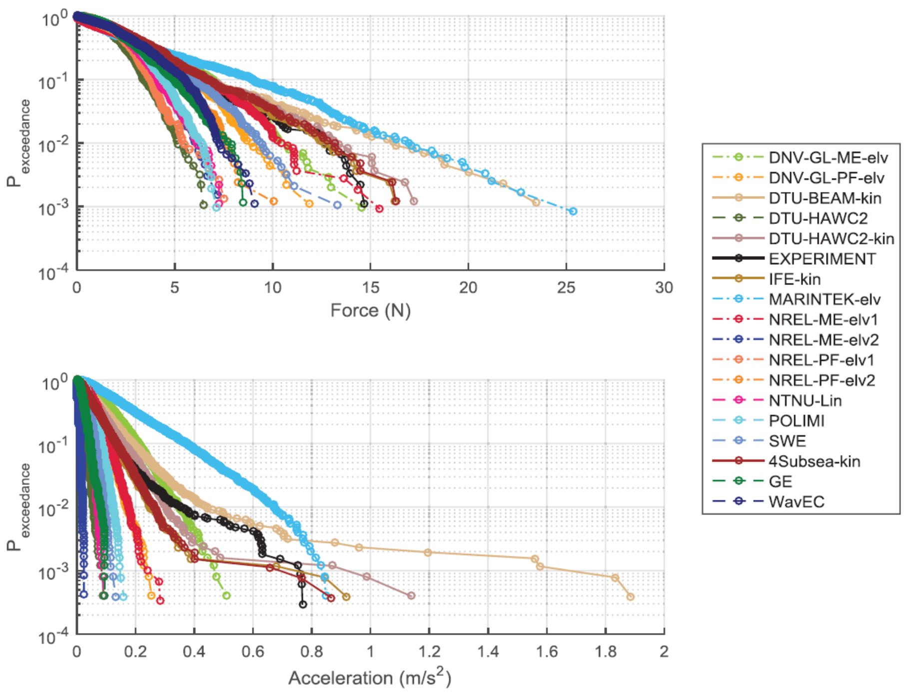

Figure 9: Exceedance probability plots of bed shear force (top panel) for the strongly nonlinear irregular wave case (test case 7). The bottom panel shows the acceleration 165cm above the bed. From Robertson et al. (2016).

DHI contributed to WP1 by developing an engineering model for estimating extreme wave induced loads on monopile foundations. Contrary to many of the partners on the OC5 project, DHI has currently no capabilities when it comes to modelling the wind loading on the wind turbines. The work is focused on the wave loading and especially for extreme slamming events in breaking waves. Conventional methods for estimating slamming events are based on Morison's equation in combination with wave kinematics derived from e.g. the non-linear stream function theory. To account for the extreme slamming load an additional load contribution is added based on empirical formulations. One drawback of this method is that it is not able to predict the probability of the slamming event to occur in a given sea state. This problem may be overcome by analyzing the load predictions based on an irregular time series of wave kinematics for the given sea state. However, the construction of such an irregular realization by linear theory will not provide the correct surface elevation and wave kinematics in shallow water, due to non-linear effects, where the majority of the monopile foundations are located.

The new engineering model seeks to overcome this problem. The main objectives of this model were to:

- Provide wave height and wave load distributions including non-linear effects on shallow water for predicting extreme slamming events and their probability of occurrence.
- Estimate the extreme slamming events by a slamming load model added to the traditional Morison's equation load prediction.

The model was implemented in two versions:

<u>Version 1.</u> A library of measured surface elevations from the laboratory forms the basis for generating an irregular time series of surface elevations for a given sea state. A laboratory experiment with wave conditions (in scale) corresponding to the prototype condition is scaled to prototype. Hereby the correct wave height distribution is achieved as all non-linear effects are included. From this the wave kinematics are constructed by linear theory and subsequent applied with Morison's equation to derive wave loads. In addition, a new formulation of the slamming term is included to capture the largest slamming events in a sea state.

<u>Version 2.</u> A numerical simulation with the fully non-linear wave model MIKE3 Wave FM providers the irregular time series of surface elevation as well as the wave kinematics directly simulated without any assumptions on linear theory. The simulation is performed in prototype. From this, Morison's equation is again applied with the additional slamming term for the largest slamming events.

The model was first tested on the experimental data from the WaveLoads project as made available for the OC5 group. Version 1 of the model was applied where no scaling of the experimental data was performed. In this way the model should reproduce the measured data directly. Test were made with and without the slamming load model. Here it was found that the model without the additional slamming load model gave a good prediction of the load distribution for waves with a low steepness. When the waves became steeper, i.e. with larger non-linearity, the model under predicted the largest slamming events. By including the additional slamming load model, the model was also able to provide a better prediction of these extreme slamming events. Figure 10 shows a comparison between measured and predicted in-line loads both with and without the slamming load model. With this version of the model, it is now possible to generate a time series of wave loads that takes the non-linear effects of the surface elevation and wave kinematics into account if the investigated sea state is represented in the library of experimental data. This stage of the model development was presented in Hansen and Kofoed-Hansen (2017).

The model was secondly developed to be used in combination with the fully non-linear wave model, MIKE3 Wave FM, denoted as Version 2 of the model. For this a second experimental data set was included based on the Derisk project. Hereby the experimental data library in Version 1 of the model was also extended to cover a wider range of wave conditions. The majority of the work involved in developing Version 2 of the model was devoted to reproducing the measured surface elevations in the MIKE3 Wave FM model. This was to validate the wave model in order to enable the usage of the model for producing surface elevation and kinematics time series as input for the load model. The work performed in relation to developing this Version 2 of the load model will enable a greater flexibility of the usage of the load model as well as providing users of the MIKE3 Wave FM model with an add-on module. Dissemination of this part of the development is currently on-going in Jensen *et al*. (2019).

Task 1.3 Summary report on WP1

The main results of WP1 have been presented in an extended conference paper (Robertson *et al*., 2016) presented at the EERA DeepWind conference in January 2016. Michael Borg, Henrik Bredmose, Anders Yde (DTU) and Flemming Schlütter (DHI) are co-authors. The paper front page is given in appendix. The paper is available online with open access in Energy Procedia.

WP2: Semi-submersible

Task 2.1 Agreement among participants about the simulation cases

Various Load Cases (LCs) were investigated starting from cases without wind/wave fields in order to calibrate the numerical models, up to cases with a combination of wind and wave external conditions. At Tables below (Tables 3-6) are summarized the calibration, only wind, only wave excitation, and the combined case of wind and waves, respectively. All the wind and wave external conditions are created by the HAWC2 except the turbulent wind cases 2.5 and 4.3 where the turbulence field is read from an external file which contains the actual measured wind field.

Table 3 Calibration load cases.

Load Case	Description	Enabled DOFs	Wind Condition	Wave Condition
1.1	Eigenanalysis	All	No wind	Still water
1.2	Static equilibrium	All	No wind	Still water
1.3a	Free decay, surge, Θ_{bl}=90deg	All	No wind	Still water
1.3b	Free decay, heave, Θ_{bl}=0deg	All	No wind	Still water
1.3c	Free decay, pitch, Θ_{bl}=90deg	All	No wind	Still water
1.3d	Free decay, yaw, Θ_{bl}=90deg	All	No wind	Still water

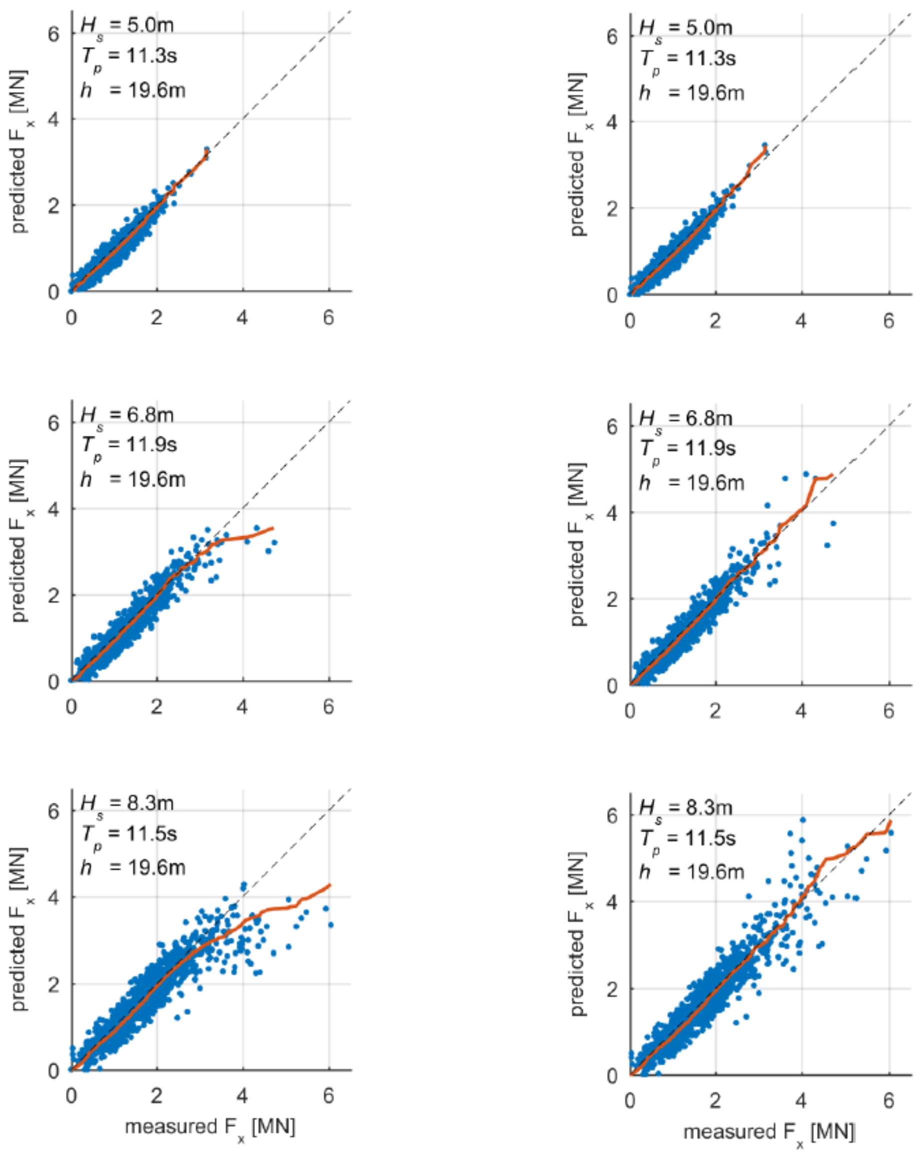

Figure 10 Comparion between measured and predicted in-line loads (Hansen and Koefod-Hansen (2017)). Measured data are taken from the WaveLoads project.

Table 4 Only wind field excitation load cases.

Load Case	Description	Enabled DOFs	Wind Condition	Wave Condition
2.1	Determin. wind, RPM=5.5-17.0, Θ_{bl}=0.86deg	Turbine base fixed	Steady, uniform, no shear, V_{hub} = 12.91m/s	-
2.2	Determin. wind, RPM=5.5-17.0, Θ_{bl}=15.0deg	Turbine base fixed	Steady, uniform, no shear, V_{hub} = 21.19m/s	-
2.3	Determin. wind, RPM=12.13, Θ_{bl}=1.22deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 21.19m/s	Still water
2.4	Determin. wind, RPM=12.12, Θ_{bl}=17.5deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 21.19m/s	Still water
2.5	Stohastic wind, RPM=12.13, Θ_{bl}=1.16deg	Turbine on Semisub	Turbulent (measured, NPD spectrum), no shear, V_{hub} = 13.05m/s	Still water

Table 5 Only wave excitation LCs.

Load Case	Description	Enabled DOFs	Wind Condition	Wave Condition
3.1	Regular waves, RPM=0, Θ_{bl}=90deg	Turbine on Semisub	No air	Regular Airy, H = 7.37m, T = 12.07s
3.2	Regular waves, RPM=0, Θ_{bl}=90deg	Turbine on Semisub	No air	Regular Airy, H = 9.41m, T = 14.3s
3.3	Irregular waves, RPM=0, Θ_{bl}=90deg	Turbine on Semisub	No air	Irregular Airy, H_s = 7.1m, T_p = 12.1s, γ = 2.2, JONSWAP spectrum
3.4	Irregular waves, RPM=0, Θ_{bl}=90deg	Turbine on Semisub	No air	Irregular Airy, H_s = 10.5m, T_p = 14.3s, γ = 3.0, JONSWAP spectrum
3.5	White noise wave, RPM=0, Θ_{bl}=90deg	Turbine on Semisub	No air	Banded white noise, H_s = 10.5m, $T_{p,range}$ = 6-26s, γ = 3.0, JONSWAP spectrum

Table 6 Load cases with combined wind and wave fields.

Load Case	Description	Enabled DOFs	Wind Condition	Wave Condition
4.1	Determin. wind, irreg. waves, RPM=12.1, Θ_{bl}=1.0deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 12.91m/s	Irregular Airy, H_s = 7.1m, T_p = 12.1s, γ = 2.2, JONSWAP spectrum
4.2	Determin. wind, irreg. waves, RPM=12.1, Θ_{bl}=17.2deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 21.19m/s	Irregular Airy, H_s = 7.1m, T_p = 12.1s, γ = 2.2, JONSWAP spectrum
4.3	Stohastic wind, irreg. waves, RPM=12.1, Θ_{bl}=17.2deg	Turbine on Semisub	Turbulent (measured, NPD spectrum), no shear, V_{hub} = 13.05m/s	Irregular Airy, H_s = 7.1m, T_p = 12.1s, γ = 2.2, JONSWAP spectrum
4.4	Determin. wind, irreg. waves, RPM=12.1, Θ_{bl}=1.0deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 12.91m/s	Irregular Airy, H_s = 7.1m, T_p = 12.1s, γ = 2.2, JONSWAP spectrum
4.5	White noise wave, Determin. wind, irreg. waves, RPM=12.1, Θ_{bl}=1.0deg	Turbine on Semisub	Steady, uniform, no shear, V_{hub} = 12.91m/s	Banded white noise, H_s = 10.5m, $T_{p,range}$ = 6-26s, γ = 2.2, JONSWAP spectrum

Task 2.2 Modeling by participants

Two modelling approaches have been implemented in HAWC2 with different hydrodynamic modelling. One uses the classical Morison's equation where the wave velocities and accelerations are converted to external forces on the structure, including added mass and drag effects of heave plates, buoyancy forces and influence of flooded water. Wave stretching was also accounted for in the modelling. The other approach is that the HAWC2 code is coupled with WAMIT which is a more advanced panel code (potential flow solver) compared to Morison's formula but with the limitation of not capturing viscus drag force and the assumption that the substructure does not deform.

The method for aerodynamic loads and mooring lines modelling are the same for both approaches. The aerodynamics are captured with a Blade-Element Momentum theory-based model, including corrections such as blade tip losses, the Glauert correction for heavily loaded rotors, the Glauert and Colemann correction to account for induction variations due to non-uniform inflow and the dynamic inflow and dynamic stall effects. The mooring lines are modelled as fully dynamic non-linear beam elements with longitudinal flexibility and no bending stiffness, which can be exposed to hydrodynamic added mass and drag. Further details of the turbine and substructure definition can be found in the published paper of Robertson *et al.* (2017).

Prior to the main validation cases, the numerical models were calibrated to ensure that they accurately represent the as-built properties of the test specimen. Calibration of properties is needed when there is some uncertainty and can be related to the environmental conditions (wind/waves) used to excite the structure as well. For this phase of OC5, it was decided that participants would calibrate their models independently. Independent calibration could potentially lead to differences in the simulation results based on differences in calibration approaches, rather than modelling theories. If uncertainty in the model/conditions of the test is small, it will not have a significant impact; however, it was not enough information in this test campaign to ascertain the levels of uncertainty. This limited our ability to draw conclusions about the reason for differences between the simulations and test measurements. Although model calibration was performed independently, procedures were shared, and so participants largely performed similar calibrations of their models. It is therefore believed that most of the differences between simulated results are caused by the modelling approaches and theories, rather than a direct consequence of calibration.

Task 2.3 Summary report on WP2

Detailed DTU results and comparisons with the other project participants have been published in Robertson *et al.* (2017).

WP3: Fixed-bottom system

Task 3.1 Agreement among participants about the simulation cases

The first part of this phase has covered the verification (code-to-code comparison) of the wind turbine models and then followed the validation where the simulated results were compared with the measured on-site system response data.

Four groups of verification load cases (LCs) of increasing complexity were defined for comparison of results and tracing back potential errors from the implementation of OWT model in different simulation tools. The Tables below (see Tables 7-8) list all the verification LCs of Phase III.

In LC group 1, mass, resulting vertical force, fore-aft and side-to-side overturning moments were examined at the tower bottom (LC 1a), at four jacket legs around the seabed (LC 1b), and at the bottom of four foundation piles (LC 1c). In LC group 2, modal properties were examined for the coupled system consisting of the RNA and the support structure with different boundary conditions. In LC 2a, the RNA and tower were modelled as flexible and 6 Degrees of Freedom (DOFs) were constrained at the tower bottom. In LC 2b, the RNA, tower, TP, and jacket substructure were modelled as flexible and 6 DOFs were constrained at four jacket legs around the seabed. In LC 2c, the entire OWT including its piles was modelled as flexible and participants could model foundation stiffness by the apparent fixity method or alternatively by applying p-y curves along the foundation piles. DTU can apply both methods, however in this study the apparent fixity method was chosen. In LC 2d, the TP and jacket substructure were set as flexible with four jacket legs constrained around the seabed, whereas the tower and the RNA were rigid.

Table 7 Verification load cases - Eigenanalysis, static forces and mass.

Load Case	Analysis Type	Enabled DOFs	Wind Condition
1a	Static forces, mass	Flexible RNA and tower, locked rotor, 6 DOFs constrained at tower bottom	Not applicable
1b	Static forces, mass	Flexible RNA, tower, TP and jacket substructure, locked rotor, 6 DOFs constrained at LAT -29.5m at 4 jacket legs	Not applicable
1c	Static forces, mass	Flexible RNA, tower, TP, jacket substructure and foundation piles, locked rotor, elastic foundation model, 6 DOFs constrained at the bottom of 4 foundation piles	Not applicable
2a	Eigenanalysis	Flexible RNA and tower, 6 DOFs constrained at tower bottom	Not applicable
2b	Eigenanalysis	Flexible RNA, tower, TP and jacket substructure, 6 DOFs constrained at LAT -29.5m at 4 jacket legs	Not applicable
2c	Eigenanalysis	Flexible RNA, tower, TP, jacket substructure and foundation piles, elastic foundation model	Not applicable
2d	Eigenanalysis	Flexible jacket substructure and TP, rigid tower and RNA, 6 DOFs constrained at LAT -29.5m at 4 jacket legs	Not applicable

Table 8 Verification load cases-Power production.

Load Case	Analysis Type	Enabled DOFs	Wind Condition
3.1	Normal power production	Rigid RNA and tower, 6 DOFs constrained at tower bottom, 1 rotational DOF for rotor, 1 rotational DOF for pitch mechanism	Steady wind, changing from Vcut-in=3m/s to Vcut-out=30m/s with step of 1m/s lasting for 50s, T=1400s, no wind shear
3.2a	Normal power production	as in LC 3.1	Stochastic wind, 6 seeds, Vhub=7m/s, σu=1.17m/s, σv=0.94m/s, σw=0.58m/s, T=600s no wind shear
3.2b	Normal power production	as in LC 3.1	Stochastic wind, 6 seeds, Vhub=13 m/s, σu=1.83m/s, σv=1.46m/s, σw=0.92m/s, T=600s, no wind shear
3.2c	Normal power production	as in LC 3.1	Stochastic wind, 6 seeds, Vhub=18m/s, σu=2.44m/s, σv=1.96m/s, σw=1.22m/s, T=600s, no wind shear
3.2d	Normal power production	as in LC 3.1	Stochastic wind, 6 seeds, Vhub=16m/s, σu=2.11m/s, σv=1.69m/s, σw=1.06m/s, T=600s, no wind shear
4.1	Normal power production	Flexible RNA and tower, 6 DOFs constrained at tower bottom	Steady, wind, changing from Vcut-in = 3m/s to Vcut-out = 30m/s with step of 1m/s lasting for 50s, T = 1400s, no wind shear
4.2c	Normal power production	as in LC 4.1	Stochastic wind, 6 seeds, Vhub=18 m/s, σu=2.44m/s, σv=1.96m/s, σw=1.22m/s, T=600s, no wind shear
4.2d	Normal power production	as in LC 4.1	Stochastic wind, 6 seeds, Vhub=16m/s, σu=2.11m/s, σv=1.69m/s, σw=1.06m/s, T=600s, no wind shear

LC groups 3 and 4 were meant for verification of the turbine controller and aerodynamic forces. In LC 3.x group, the RNA and tower are modelled as rigid, whereas in the LC 4.x group as flexible. In LCs 3.1 and 4.1, the stepwise deterministic wind is applied to investigate transient response of the system at all operating wind speeds from Vcut-in of 3m/s to Vcut-out of 30m/s. In LCs 3.2x and LCs 4.2c and wind turbine response and controller performance were analyzed with turbulent wind at different operating wind speeds, below rated, around rated, and above rated, respectively.

In all verification LCs the marine environment was disregarded. This means that features as waves, tides, currents, buoyancy force, marine growth, and flooded elements were not accounted for in the analysis. However, such features were included in the validation part of Phase III. Turbulent wind fields were generated at for LC groups 3.2 and 4.2 based on the specification from IWES. Six independent wind seeds were used, each 10 minutes long, for every single LC in order to get statistically comparable results as recommended in the IEC 61400-1 standard. Different components of the OWT were modelled as flexible or rigid according to the LC type. Environmental loads were applied depending on the definition of the given LC. For each LC, the outputs were recorded at a few nodal points denoted as sensors located at the RNA and the tower. The location of outputs was chosen to capture the global response of the OWT. Simulation code start-up transients were removed by using a pre-simulation and it was chosen individually by each participant in order to avoid initial numerical transients and to satisfy the initial conditions of the given LC. The time step for data output was defined at 0.05s for the international comparison for all LCs, even though the actual simulation time step in HAWC2 was set to a finer value of 0.01s. The Table 9 shows all the validation LCs of Phase III.

Task 3.2 Modeling by participants.

Based on the given data from IWES the numerical model of the Senvion 5MW turbine with the jacket support structure was set up in the simulation tools. Due to intellectual property (IP) the OC5 Phase III participants have access to limited data of the wind turbine (WT) such as the full definition of the controller, detailed structural and aerodynamic properties of the blades. Therefore, the controller and the blades were adapted from a generic turbine model (NREL 5MW RWT) of the same power class that is available in the public domain. Then the models were tuned and verified prior the validation phase.

The verification and tuning were performed against an OWT model implemented in Flex5-Poseidon by the University of Stuttgart—Stuttgart Wind Energy (SWE), and documentation provided by Senvion and OWEC Tower. The OWT model from SWE contains structural and aerodynamic properties of the real blades, and the fully functional controller that could not be disclosed to the OC5 Phase III participants. The SWE model was extensively validated by Kaufer *et al. (2013)* and Muller *et al.* (2016) and it is considered as a reference model for the verification of other numerical models within Phase III. A set of state-of-the-art simulation tools for OWT modelling is represented in Phase III. Table 10 summarizes the simulation capabilities that are important for the OWT model verification. The hydrodynamic capabilities are not listed herein, as the verification part was focused on the structural dynamics, aerodynamics, and the controller of the WT without the jacket substructure.

HAWC2 is used by DTU with the Morison's equation approach for the hydrodynamics where the wave velocities and accelerations are converted to external forces on the structure, including added mass and drag effects of heave plates, buoyancy forces and influence of flooded water. Wave stretching is also accounted for in the modelling.

The full definition of the Senvion 5MW turbine controller including the DLL, which is a standard input parameter to simulation tools, could not be disclosed to the participants due to IP issues. Therefore, the baseline NREL 5MW RWT controller was adapted. Basic control parameters were tuned to match the dynamic behavior of the reference OWT model with the full Senvion 5MW controller, which was available for comparison at SWE. The tuning was focused on two operating regions: (1) the variable speed region for optimal power tracking below the rated wind speed, and (2) the constant power region above the rated wind speed. During this phase the control DLL interface (wrapper) that facilitates the coupling of external bladed style controllers to HAWC2 was updated to be used with the latest HAWC2 version.

The interaction of the jacket sub-structure to the soil was modelled in HAWC2 based on the aparent fixity method. Additionally, the auto-generation of the jacket sub-structures in HAWC2 format based on member properties (multi-member pre-processor) was improved including more tags to automatically assigned in the generated jacket structure.

Table 9 Validation load cases.

Load Case	Analysis Type	Enabled DOFs	Wind and Wave Conditions
1.0	Idling turbine below cut-in	Fully flexible OWT, yaw position 26.8deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North, pitch angle 90deg	Deterministic wind, Dir=270deg wrt True North, Vhub=3.61m/s, Power law wind shear with exponent of 0.14, still water, including marine growth, T=100s
1.1x	Idling turbine below cut-in	Fully flexible OWT, yaw position 26.8deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North, pitch angle 90deg	Deterministic wind, Dir=270deg wrt True North, Vhub=3.61m/s, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=345.8deg wrt True north, Hs=0.89m,Tp=9.88s, including marine growth, six 10min simulations
1.2	Idling turbine below cut-in, RNA rotation	Fully flexible OWT, yaw rate= -0.28deg/s initial yaw position 20deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North, pitch angle 90deg	Deterministic wind, Dir=263.6deg wrt True North, Vhub=3.61m/s, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=344.6deg wrt True north, Hs=0.57m,Tp=10.65s, including marine growth, T=1150s
2.1x	Normal power production	Fully flexible OWT, yaw position 254.9deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North	Turbulent wind, Dir=254.8deg wrt True North, Vhub=7.91m/s, σ_{long}=0.3m/s, σ_{lat}=0.21m/s, σ_{vert}=0.147m/s, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=324.4deg wrt True north, Hs=2.64m,Tp=6.33s, including marine growth, six 10min simulations
2.2x	Normal power production	Fully flexible OWT, yaw position 230.01deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North	Turbulent wind, Dir=218.3deg wrt True North, Vhub=16.57m/s, σ_{long}=0.45m/s, σ_{lat}=0.315m/s, σ_{vert}=0.225m/s, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=260.41deg wrt True north, Hs=1.6m,Tp=6.26s, including marine growth, six 10min simulations
2.3x	Normal power production	Fully flexible OWT, yaw position 244.39deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North	Turbulent wind, Dir=231.6deg wrt True North, Vhub=18.93m/s, σ_{long}=0.33m/s, σ_{lat}=0.0.231m/s, σ_{vert}=0.165m/s, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=272.71deg wrt True north, Hs=1.34m,Tp=5.84s, including marine growth, six 10min simulations
3.1x	Shut down	Fully flexible OWT, yaw position 263deg, jacket sub-structure rotated 30deg anti-clockwise w.r.t. True North	Turbulent wind, Dir=247.4deg wrt True North, Vhub=14.12m/s, σ_{long}=0.56m/s, σ_{lat}=0.7*σ_{long}, σ_{vert}=0.5*σ_{long}, Power law wind shear with exponent of 0.14, Irregular waves (PM spectrum) with dir=284.4deg wrt True north, Hs=1.51m,Tp=6.82s, including marine growth, six 10min simulations

Table 10 Overview of the simulation tools capabilities within phase III.

Tool	Structural (elastic)	Aerodynamics (aero)	Control (servo)
ASHES	FEM, Euler-Bernoulli	BEM + Glauert correction + Prandtl tip and hub loss, DS	DLL, UD
Bladed V4.8	MBS + flexible modally reduced bodies, Timoshenko	BEM + Glauert correction + Prandtl tip and hub loss + skew inflow correction	DLL, UD
DeepLinesWind - V5R2	FEM, Mindlin	BEM + Glauert correction + Prandtl tip and hub loss + skew inflow correction, relaxation of induction factors	DLL
FAST V8	Substructure: FEM + Craig-Bampton, Timoshenko, Turbine: FEM preprocessor + Modal/MBS, Euler-Bernoulli, Blades: FEM, Timoshenko	BEM + Glauert correction + Prandtl tip and root losses + Pitt and Peters skewed wake	DLL, UD
Flex5-Poseidon	FEM + Modal	BEM or GDW + DS	DLL, UD
FloaWDyn	MBS/FEM, Euler-Bernoulli	(Aerodyn module) BEM + Glauert correction + Prandtl tip and root losses	DLL, UD
FOCUS6 Offshore	FEM, Timoshenko	BEM + Wilson and Lissaman correction + Prandtl tip and root losses	DLL, UD
HAWC2	MBS/FEM/stiffness-proportional Rayleigh damping, Timoshenko	BEM with 'Madsen and Larsen' correction for shear and dynamic inflow, Glauert and Coleman modification for skewed inflow and dynamic stall	DLL
NK-UTWind	FEM, Euler-Bernoulli	BEM (AeroDyn14)	DLL
MoWiT	MBS/FEM/modal reduced bodies, Euler-Bernoulli	BEM + Glauert correction + Prandtl tip and hub loss + skew inflow correction, relaxation of induction factors	DLL
SAMCEF Wind Turbines 17.1 (SWT)	FEM/MBS, Timoshenko	BEM + DS + Glauert correction + Prandtl tip and hub loss + dynamic wake + skew inflow + relaxation of induction factors	DLL, UD
SIMA	FEM, Euler-Bernoulli with shear correction	BEM + Glauert correction + Prandtl tip loss + skew inflow correction + Øye correction for dynamic stall and inflow	DLL, UD
Simpack	MBS, modal reduced FEM, Timoshenko	BEM + Glauert correction + Prandtl tip and root losses + Pitt and Peters skewed wake	DLL
SiWEC	MBS/FEM, modal reduced, Euler-Bernoulli	BEM + Glauert correction + Prandtl tip loss + skew inflow correction + Øye correction for dynamic stall	DLL, UD

BEM – blade element momentum
DLL – dynamic-link library
DS – dynamic stall implementation
FEM – finite element method
GDW – generalized dynamic wake
MBS – multibody-dynamics formulation
Modal – modal reduced system
UD – user-defined subroutine

It must be emphasized that due to the differences in blade aerodynamics between the tuned NREL 5-MW blades (utilized in OC5 Phase III) and Senvion 5MW reference turbine model (available for comparison at SWE), it was not possible to obtain a comparable system response at all operating regions of the turbine. Therefore, verification and validation could only be performed at certain ranges of operating wind speeds, as further described in the results. It should be noted that tuning of the NREL blade aerodynamic properties in order to achieve a similar response to the real blade in all operating conditions would be very time consuming, and therefore not feasible within the time frame of Phase III.

In WP3 DHI investigated the usage of a CFD model to simulate wave interaction with a bottom fixed jacket structure. The geometry of a jacket structure from OWEC Tower was made available for the OC5 group, however the provided information was under a strict confidentiality agreement. Due to the limited time available on the project, the work by DHI was focused on a proof-of-concept model setup which should form the basis for interaction with clients regarding further development of such solutions.

The CFD model applied at DHI is the Open Source model OpenFOAM®. DHI has 10 years of experience with this model in terms of applications for consultancy within coastal and marine engineering as well as research and development projects.
The geometry of the jacket structure was prepared in a CAD tool to generate a digital stl-surface of the jacket structure. The computational mesh was generated by automated mesh generation with the snappyHexMesh functionality in OpenFoam which creates a hexahedron based mesh with a small number of tetrahedron elements near the structure to achieve a mesh that conforms to the surface of the jacket structure. Figure 11 presents the computational mesh on the surface of the structure.

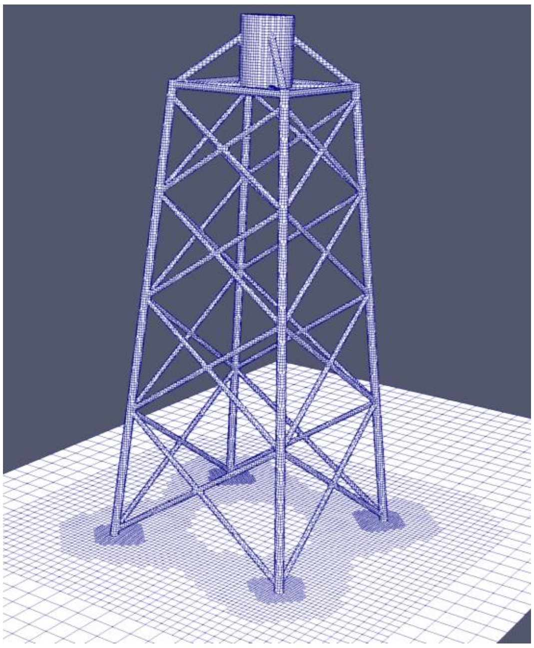

Figure 11 Computational mesh with the jacket structure resolved.

The model was tested with a regular wave based on stream function theory with a wave height of 14*m* and a wave period of 15*s*. The water depth was 26*m*. Figure 12 shows an instantaneus representation of the water surface during a passage of the jacket structure.

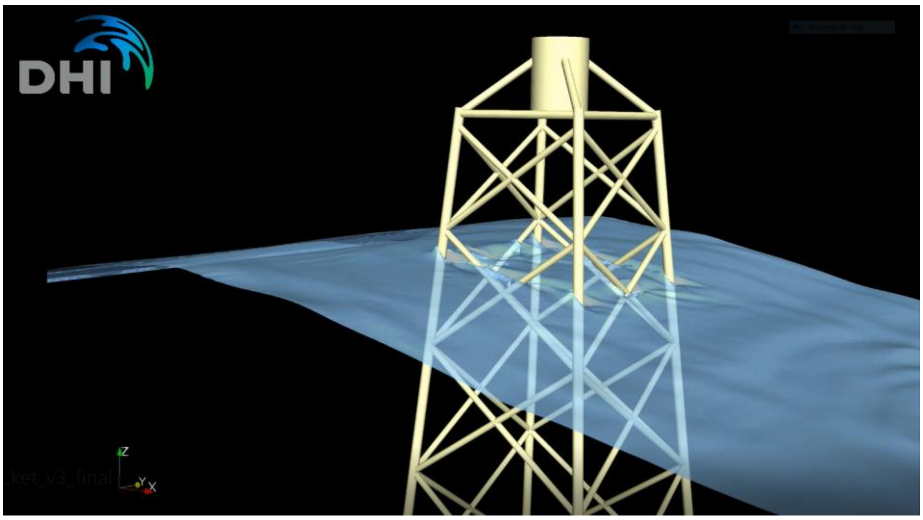

Figure 12 Snap-shoot of the water surface during a wave passage through the jacket structure.

Task 3.3 Summary report on WP3

Simulation results were delivered by the project participants in terms of time series data to Fraunhofer IWES which has the responsibility of post processing for this project phase. LCs with deterministic wind were visually compared in terms of their time series. The results accuracy was checked by the non-dimensional root mean square error (RMSE). The RMSE can be used as a measure of the difference between time series data points, Xt, predicted by every single OC5 Phase III model and the time series data points, XSWE, as obtained from the reference SWE model. These individual differences, at each time step, t, are aggregated by the RMSE into a single value. The RMSE is defined as the square root of the mean squared error divided over the number of the data points, n, in the analyzed time series.

Detailed DTU results and comparisons with other project participants have been published and can be found from Popko W. *et al*., (2018). Furthermore, the detailed results from the validation phase are being finalized and will be presented in a conference during 2019.

Dissemination

At DHI the activities are disseminated internally via code development, technical nores and presentations. Furthermore, the load model was presented externally in Hansen and Kofoed-Hansen (2017) and a paper on the integration between the load model and the MIKE3 Wave FM model is in preperation as Jensen *et al*. (2019).

The obtained knowledge from this project was shared among the participants, the results have been presented and disseminated in the following conferences:

- OC5 Project Phase I: Validation of Hydrodynamic Loading on a Fixed Cylinder, ISOPE conference, June 2015.
- OC5 Project Phase Ib: Validation of Hydrodynamic Loading on a Fixed, Flexible Cylinder for Offshore Wind Applications, 13th EERA DeepWind Conference, January 2016.
- OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semi-submersible Wind Turbine, 14th EERA DeepWind Conference, January 2017.
- Verification of a Numerical Model of the Offshore Wind Turbine from the Alpha Ventus Wind Farm within OC5 Phase III, 37th ASME International Conference on Ocean, Offshore and Arctic Engineering Conference, June 2018.
- A paper based on the validation study of OC5 phase III is being written and will be presented during 2019

An important part of the project is the sharing of knowledge between the participants, which to a large degree has been done through physical meeting during the project. These meetings have been placed in conjunction with important conferences that people planned on attending. The list of meeting is shown below:

Meeting 1: San Francisco, USA, June 13, 2014
Meeting 2: Trondheim, Norway, February 6, 2015
Meeting 3: Hawai, USA, June 26, 2015
Meeting 4: Trondheim, Norway, January 22, 2016
Meeting 5: Rhodes, Greece, July 1, 2016
Meeting 6: Trondheim, Norway, January 20, 2017
Meeting 7: San Francisco, USA, June 30, 2017

Meeting 8: Trondheim, Norway, January 19, 2018
Meeting 9: Madrid, Spain, June 13, 2018

Additionally, **32 times** net-meetings have been carried out during the project, which also contributed to sharing of knowledge between the participants.

During phases I to III of the IEA Annex 30 OC5 project the following people have been involved (in alphabetical order per institution/industry):

- From Denmark:

Anders M. Hansen, Anders Yde, Christos Galinos, Henrik Bredmose, Michael Borg, Taeseong Kim and Torben J. Larsen, Technical University of Denmark, Department of Wind Energy
Bjarne Jensen, Flemming Schlutter, Danish Hydraulic Institute, DHI

- From Europe:

Jean-Baptiste Le Dreff, Electricitie de France, Recherche et Developpement, France
Pauline Bozonnet and Philippe Gilbert, IFP Energies Nouvelles, France
Bertrand Auriac and Ludovic Bouy, Principia, France
Matthias L. Huhn and Wojciech Popko, Fraunhofer Institute for Wind Energy Systems IWES, Germany
Francisco Navarro Vllora, Siemens Gamesa Renewable Energy, Germany
Paul Schuunemann, University of Rostock, Endowed Chair of Wind Energy Technology, Germany
Friedemann Borisade, Kolja Muller and Matthias Kretschmer, University of Stuttgart,
Germany
Fabian Vorpahl, Senvion, Germany
Ilmas Bayati and Marco Belloli, Politecnico di Milano, Department of Mechanical Engineering, Italy
Jacobus Bernardus de Vaal, Luca Oggiano and Tor Anders Nygaard Institute for Energy Technology, Norway
Erin Bachynski, Stian Hegh Srum and Ying Tu, Norwegian University of Science and Technology, Department of Marine Technology, Norway Jacob Qvist, 4Subsea, Norway
Torbjrn Ruud Hagen, OWEC Tower AS, Norway
Paul E. Thomassen, Simis AS, Norway
Emre Uzunoglug and Carlos Guedes Soares, CENTEC, Portugal
Matthieu Guerinel and Yannick Debruyne, WavEC Offshore Renewables, Portugal
Climent Molins, Polytechnic University of Catalonia, Spain
Josean Galvan and Inigo Mendikoa, TECNALIA, Spain
Felipe Vittori and Jos Azcona, National Renewable Energy Centre, CENER, Spain
Carlos Barrera Sanchez and Raul Guanche Garca, Universidad de Cantabria, Spain
Paul Bonnet, Siemens Industry Software, Spain
Koen Hermans, European Centre of the Netherlands, The Netherlands
Sebastien Gueydond, Maritime Research Institute Netherlands, The Netherlands
Tjeerd van der Zee, Knowledge Centre WMC, The Netherlands
Rob Harries, DNV GL, UK

- From US:

Amy Robertson, Jason Jonkman and Fabian Wendt, National Renewable Energy Laboratory, USA
Habib Dagher, University of Maine, USA

- From Asia:

Roger Bergua and Kai Wang, Envision Energy Limited, Shanghai, China
Pengcheng Fu and Jifeng Cai, China General Certification Center, China
Sho Oh and Nippon Kaiji Kyokai, University of Tokyo, Japan
Yoshitaka Totsuka, Wind Energy Institute of Tokyo Inc., Japan
Hyunkyoung Shin, University of Ulsan, School of Naval Architecture and Ocean Engineering, The Republic of Korea

1.6 Utilization of project results

The results from the validation study of the full system with real measurements from the study (phase III) shown that HAWC2 results and real measurements match quite well. This comparison facilitated the identification of areas for further improvement of the code and ensures a useful tool for high fidelity wind system global response and loading prediction.

The wave load modelling tools for monopile foundations (WP1) developed at DHI were focused on a direct need for an engineering, easily applicable, load model to predict extreme loads. The feedbacks that DHI receives from clients are that the traditional methods are not reliable for all cases, and most of all, they do not provide an estimate on the probability of occurrence of the largest extreme slamming events. More accurate methods, such a physical model tests and detailed CFD simulations are often not an option in the first phases of development of a new offshore wind farm, hence the need for an engineering tool that can be applied as a first screening and prediction of extreme events. At DHI this new development is used actively in our marketing and contact with clients and it is expected that the possibility to provide this type of solution will secure new projects.

The initial investigations performed regarding detailed CFD simulations of wave loads on a bottom fixed jacket structures (WP3) at DHI was performed in order to gain some understanding of the feasibility of this type of detailed simulations in an engineering context. At this stage the methodology and models need more validation to be able to provide a confident answer regarding the usage of CFD in consulting project. However, the first simulations performed as part of OC5 showed the potential for this type of simulations. At this stage we use these first simulations in our marketing to make clients aware that this is an area we are developing and that we have a potential solution to offer.

The wave kinematics computations of DTU in WP1 has been extended to further 3 cases of irregular waves and have been used to benchmark a new force model in collaboration with a PhD student from NTNU.

1.7 Project conclusion and perspective

The project fulfilled its main objective which was to assess the ability of the modelling tools to accurately predict real system responses, which was also a need for the offshore wind industry. Additionally, the work provided further de-risking of numerical tools for the design of offshore wind turbines.

Through the OC5 project DTU Wind Energy (WE) and DHI developed and validated their state-of-the art numerical analysis tools which are available to use for Danish Industries to design and analyse the offshore wind turbine both bottom fixed and floating concepts. The main achievements at DTU WE and DHI are summarized in the following:

1. In WP1, DTU's international position in calculation and application of fully nonlinear wave kinematics was re-inforced by sharing numerical results with the full consortium. The response modelling further demonstrated the importance of proper inclusion of nonlinearity in wave- and force-modelling. Generally a good

match was found for the DTU models with fully nonlinear kinematics, although the structural accelerations were in some cases not accurate. This may be linked to in-accurate damping description and also to the load effects of breaking waves.

2. For floating wind turbines, two developed methods (HAWC2-WAMIT and HAWC2-Morison equations) were applied and verified within WP2. Generally, the HAWC2 results are well predicted compared to other numerical and experimental results. Small discrepancies with measurements were identified and they will be investigations in future project such as OC6.

3. During WP3, the tool for generating the data model for jacket foundations was improved, minimizing the manual work that is needed on the modeling. Additionally, the controller coupling within HAWC2 framework was updated.

4. The most important achievement was the full-scale validation of the turbine and the jacket aeroelastic model with measurements from the Alpha Ventus wind farm.

5. DHI developed and explored calculation tools for offshore monopile foundation and bottom fixed jacket foundations as well. The load model reported in Hansen and Kofoed-Hansen (2017) was further developed based on laboratory data and recalibrated on a new data set. With this the model was lifted to a state where it may be applied in consulting projects.

6. The load model was extended to be used with wave kinematics from the fully non-linear wave model MIKE3 Wave FM. This formed the bases for future validation of the integration between the load model and the wave model.

7. The MIKE3 Wave FM model was tested and validated against model experiments from the DHI test facility. This forms the basis for a general validation of the MIKE3 Wave FM models which is needed in order to apply the model for generating input for the load model. Further validation will be performed in future project.

8. The CFD model OpenFoam was setup and applied for simulating wave interaction with a bottom fixed jacket foundation. This was a proof-of-concept at showed that this type of simulation can be a valuable addition to the offerings provided by DHI within offshore engineering. Further validation is needed and will be performed in future projects.

High priority was also given in the dissemination of all WP results which have high value for further research and applications in the area of offshore turbines and support structures. DTU and DHI have taken part in all meetings and journal publications where the state-of-the art research activities were shared, discussed and disseminated. This has helped to maintain the Danish position as part of the leading international network in the offshore wind energy research field.

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Annex

Publication lists

➢ OC5 Project Phase I: Validation of Hydrodynamic Loading on a Fixed Cylinder

Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference
Kona, Big Island, Hawaii, USA, June 21-26, 2015
Copyright © 2015 by the International Society of Offshore and Polar Engineers (ISOPE)
ISBN 978-1-880653-89-0; ISSN 1098-6189

www.isope.org

OC5 Project Phase I: Validation of Hydrodynamic Loading on a Fixed Cylinder

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ABSTRACT

This paper describes work performed during the first half of Phase I of the Offshore Code Comparison Collaboration Continuation, with Correlation project (OC5). OC5 is a project run under the International Energy Agency Wind Research Task 30, and is focused on validating the tools used for modeling offshore wind systems. In this first phase, simulated responses from a variety of offshore wind modeling tools were validated against tank test data of a fixed, suspended cylinder (without a wind turbine) that was tested under regular and irregular wave conditions at MARINTEK. The results from this phase include an examination of different approaches one can use for defining and calibrating hydrodynamic coefficients for a model, and the importance of higher-order wave models in accurately modeling the hydrodynamic loads on offshore substructures.

KEY WORDS: Offshore wind; code comparison; wave harmonics

INTRODUCTION

Offshore wind turbines (OWTs) are designed and analyzed using comprehensive simulation tools (or codes) that account for the coupled dynamics of the wind inflow, aerodynamics, elasticity, and controls of the turbine, along with the incident waves, sea current, hydrodynamics, mooring dynamics, and foundation dynamics of the support structure. The OC3 and OC4 projects (Offshore Code Comparison Collaboration and Offshore Code Comparison Collaboration Continuation), which operated under International Energy Agency (IEA) Wind Tasks 23 and 30, were created to verify the accuracy of OWT modeling tools through code-to-code comparisons. These projects were successful in showing the influence of different modeling approaches on the simulated response of offshore wind systems. Code-to-code comparisons, though, can only identify differences. They do not determine which solution is the most accurate. To address this limitation, an extension of Task 30 was initiated, which is called OC5. This project's objective is validating offshore wind modeling tools through the comparison of simulated responses to physical response data from actual measurements. 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.

The first phase of OC5 is focused on examining the hydrodynamic loads on fixed cylinders. No wind turbine is present in these tests because the purpose is to examine hydrodynamic loads only, before moving on to the complexity of coupled wind/wave loads and dynamic system response. Because this is the first time the group has used measured test data, a simple structure is chosen to ease into the complications involved when using real data. The first phase was also used to develop the model calibration and validation processes that will be used by the group throughout the project. Two different sets of data will be examined in this phase, and this paper focuses on the validation work for the first dataset, which came from MARINTEK.

MODEL AND TEST DESCRIPTION

The first test data examined in Phase I of OC5 were generated in the towing tank at MARINTEK in Trondheim, Norway, during two separate test campaigns (see references to Tests I and II in Marthinsen, 1996; Stansberg, 1995; and Stansberg, 1997 for more information). The tank is 80-m long, 10.5-m wide, and 10-m deep, and is equipped with a hydraulic double-flap longcrested wavemaker at one end. At the opposite end of the tank is a wave-absorbing beach, and the side walls contain wave absorbers. The test specimens were placed 38.6 m from the wave maker, in the middle of the tank width-wise.

The units tested were single steel cylinders with varying diameters. The draft of each was 1.44 m, meaning that the bottom surface of the cylinder is exposed to the water and the upper surface pierces the still water line (SWL). The cylinders were attached to a stiff framework through two force transducers at the SWL and at 0.7 m below (see Fig.

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Available online at www.sciencedirect.com

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Energy Procedia 94 (2016) 82 – 101

Energy Procedia

13th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2016, 20-22 January 2016, Trondheim, Norway

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2016.09.201

➢ OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semi-submersible Wind Turbine

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 137 (2017) 38–57

Energy Procedia

www.elsevier.com/locate/procedia

14th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2017, 18-20 January 2017, Trondheim, Norway

OC5 Project Phase II: Validation of Global Loads of the DeepCwind Floating Semisubmersible Wind Turbine

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10.1016/j.egypro.2017.10.333

➢ Verification Of a Numerical Model of the Offshore Wind Turbine from the Alpha Ventus Wind Farm within OC5 Phase III

Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering
OMAE 2018
June 17–22, 2018, Madrid, Spain

OMAE2018-77589

VERIFICATION OF A NUMERICAL MODEL OF THE OFFSHORE WIND TURBINE FROM THE ALPHA VENTUS WIND FARM WITHIN OC5 PHASE III

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ABSTRACT

The main objective of the Offshore Code Comparison Collaboration Continuation, with Correlation (OC5) project, is validation of aero-hydro-servo-elastic simulation tools for offshore wind turbines (OWTs) through comparison of simulated results to the response data of physical systems. Phase III of the OC5 project analyzes the Senvion 5M wind turbine supported by the OWEC Quattropod from the alpha ventus offshore wind farm. This paper shows results of the verification of the OWT models (code-to-code comparison). A subsequent publication will focus on their validation (comparison of simulated results to measured physical system response data). Based on the available data, the participants of Phase III set up numerical models of the OWT in their simulation tools. It was necessary to verify and to tune these models. The verification and tuning were performed against an OWT model available at the University of Stuttgart – Stuttgart Wind Energy (SWE) and documentation provided by Senvion and OWEC Tower. A very good match was achieved between the results from the reference SWE model and models set up by OC5 Phase III participants.

INTRODUCTION

The Offshore Code Comparison Collaboration Continuation, with Correlation (OC5) project [1], which operates under the International Energy Agency (IEA) Wind Task 30 is the follow-up project of OC3 and OC4, which ran from 2005 to 2009