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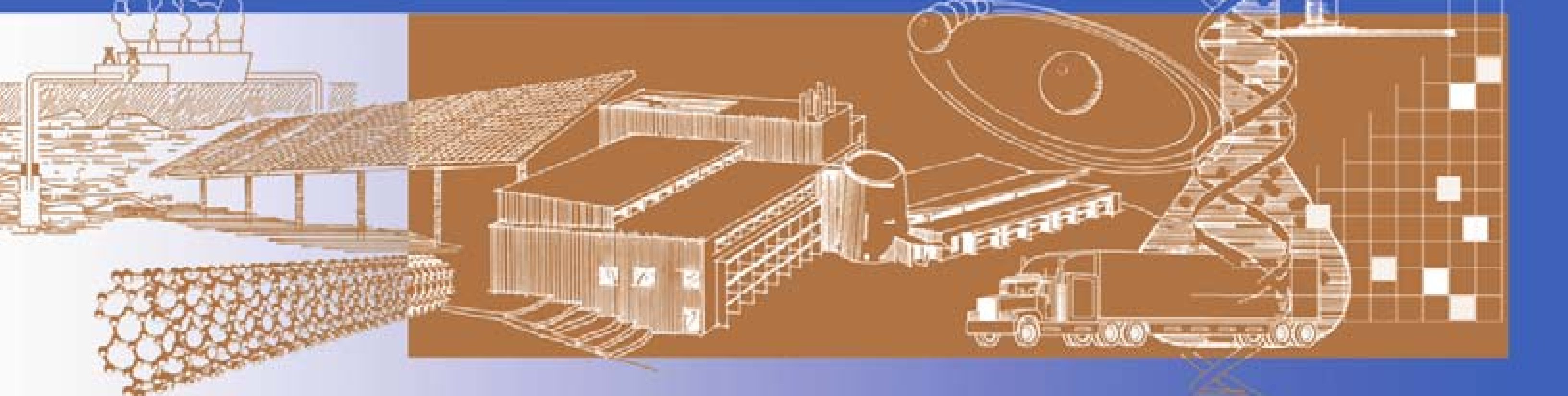

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OC3–Benchmark Exercise of Aero-elastic Offshore Wind Turbine Codes

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Abstract This paper introduces the work content and status of the first international investigation and verification of aero-elastic codes for offshore wind turbines as performed by the "Offshore Code Comparison Collaboration"(OC3) within the "IEA Wind Annex XXIII – Subtask 2". An overview is given on the state-of-the-art of the concerned offshore wind turbine simulation codes. Exemplary results of benchmark simulations from the first phase of the project are presented and discussed while subsequent phases are introduced. Furthermore, the paper discusses areas where differences between the codes have been identified and the sources of those differences, such as the differing theories implemented into the individual codes. Finally, further research and code development needs are presented based on the latest findings from the current state of the project.

1. Introduction

Offshore wind energy has a large potential to play a significant role in meeting worldwide energy needs. International development plans for offshore wind energy aim to utilize a large variety of sites all over the world, which require the application of different types of bottom-mounted and floating support structures due to the large variability in water depths and environmental conditions.
In this context, the offshore wind energy community has to face many new challenges e.g. connected to the development of cost-efficient support structures of different types. The design of such cost-efficient support structures strongly depends on a proper prediction of fatigue and extreme loads, which are only possible with aero-elastic simulation codes that can account for the dynamic behaviour of the entire system under simultaneous aerodynamic and hydrodynamic loading.

1.1. OC3 Project - Motivation and Objectives

Today only a small number of codes exist for aero-elastic simulation of the dynamic behaviour and loads of offshore wind turbines. Furthermore, those codes have certain development and verification needs, especially when addressing support structures different than the monopile or gravity base. To date, only a few of such innovative structures have been designed and installed for offshore wind turbines. Therefore, no measurements and only limited practical experiences are available. These shortcomings require a verification and investigation of the available codes by a benchmark test. The "IEA Wind Annex XXIII – Subtask 2", under the coordination of the National Renewable Energy Laboratory (NREL), addresses these important aspects with the "Offshore Code Comparison Collaboration"(OC3) [1], which is scheduled for a period of 3.5 years and started in 2005.
In accordance to the short-term to long-term requirements for the further development of offshore wind energy worldwide, the following project objectives have been formulated by the partners:

- Establishment of a suite of benchmark simulations to test new codes and train new analysts
- Identification and verification of code capabilities and limitations of implemented theories
- Investigation and refinement of applied analysis methodologies
- Investigation on the accuracy and reliability of results obtained by simulations to establish confidence in the predictive capabilities of the codes
- Identification of further research and development needs

These objectives are achieved by a sophisticated approach investigating different types of bottom-mounted and floating support structures. Although the emphasis of the benchmark exercise is put on the support structure, various issues, important to the overall dynamics of offshore wind turbines, the turbulent inflow and the aero-elastic behaviour are investigated in the course of the project.

1.2. Project Partners

The group consists of participants from research bodies, universities and the industry, including the National Renewable Energy Laboratory (NREL) (USA), the Endowed Chair of Wind Energy of the Universität Stuttgart (D), Garrad Hassan (UK), Risø National Laboratory (DK), DONG energy (DK), Vestas A/S (DK), Det Norske Veritas (DK), Siemens Wind Power A/S (DK) and the National Renewable Energies Center (CENER) (ESP). Each partner brings specific expertise from different fields related to offshore wind energy. Furthermore, many new participants from different countries, e.g. Norway, South Korea, Ireland and Spain, have been motivated to enter the project within the last two years due to the successful and productive cooperation of the group.

1.3. Aero-elastic Codes within the Project

Almost all of the existing simulation codes for offshore wind turbines are included in the project. In particular, the codes investigated within the project are: GH Bladed, FAST, ADAMS, HAWC, HAWC2, BHAWC and different versions of Flex5.

Table 1. Overview of selected modelling capabilities and characteristics of the aero-elastic codes within OC3

Offshore environment	**GH Bladed**	**HAWC**	**HAWC2**	**BHAWC**	**FAST**	**ADAMS**	**Flex5 (Vestas A/S)**	**Flex5 (DONG)**	**Flex5 (SWE)**
Deterministic waves	Airy$^+$, Stream	Airy, UD	UD	Airy$^+$, Stream	Airy$^+$	Airy$^+$	Airy$^+$, Stream	Airy$^+$, Stream	Airy$^+$, Stream
Stochastic waves	PM, UD, JONSWAP, Airy$^+$, CNW	PM, UD	UD	JONSWAP, Airy$^+$	PM, UD, JONSWAP, Airy$^+$	PM, UD, JONSWAP, Airy$^+$	PM, UD, JONSWAP, Airy$^+$	PM, UD, JONSWAP, Airy$^+$	PM, UD, JONSWAP, Airy$^+$
Hydrodynamic load calculation	ME^{1,2,3}	ME^{2,3,7}	ME^{1,2,3}	ME^{1,2,3,4}	ME^{1,2,3,} PFT	ME^{1,2,3}, PFT	ME^{1,2,3,4}	ME^{1,2,3,4}	ME^{1,2,3,4}
Structural modelling									
Analysis method	Modal, FEM	FEM	MBS, FEM	FEM^1	Modal, MBS^1	MBS	Modal, FEM	Modal, FEM	Modal, FEM
Tower & sub-structure types	MT, MP, SF, GBS, FL	MT	MT, FL, SF	MT, MP, GBS	MPI (MT, MP, GBS), FL	MT, MP, SF, GBS, FL	MT, MP,GBS,FL	MT, MP,GBS, SF	MT, MP, GBS
Foundation types	MP,GBS,GP, SC	MP, GBS, GP	MP, GBS, GP	MP, GBS	MPI (MP, GB, GBS), UD	MP, GBS, GP, UD	MP, GBS, GP,UD	MP, GBS, GP,UD	MT, GBS
Foundation models	AF, DS^{1,2,3,4,5,6}	AF	AF, DS^{1,2,3,5,6}	AF, DS^{1,2,6}	AF, DS^{1,2,3,4,5,6}, UD	AF, DS^{1,2,3,4,5,6}, UD	AF, DS^{1,3,6}, UD	AF, DS^{1,3,6}, UD	AF
Rotor aero-dynamics									
Loading	BEM, GDW	BEM, GDW	BEM, GDW	BEM	BEM, GDW	BEM, GDW	BEM	BEM	BEM

PM - *Pierson-Moskowitz*
UD - *user defined*
Airy$^+$ - *modification for free surface effects, e.g. Wheeler-stretching*
CNW- *Constrained NewWave with Streamfunction*
PFT – *potential flow theory, taking into account diffraction and radiation*

ME$^{1,...,n}$ - *Morison equation for calculation of*
1) relative kinematics
2) drag and inertia
3) added mass
4) slam
5) slap
6) breaking wave impact
7) MacCamy-Fuchs correction for diffraction

SS - *support structure*
RNA - *rotor-nacelle assembly*
MT - *mono-tower*
FL - *floating structures*
SF - *arbitrary space frame structures, e.g. jackets*

MP - *monopile*
GBS - *gravity base structure*
SC - *suction caisson*
GP - *general pile (axially and laterally loaded)*
MPI - *user input of modal properties or system matrices*

DS$^{1,...,n}$ - *discrete springs*
1) lateral (translational)
2) axial (translational)
3) rotational
4) distributed (Winkler-springs)
5) coupled
6) non-linear, e.g. (p-y, t-z-curves)
AF - *apparent fixity length i.e. cantilever beam*

BEM – *Blade Element Momentum Theory*
GDW – *Generalized dynamic wake*

FEM - *finite elements*
1) geometric non-linear by use of a co-rotational formulation
MBS - *multi-body-system*
1) combined modal and multi-body dynamics formulation

Table 1 provides a brief overview of certain characteristics and features of the codes in their current versions. However, further developments and improvements of the codes within the course of the OC3-project are intended by the partners.

2. Project Phases and Approach for the Benchmark Exercise

Emphasis within the benchmark exercise is put on the verification of support structures as a part of the aero-elastic system. Therefore, a representative selection of four different support structures as indicated in figure 1 is investigated within OC3.

In the first phase, a reference configuration, using a monopile with a rigid foundation in 20 m water depth, is established for calibration of the codes and model parameters of the turbine and control system. Calibrations in this reference phase are important since especially the same turbine model and controller are used in all subsequent phases. The second phase investigates a monopile with a flexible foundation applying different linear and non-linear models for the pile-soil-interactions. The same environmental conditions, as defined for Phase I, are also applied for Phase II. A tripod configuration in 45 m water depth, representing a braced support structure concept, is the subject of investigation in the third phase while the fourth phase is devoted to a floating type configuration. However, the aero-elastic behaviour of the overall system with influences from the controller is considered by application of a representative variable speed, pitch-controlled 5-MW turbine from NREL, whose characteristics are similar to the REpower 5M turbine [2]. The main turbine characteristics are described in table 2. For a more detailed description the reader is referred to Jonkman [3].

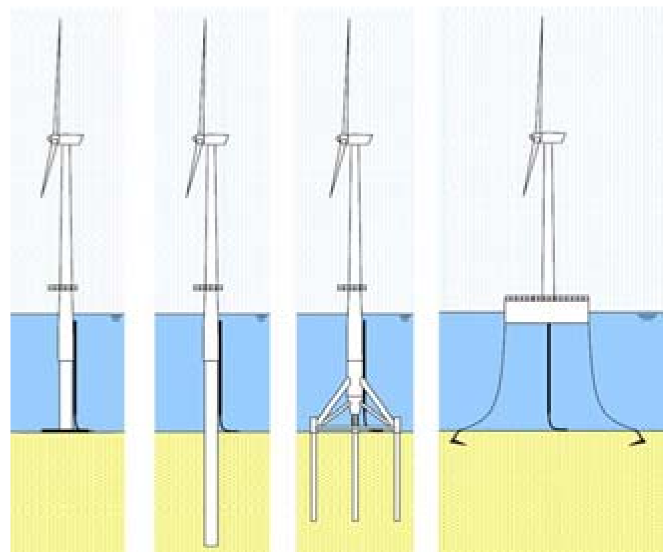


Figure 1. Support structure concepts investigated within the OC3 project [4]

Models for operating offshore wind turbines under stochastic aerodynamic and hydrodynamic loading are very complex. The benchmark task therefore requires a sophisticated approach that allows for the identification of sources of differences, which is possible only with a stepwise verification procedure.

Within the course of OC3, this is achieved by the comparison of a number of sensors in the time domain and the frequency domain for different load cases. Furthermore, a variety of deterministic and stochastic external conditions are applied for each phase. The complexity of the aerodynamic, hydrodynamic and structural models, as well as interactions between them, is increased stepwise between the load cases. Such an approach allows for a qualitative and quantitative identification of sources of discrepancies, introduced by particular models and methods implemented in the individual codes.

Table 2. Characteristics of the reference turbine

Rated power	5000	kW
Rotor diameter	126	m
Drivetrain	High Speed, Multiple Stage Gearbox	
Control	Variable Speed, Collective Pitch, Active Yaw	
Rated wind speed	11.4	m/s
Cut-in, rated speed	6.9 -12.1	rpm
Mass of Rotor-Nacelle-Assembly	350	t

The partners agreed that the aerodynamic and hydrodynamic load calculations should be based on identical wind and wave kinematics in order to eliminate a significant source of differences introduced e.g. from different turbulence models, wave theories for non-linear deterministic waves as well as from different realizations of the turbulence fields and stochastic sea states. For this reason, both the wave kinematics as well as the turbulent wind field were established a priori and provided to all partners. Furthermore, the same controller is used for all codes. This controller has been provided by NREL as a dynamic link library.

Investigations on the reference configuration in Phase I of the OC3 project have been completed. Phase III, dealing with the tripod configuration, has been initiated while Phase II with the flexible monopile foundation is almost finished. The next chapter provides further details on the wind and wave fields applied in Phase I as well as simulation results of this phase.

3. Load Cases and Results of the First Project Phase

In Phase I a set of 16 load cases has been defined for the offshore wind turbine with monopile substructure and rigid foundation in 20 m water depth. For each load case, a total of 47 sensors, as indicated in figure 2, are analysed. The analyses of the sensors are performed in the time domain for the deterministic load cases and in the frequency domain as well as on basis of statistical parameters and damage equivalent loads for the stochastic load cases. Furthermore, the modal properties in terms of the coupled subsystem eigenfrequencies are analysed.

The individual subsystems are modelled flexible or rigid dependent on the actual load case. In addition, the environmental conditions in terms of the wind and wave field are varied.

By this approach the offshore wind turbine model is reduced to the following configurations, which allowed for identification of model-dependent differences in the simulation results:

- Completely rigid structure
- Flexible onshore wind turbine (rigid substructure)
- Flexible offshore structure with tower top mass (rigid nacelle and rotor)
- Fully flexible offshore wind turbine

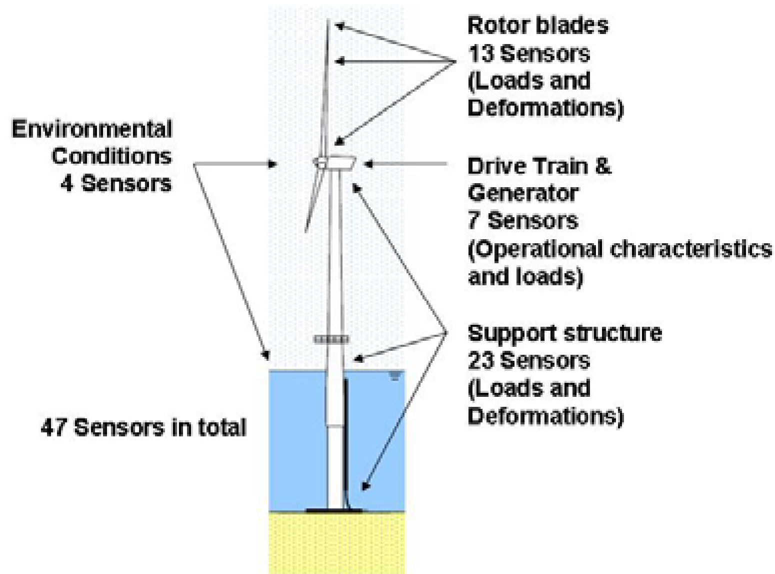


Figure 2. Selected sensors for Phase I simulations

All relevant aerodynamic and hydrodynamic effects, e.g. turbulence, tower shadow, dynamic stall, wind shear and Wheeler stretching are included in the load cases of Phase I and will be included in investigations of subsequent phases as well. Table 3 provides an overview on the analysed load cases in Phase I. Furthermore, the modal properties in terms of the coupled subsystem eigenfrequencies have been investigated within the load case set 1.x.

Table 3. Summary of load cases and environmental conditions for Phase I

Load Case	Flexible subsystems	Wind conditions	Wave conditions
2.1a	None[2]	V_{hub} = 8m/s: Steady, uniform	None: $\rho_{water} = 0$
2.1b	None		
2.2	None	V_{hub} = 11.4m/s, I_{ref} = 0.14	None: $\rho_{water} = 0$
2.3	None	V_{hub} = 18m/s, I_{ref} = 0.14	None: $\rho_{water} = 0$
2.4	None	None: $\rho_{air} = 0$	Regular Airy, H = 6m, T = 10s
2.5	None	None: $\rho_{air} = 0$	Irregular Airy, H_s = 6m, T_p = 10s
2.6	None	None: $\rho_{air} = 0$	Stream Function, H = 6m, T = 10s
3.1	Tower, drivetrain, blades	V_{hub} = 8m/s: Steady, uniform	None: $\rho_{water} = 0$
3.2	Tower, drivetrain, blades	V_{hub} = 11.4m/s, I_{ref} = 0.14	None: $\rho_{water} = 0$
3.3	Tower, drivetrain, blades	V_{hub} = 18m/s, I_{ref} = 0.14	None: $\rho_{water} = 0$
4.1	Substructure, tower	None: $\rho_{air} = 0$	Regular Airy, H = 6m, T = 10s
4.2	Substructure, tower	None: $\rho_{air} = 0$	Irregular Airy, H_s = 6m, T_p = 10s
4.3	Substructure, tower	None: $\rho_{air} = 0$	Stream Function, H = 6m, T = 10s
5.1	All[1]	V_{hub} = 8m/s: Steady, uniform	Regular Airy, H = 6m, T = 10s
5.2	All[1]	V_{hub} = 11.4m/s, I_{ref} = 0.14	Irregular Airy, H_s = 6m, T_p = 10s
5.3	All[1]	V_{hub} = 18m/s, I_{ref} = 0.14	Irregular Airy, H_s = 6m, T_p = 10s

[1] The subsystems included in the offshore wind turbine model are the substructure, tower, drivetrain & blades
The support structure consists of the foundation, substructure and tower. The foundation in Phase I is rigid.
[2] Constant rotor speed & fixed blade pitch

3.1. Implementation of the turbulent wind field

Turbulent wind conditions are considered for a number of load cases using two sets of turbulent wind fields. These turbulence fields were created with the IEC Turbulence Simulator from the WAsP Engineering model [5], one at V_{hub} = 11.4 m/s, i.e. rated wind speed, and one at V_{hub} = 18 m/s, i.e. in the full load range of the turbine. Both turbulence fields are created with the Mann model [6] in conformity with IEC61400-1 ed.3 using a reference value of I_{ref} = 0.14 for the turbulence intensity. Both wind field sets needed to be defined in a rectangular grid as well as in a polar grid due to requirements within the different codes.

The fields consist of 8192 longitudinal planes of cross-sectional grids consisting of 32x32 points for the rectangular format and 16x64+1 point for the polar format. The turbulence fields were established in the rectangular grid first and subsequently interpolated into the polar grid to ensure that the same wind fields are used in the simulations of all codes. However, certain differences between the turbulence fields in the rectangular and polar grid are introduced by the interpolation. Also, the codes requiring the use of a polar grid employ two interpolations (one to create the polar grid and one to interpolate within grid) and exhibit smoother characteristics than the codes using the rectangular grid, which only invoke one interpolation (to interpolate within the grid). This issue was investigated by Thomsen [7] on the basis of simulations with the HAWC2 code applied to a rigid structure with fixed rotor speed and pitch angle and a mean wind speed of 11 m/s at hub height. This approach introduces no differences from the dynamics and controller. Thomsen quantified the differences on the basis of time histories and spectra, e.g. for the relative velocity and angle of attack on a fixed position of one rotor blade, i.e. radial position at 48 m from the hub centre.

Extracted parts from resulting time histories are given in figure 3 for the inflow velocity as well as for the angle of attack. The pictures clearly show that the turbulences in the polar grid become smoother by the interpolation, affecting the aerodynamic inflow conditions at the rotor blades.

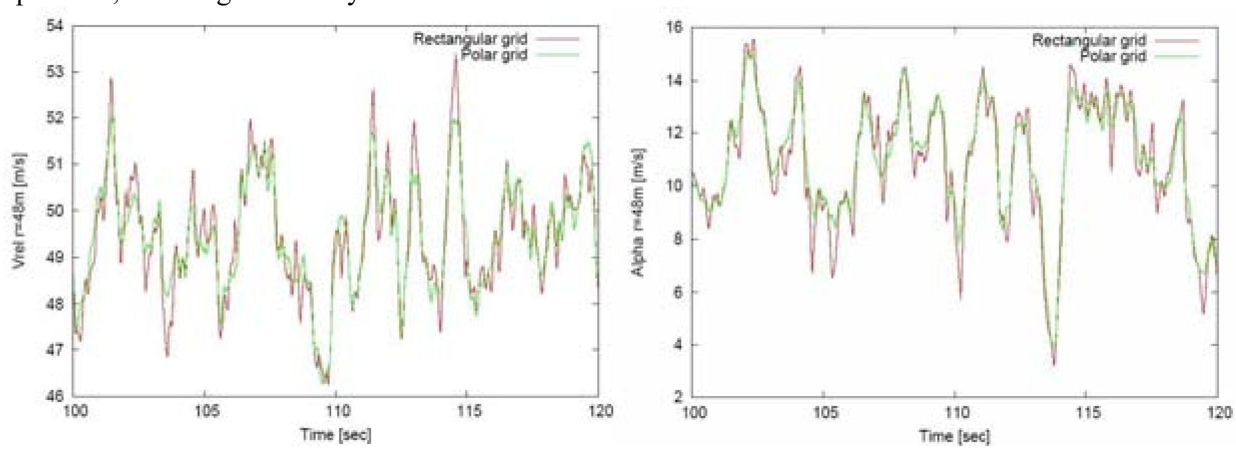


Figure 3. Time history for the inflow velocity (left) and the angle of attack (right) of blade 1 at a radial position of 48 m from the hub centre

Table 4 compares the relation of damage-equivalent loads of a rotor blade and the tower obtained for the rectangular and polar grid simulations. While differences of 2-4% occur for a rotor blade, a difference of more than 10% is introduced for the tower. This must be kept in mind when comparing the results from the codes that use rectangular wind field grids to results from codes that use polar wind field grid codes. The smoothing effect of the two interpolations is even larger with a more coarse resolution of the grids.

Table 4. Relation of damage equivalent loads (Rectangular/Polar)

Flapwise blade root moment (m=12)	1.04
Edgewise blade root moment (m=12)	1.02
Tower bottom fore-aft moment (m=4)	1.11

3.2. Implementation of the Incident Waves

Wave kinematics for the deterministic and the stochastic wave conditions of Phase I have been derived with the standard wave generator from GH Bladed and used by all partners for wave load calculations.

In total, the water particle velocities as well as accelerations are provided with time step sizes of 0.1 s for all three spatial directions for 42 nodes along the monopile with closer nodal spacing in the sea surface elevation range.

The following waves are included in Phase I simulations of OC3:

- Linear, regular wave based on Airy theory with Wheeler stretching
  H = 6 m (wave height), T = 10 s (wave period)
- Non-linear, regular wave based on stream function theory according to Chaplin [8]
  H = 6 m (wave height), T = 10 s (wave period)
- Linear, irregular wave based on composition of Airy waves with Wheeler stretching
  H_s = 6 m (significant wave height), T_p = 10 s (peak spectral period)

Irregular waves are representations of certain sea state conditions that are modelled on the basis of spectra for sea surface elevations. Such spectra provide information on the energy contents in dependence of the wave frequencies, i.e. inverse wave periods, of the single wave trains included in the sea state. Commonly, either the Pierson-Moskowitz spectrum for fully developed sea states or the JONSWAP spectrum for developing sea states is used. As shown in figure 4, Pierson-Moskowitz spectra show a less pronounced peak at the peak frequency $f_p=1/T_p$, but larger energy contents in the frequency ranges that are approx. 10-15% higher or lower than the peak frequency. Support structures with natural frequencies outside the peak frequency of the particular sea state therefore experience larger hydrodynamic excitations from fully developed sea states compared to the developing sea state situation. Certain hydrodynamic excitations of the support structure are desired within the course of OC3, since one of the main objectives addresses the verification of the coupled aerodynamics, hydrodynamics and structural dynamics of the simulation codes.
The support structure configuration applied for Phase I has a first eigenfrequency in the range of 0.28 Hz while the support structure configuration with the flexible foundation of Phase II has an even lower natural frequency of approx. 0.25 Hz. Figure 4 shows the Pierson-Moskowitz spectrum and the JONSWAP spectrum for a peakedness factor of γ = 3.3 based on the expression by Goda [9] for the irregular wave as well as the 1st eigenfrequencies of the support structure configurations applied for phase I and II.
The main energy contents of both spectra are rather low in the range of the 1st support structure eigenfrequencies, especially for the Phase I configuration. Relative to the JONSWAP spectrum however, the Pierson-Moskowitz spectrum shows approximately 50% larger energy contents in the frequency range relevant for dynamic amplification effects of the wave response and was therefore selected for the Phase I and II investigations of OC3. As a result, the desired dynamic amplification effects could be observed in the initial simulations for Phase II.

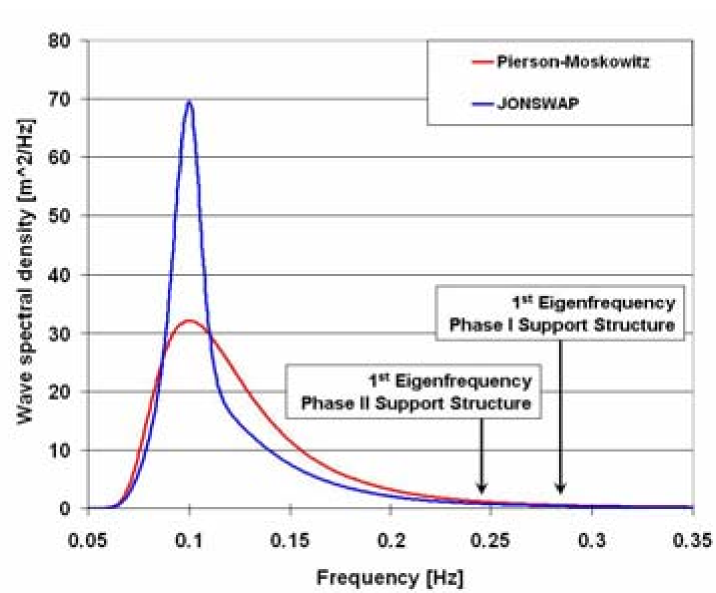


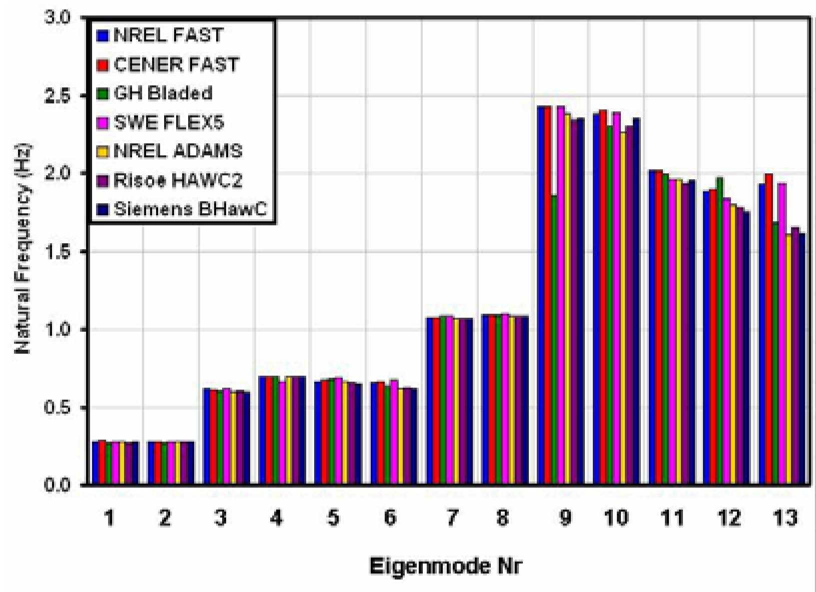
Figure 4. Pierson-Moskowitz & JONSWAP spectra

3.3. Exemplary Results of Phase I

This section provides a brief summary of the status and results of the investigations on the reference configurations of Phase I. Final Flex5 results from DONG and VESTAS as well as final HAWC results from Risø and DNV were not available at the time of writing. However, the missing results are expected to be available soon.

In general, the results from the different simulation codes compare very well. However, this was only achieved within a process that included adjustments to codes, modifications to the implementation of the controller interface and corrections of misinterpreted turbine data specifications and sign conventions. The results provided here are taken from the fifth revision of simulations and are given as coupled eigenfrequencies of the main subsystems, time histories for the deterministic load cases and power spectra for the stochastic load cases.

Figure 5 gives the coupled eigenfrequencies of the main subsystems as calculated by the different codes. The figure shows that the 1st eigenfrequencies of the subsystems compare very well for all codes; significant differences occur only for the 2nd flapwise eigenfrequencies of the blades in the asymmetric modes as well as for the 2nd fore-aft eigenfrequency of the support structure. For the most part, the modal-based codes (FAST, Bladed, FLEX5) predict higher natural frequencies than the multibody- and FEM-based codes (ADAMS, HAWC2, BHawC) for the 2nd blade asymmetric flapwise eigenfrequencies. Certain differences can therefore be expected in the higher frequency range from the results of the different codes. Furthermore, the 2nd fore-aft mode of the support structure is in fact coupled with a flapwise blade mode. A differing 2nd tower fore-aft eigenfrequency is obtained by Bladed compared to the other codes, because the 2nd fore-aft mode is coupled to a different flapwise blade mode. However, both types of these 2nd tower fore-aft modes could be reproduced by ANSYS as well as ADAMS. Garrad Hassan (GH) is currently investigating why Bladed identifies a different 2nd tower fore-aft mode compared to the other codes.



Nr	Full System Eigenmode	Comments
1	1st Tower Fore-Aft	
2	1st Tower Side-to-Side	
3	1st Drivetrain Torsion	High-speed shaft locked by brake
4	1st Blade Collective Flap	All blades in-phase
5	1st Blade Asymmetric Flap 1	Blades 2 & 3 in-phase, blade 1 out-of-phase
6	1st Blade Asymmetric Flap 2	Blades 2 & 3 out-of-phase, blade 1 stationary
7	1st Blade Asymmetric Edge 1	Blades 2 & 3 out-of-phase, blade 1 stationary
8	1st Blade Asymmetric Edge 2	Blades 2 & 3 in-phase, blade 1 out-of-phase
9	2nd Tower Fore-Aft	
10	2nd Tower Side-to-Side	
11	2nd Blade Collective Flap	All blades in-phase
12	2nd Blade Asymmetric Flapwise 1	Blades 2 & 3 in-phase, blade 1 out-of-phase
13	2nd Blade Asymmetric Flapwise 2	Blades 2 & 3 out-of-phase, blade 1 stationary

Figure 5. Coupled eigenfrequencies of the main subsystems obtained from the individual codes

Initial transients are present in the first 30 *s* of most dynamic simulations. These transients have *mostly* been excluded from the results. Therefore, the first 30 *s* of the 90 *s* simulations for the deterministic load cases as well as the first 30 s of the 630 s simulations involving stochastic conditions have been eliminated.

Figures 6 and 7 show the results for the blade loads and the rotor torque from load case 2.1a, i.e. for rigid subsystems and fixed rotor speed and pitch angle. The simulation time of 0 s represents the end of the 30-s start-up transient. This load case is mainly intended to compare the aerodynamic loads as calculated by the individual codes. No hydrodynamic loads are included while a constant wind speed of 8 m/s, i.e. well below rated, and a constant rotor rotation of 9 rpm is applied. The figures show very well that certain differences are apparent in the aerodynamic blade load calculations. This is due to the variety of aerodynamic models and corrections that are implemented into the individual codes, as partially indicated by table 1. The differences in the mean magnitude of rotor torque in figure 7 for example are in the order of 5%. The oscillating behaviour is the result of gravity, shaft tilt and tower shadow influence. The “spikes” in the ADAMS rotor torque output are the result of numerical problems in the way the code enforces the rigid system constraints. In practice, these would need to be filtered out.

Similar trends, with the same quantitative order of 5%, can be observed in the results from load case 2.1b, which differs from 2.1a by the consideration of the controller, i.e. variable rotor speed and pitch angle. Figure 8 presents comparisons of the results for the rotor torque and the thrust force at yaw bearing level.

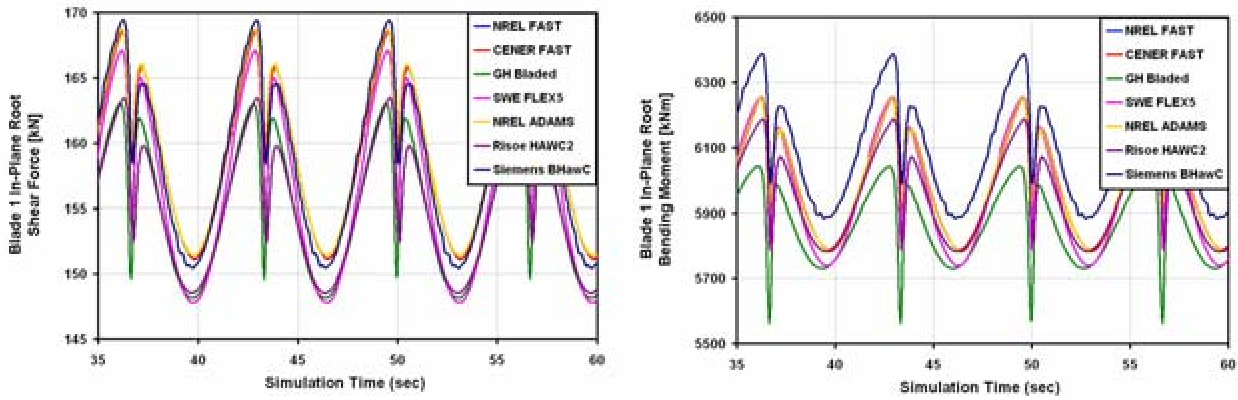


Figure 6. Time series of blade 1 out-of-plane shear force (left) and bending moment (right) at the root for load case 2.1a

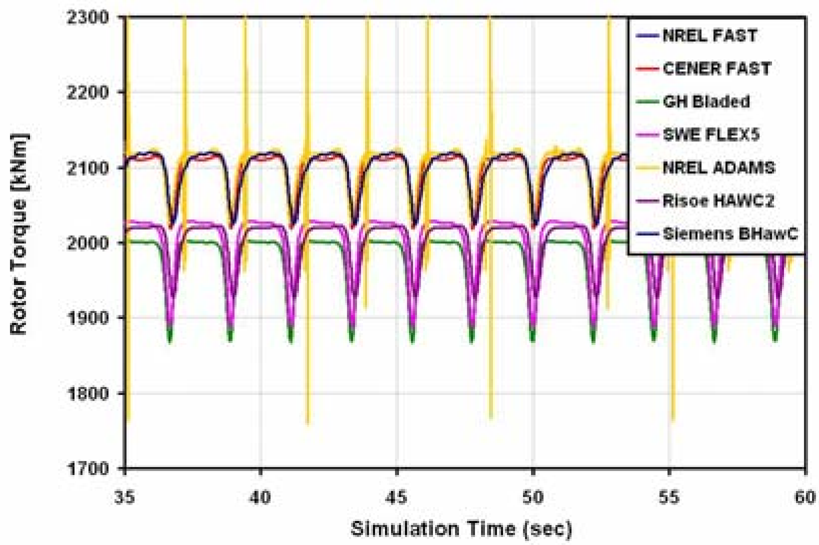


Figure 7. Time series of the rotor torque for load case 2.1a

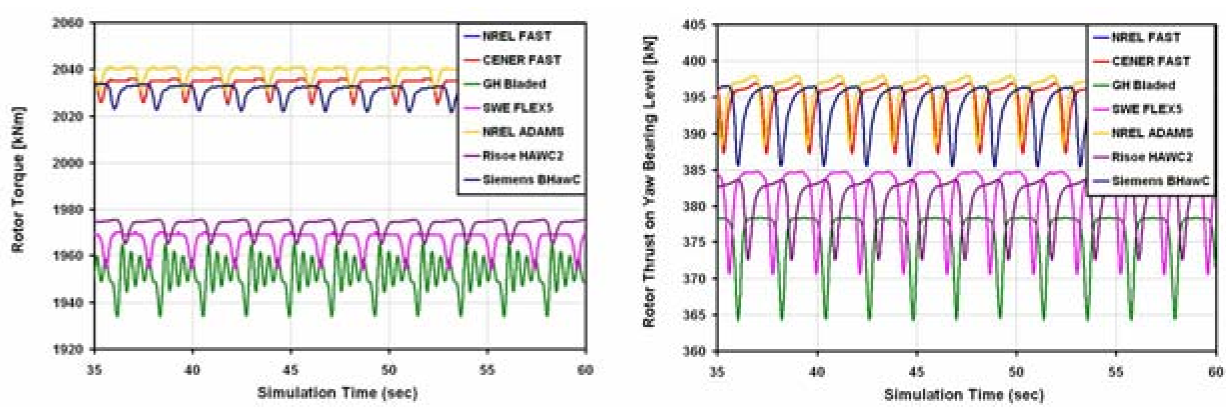


Figure 8. Time series of rotor torque (left) and thrust force on yaw bearing level (right) for load case 2.1b

Load case set 3.x deals with a flexible structure under wind conditions only, i.e. an onshore wind turbine. Both, deterministic as well as stochastic wind fields are included. The results from the different codes generally compare very well, especially for the stochastic load case 3.2, i.e. at rated wind speed, and 3.3, i.e. well above rated wind speed. Here, differences caused by aerodynamic blade load calculations are somewhat compensated by the pitch controller. It should also be noted that some codes (ADAMS, HAWC2 and BHawC) include the torsional flexibility of the blades whereas the other codes neglect this flexibility. Tip rotations up to 4 degree were seen in some of the simulations. Larger differences occur particularly for the in-plane blade loads and deflections. This is shown for load case 3.2 in figures 9 and 10 for the out-of-plane and in-plane root bending moments and tip deflections. The aforementioned differences for the in-plane blade loads and deflections can be observed very well in the figures. However, the results still compare very well in the frequency range of

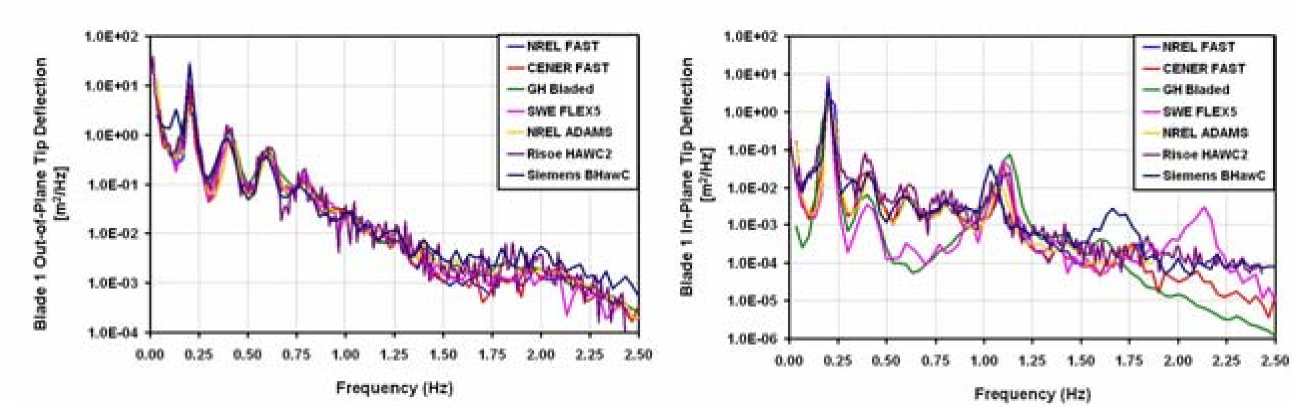


Figure 9. Power spectra of out-of-plane (left) and in-plane (right) tip deflections of blade 1 for load case 3.2

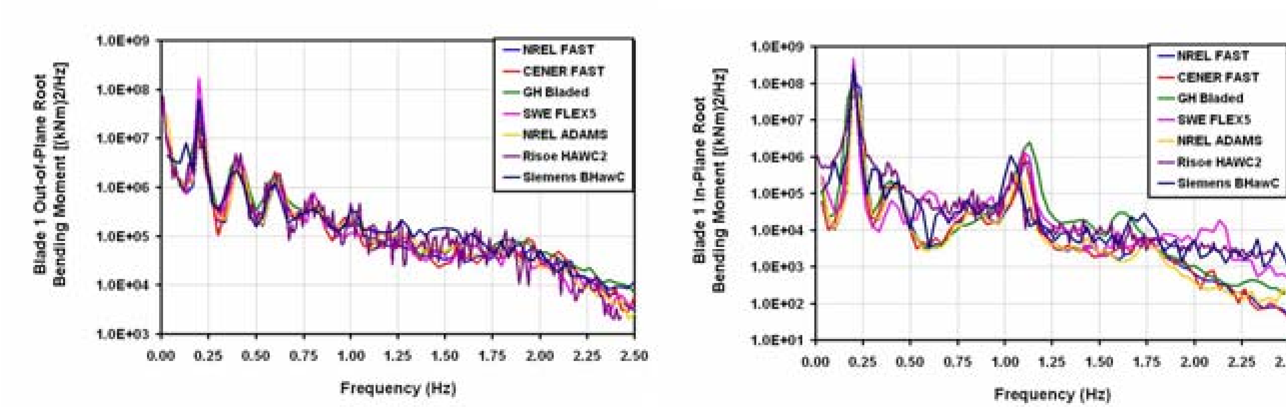


Figure 10. Power spectra of out-of-plane (left) and in-plane (right) root bending moment of blade 1 for load case 3.2

high energy contents, i.e. at approx. 0.2 Hz (1p), as well as in the frequency range of approx. 1 Hz, i.e. the 1st edgewise blade eigenfrequency[1]. The out-of-plane results on the other hand compare very well for the individual codes.

Results for the 4.x load set, i.e. the flexible offshore structure with no wind data and a rigid nacelle-rotor-assembly also compare very well. Significant differences occur only in the frequency ranges well above the excitation frequency range where the responses show low energy contents. Figure 11 shows the base shear and overturning moment as representative sensors for the deterministic load case 4.3, which uses the non-linear, regular wave. Very small differences can be observed for the overturning moment while the base shear is almost identical. The differences in the overturning moment are introduced by different structural discretisations, especially in the vicinity of the free sea surface.

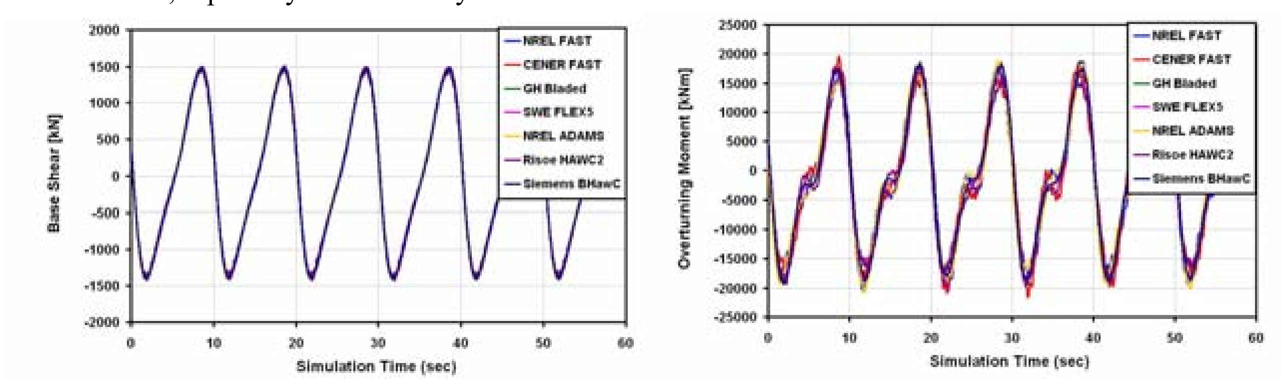


Figure 11. Time history of base shear (left) and overturning moment (right) for load case 4.3

[1] the edgewise direction is parallel to in-plane for this load case with a 0° pitch angle.

The fully coupled, flexible offshore wind turbine is considered in the load sets 5.x. The following figures show various results from load case 5.3. Here, stochastic wind and wave conditions are applied. Figure 12 shows the generator power as well as the thrust force at yaw bearing level while figure 13 addresses the spectral responses of base shear and overturning moment. Figures 14 and 15 show the edgewise and flapwise bending moments of blade 1 at a radial position of 50% of the span and the blade root pitch moment respectively. The mean wind speed is at 18 m/s, i.e. well above rated. The blade root pitch moment response agrees well, although a large influence on the overall turbine behaviour is introduced by the pitch controller and although the individual codes have differing fidelities in their respective blades models.

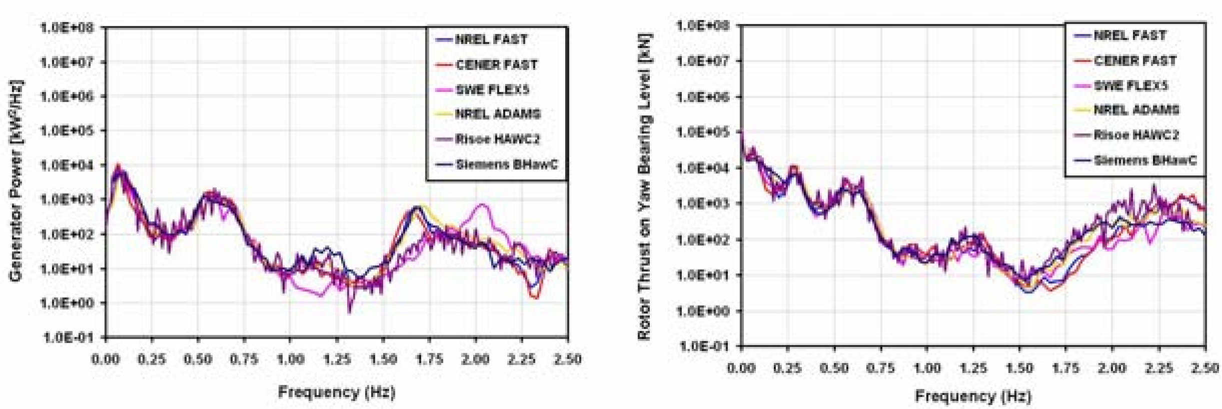


Figure 12. Power spectra of the generator power (left) and thrust force on yaw bearing level (right) for load case 5.3

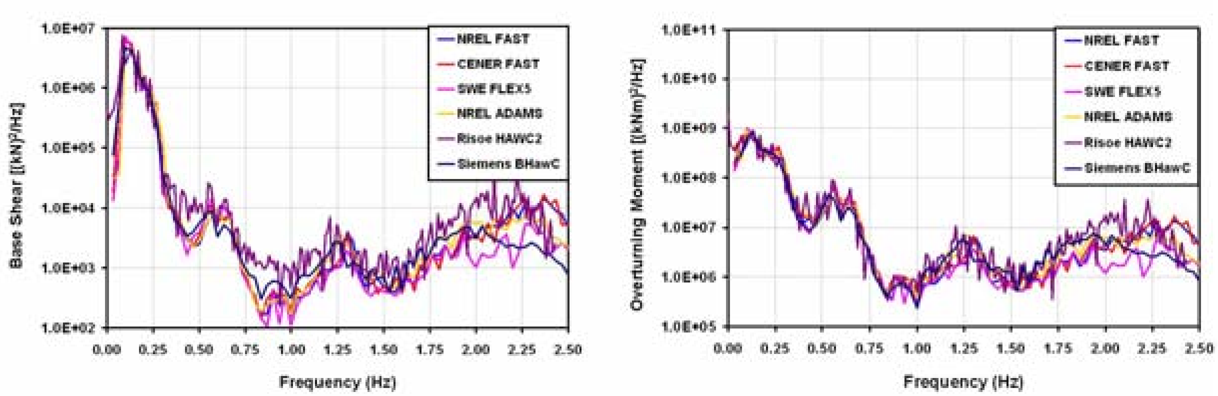


Figure 13. Power spectra of base shear (left) and overturning moment (right) for load case 5.3

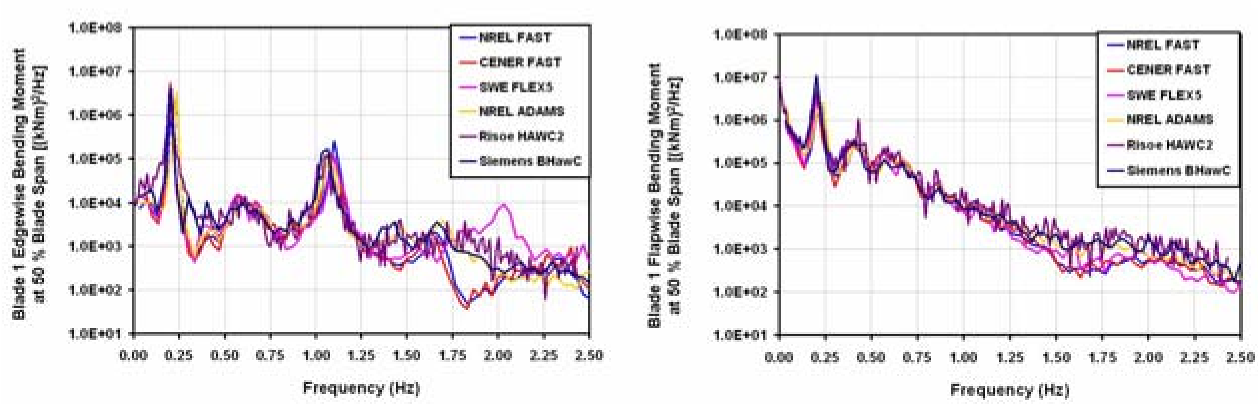


Figure 14. Power spectra of edgewise (left) and flapwise (right) bending moment at 50% span of blade 1 for load case 5.3

In general, the results compare very well for the different codes, especially in the frequency range up to 1.5 Hz. The differences in the higher frequency ranges are influenced by differences in the higher modes of the coupled subsystems as calculated by the individual codes.
However, no significant additional differences become apparent when comparing the results of the fully coupled system load sets 5.x with the results of the simplified system load sets 2.x–4.x. It can therefore be assumed that the differences in the 5.x load sets are introduced by the same sources as identified for the simplified system load case sets, e.g. different turbulence description, different modal properties of the coupled subsystems and different rotor aerodynamics between the individual codes.

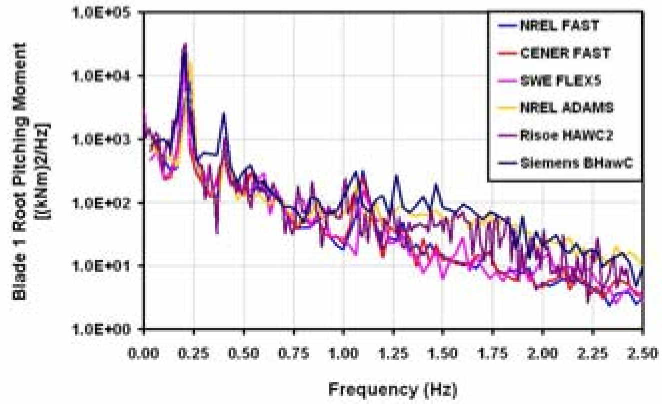


Figure 15. Power spectra of the blade root pitch moment for load case 5.3

4. Project Status and Future Work

The simulations of Phase I are completed while Phase II is wrapping up. Thus, results of Phase II are expected to be published in the second half of 2007. Phase III started in April 2007 and differs from Phase I and II with respect to the support structure and water depth, the latter being increased from 20 to 45 m. Here, code modifications or simplified modelling approaches are required for some of the codes since not all of the involved codes permit the modelling of space frame structures. These approaches are currently being discussed by the partners. First results from Phase III simulations are expected in the third quarter of 2007 while final results should be available by the end of the year. The configuration for the floating structure, which is the subject of Phase IV, has not been defined yet. It will be defined by the third quarter of this year while first simulation results are expected by the end of the year. Phase IV should be completed in the beginning of the second quarter of 2008. The OC3 project within IEA Wind Annex XXIII Subtask 2 should then be completed in May 2008. All final results of the project will be published at that time.

5. Conclusions and Project Benefits

So far good progress of the OC3 project could be realized by the active and constructive cooperation of the project partners. Phase I simulations have been completed after some revisions, which were mainly devoted to adjustments of the model parameters and post-processing issues. Similar good progress is expected also for the subsequent Phases II to IV.
In general, the results of Phase I compare very well. However, certain differences are present in the edgewise blade deformations and loads results. This might be connected to the different rotor aerodynamics models and various structural models of the blades implemented into the codes. Furthermore, certain differences have been observed in the higher modes of the coupled subsystems and therefore in the dynamic responses influenced by these modes.
The OC3 project offers significant benefits to the project partners as well as to the offshore and onshore wind energy community in general. Not only is a vital exchange of experiences and knowledge stimulated between the participants, but also a necessary verification platform for the aero-elastic offshore wind turbine codes provided. Almost all participating codes have been or will be modified and extended within the course of OC3. Some of these extensions are based on certain modelling requirements for the single phases. Others are based on experiences and knowledge gained within the course of OC3 e.g. from the consensus of active discussions of the participating experts with various technical backgrounds related to offshore wind energy application. These code improvements and developments in the context of OC3 provide adequate and verified tools to the offshore wind energy community, which are necessary to face new challenges connected to the short-term and long-term development plans for offshore wind farms with various support structure configurations.
Furthermore, the aerodynamic models, as well as the models for the subsystems of the rotor-nacelle-assembly, in the codes are also addressed within the benchmark exercise. Verification of such models and aspects are desired as well, since developments and implementation of various aspects have lately taken place. Such aspects cover for example the aerodynamics, e.g. implementation of the generalized dynamic wake theory, as well as blade models, e.g. implementation of various approaches for the bend-twist coupling problem.

The 5 MW reference turbine including the control system has been improved within the course of OC3 and is now used for various work packages of the EU Integrated UpWind project [10]. Furthermore, different aspects regarding the support structure configurations as well as the verified models from Phase I to IV will be used as input for work package 4 “Offshore support structures and foundations” of the EU UpWind project.
All of the results, including the models of the 5 MW reference turbine from the OC3 project, will be published and can therefore serve as a verification basis for future aero-elastic codes as well as for further research purposes.

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14. ABSTRACT *(Maximum 200 Words)*

This paper introduces the work content and status of the first international investigation and verification of aero-elastic codes for offshore wind turbines as performed by the “Offshore Code Comparison Collaboration“(OC3) within the “IEA Wind Annex XXIII – Subtask 2”.

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offshore wind turbines; wind turbine design; wind energy; International Energy Agency

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