Prototype test and modeling of a combined wave and wind energy conversion system

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Abstract

This paper deals with the possibility of mounting wind turbines on a wave energy plant. The basis is the Poseidon combined wave and wind energy conversion platform. The wave energy part of the Poseidon platform has been tested at sea and a comprehensive measurement campaign has been carried out, measuring platform motion and waves, current and wind conditions. The measurement form the basis for aeroelastic simulations of a wind turbine mounted on the platform. The aeroelastic simulations show that the tower bottom bending moment has increased and extra considerations need to be taken about the turbine tower construction. The specific turbine is found to damp the platform roll motion.

Keywords: wave energy, wind energy, multipurpose platform, Poseidon

1 Introduction

Increasing energy demand requires new energy solutions. Combining wind and wave power in offshore projects is one of the solutions.

Wave energy conversion has become a growing field in the renewable energy sector. It first attracted interest in the 1970s, when Stephen Salter from the University of Edinburgh devised a device that converted the motion of waves into electricity [1]. Over the past few decades, both scientific and industrial communities have produced a great interest to wave energy, and many wave energy conversion devices have been developed to extract the hydro-kinetic and hydro-potential energy from wave motion. Wave energy conversion devices in the market can be classified into two major categories based on their orientation and functionality: Turbine-type or oscillating water column converters (e.g. LIMPET) and buoy-type or point absorber converters (e.g. Wave Star). A systematic and comprehensive overview of wave energy converters can be found in [2, 3].

Wind energy has until now been one of the most successful renewable energy sources. The technology for conversion of wind energy into electrical energy has converged into a few types. Although the three bladed horizontal axis turbine with a gearbox (known as the Danish concept) has been the most favoured design, a two bladed design has also had some success, especially for smaller turbines. One of the main development areas in the expansion of wind energy is to establish offshore wind turbine parks [4]. The offshore wind quality is superior to onshore for most sites and the offshore wind turbine structures don't scar the landscape. The present offshore wind turbine technology, with bottom fixed foundations, allows only water depths up to ≈ 30 m. To overcome the water depth limit on wind turbine sites, the floating wind turbine concepts have been developed. One of these concepts is the Hywind project,

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which consists of a large spar-buoy filled with ballast at the bottom of the buoy and a conventional turbine on the top. The system is stabilized by the ballast in the bottom of the buoy and kept in position by three anchors. Another floating wind turbine concept is the SWAY, which has an integrated spar-buoy turbine concept stabilized and kept in position by a tension leg and a gravity anchor.

Building large offshore constructions, such as floating wave and wind energy conversion systems, including anchor system and power connection are very expensive. The high construction and connection costs motivate the idea of combining wind and wave energy conversion systems, and thereby share common components, such as power connection and anchor system. Furthermore there will be some synergy effects: wave energy conversion system may reduce the wave excitation of a floating foundation, while wind turbines may damp the motion of the floating foundation, and wind and wave energy intensity will have some phase shift in time and the total power production will be smoothing.

The Poseidon project combines wind and wave energy. The concept is owned by Floating Power Plant A/S and is based on a large stable triangular floating foundation, which works both as a floating platform for a patented wave energy concept and wind turbines. The wave energy part of the concept is a multi absorber system, where the waves force the dynamically ballasted floats up and down. The floats activate hydraulic cylinders that pump water through a water turbine, which drives an electric generator. The wind energy part of the concept utilizes the large stable platform as a floating foundation for wind turbines. The present version of Poseidon is a 37 meter wide off-shore test plant for the wave energy conversion system with an expected wave energy effect on 140 kW (Figure 1). The test plant is prepared for installation of three 11 kW wind turbines. The platform was launched in September 2008 and placed north of Lolland in Denmark next to DONG Energy's Wind Turbine park, Vindeby.

This paper presents results from the demonstration plant, an analysis of the platform motion's effect on the wind turbines and an analysis of the wind turbine's effect on the platform. Both analysises have been realized by using aeroelastic simulations.

2 Platform Motion

This section presents measurements from the Poseidon demonstration platform. The measured platform motion is compared to computed eigenfrequencies of the platform.

From 4/8-2008 to 17/2-2009 the Poseidon demonstration plant has been tested at sea without the wind turbines. This test period has been used to adjust the operation of the wave energy conversion system and to collect data describing the wave and wind conditions together with the motion of the platform. The data includes: i) one three-axis accelerometer in each of the three turbine foundations, ii) roll and pitch angle measurements in one turbine foundation, iii) angular position of one wave energy extracting float, iv) wind speed in three directions. All sensors are sampled with 32 Hz. Wave height, wave period, current speed, and position of the platform have been recorded with 20 and 10 minutes sequences respectively.

Figure 1: Picture of the Poseidon wave energy conversion platform at the test site at sea. The turbines are manipulated into the picture to show how they are suppose to be positioned.

Figure 2 and 3 show the 10 minute statistics for the platform roll and pitch, together with the significant wave hight. The shown period is the one with the highest significant wave heights during the measurements. The platform motion follows the significant wave height closely, having roll and pitch amplitudes on up to 3 deg where the significant wave height is largest. The offset of ≈ 1 deg can be adjusted by trimming the platform with ballast water. Trimming the platform is a part of the optimization process of the wave energy conversion system.

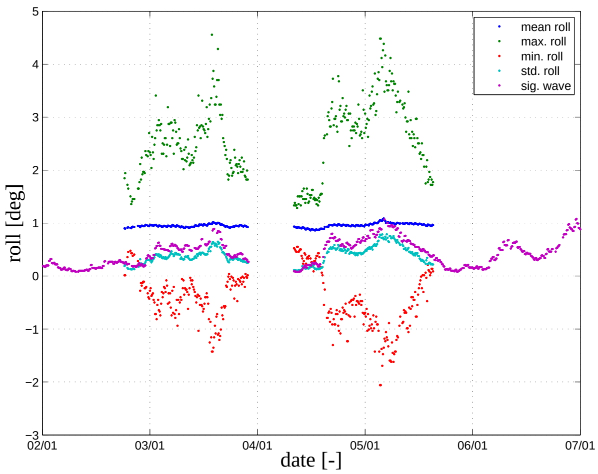

Figure 2: Statistics for roll of platform together with the significant wave height, positive = starboard down.

Figure 4 shows the power spectrum of roll and pitch of the platform.

The eigenfrequencies of the platform have been computed using the time-domain code for vessel motion analysis, WAMSIM, developed by DHI. WAM-

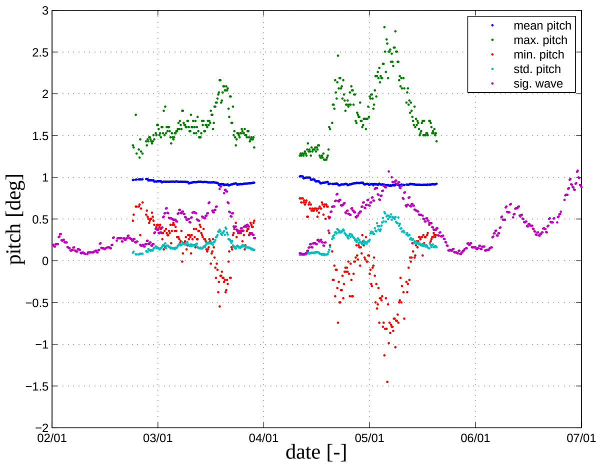

Figure 3: Statistics for pitch of platform together with the significant wave height, positive = bow down.

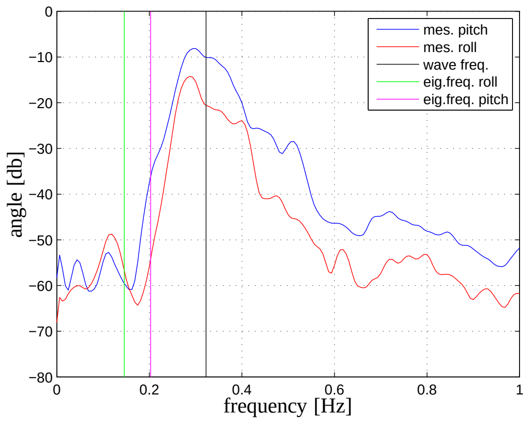

Figure 4: Power spectrum of measured pitch and roll angle of platform at 0:00 to 0:35 the 3th January 2009. Measured wave frequency and computed platform eigenfrequencies are also shown.

SIM relies on the industry standard radiation-diffraction program WAMIT to solve the first-order radiation-diffraction problem in the frequency domain over bodies discritized with quadrilateral panels. WAMSIM takes the hydrodynamic quantities into the time domain through a Fourier transform and combines them with incident wave forcing, wind forcing, forcing from a non-linear mooring system and viscous damping forces in order to solve the equations of motions for the body in 6 degree of freedom. The method is further described and validated in [5] and [6].

The panel representation of the wave energy converter is shown in Figure 5. Decay test analyzes have been conducted in the numerical WAMSIM model. The wave energy converter has been given an initial displacement away from equilibrium and the oscillating, decaying motion back to equilibrium analyzed with respect to its frequency. The catenary anchor chain mooring system of the wave energy converter is included in the model. While eigenfrequencies in heave, roll and pitch are dominated by the mass and shape of the floating platform itself, the surge eigenfrequency is governed by the mooring system. Table 1 shows the computed eigenfrequencies. The power spectrum for the platform roll shows a

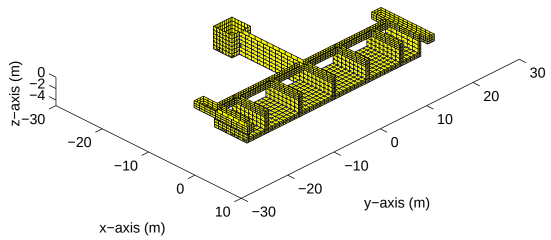

Figure 5: Panel representation of floating wave energy converter, Poseidon.

mode	frequency
surge	0.017 Hz
heave	0.098 Hz
roll	0.146 Hz
pitch	0.203 Hz

Table 1: Eigenfrequencies of the platform computed by the WAMSIM model.

small peak close to the natural roll frequency (0.146 Hz) but the major frequency content is at ≈0.3 Hz. The main part of the frequency contents of the pitch motion is also at ≈0.3 Hz. The wave frequency corresponds well to the main peaks in the power spectrum of platform roll and pitch showing that the platform motion is dominated by the waves. Figure 6 shows the zero crossing frequency from all the wave statistics. It is seen that the wave periods are normally higher than the eigenfrequencies of the platform. The wave period is likely to coincide with the platform eigenfrequency only for very extreme events. No such events have so far occurred during the testing of the wave energy converter.

3 Special Issues for Turbine on Floating Foundation

Mounting wind turbines on a floating foundation, such as the Poseidon demonstration platform, imposes a series of known issues compare to turbines with fixed foundations.

Issue 1 Generally, for all turbine concepts the roll and pitch angle of the platform tilt the tower, whereby the center of gravity of the tower top mass is offset from the tower bottom. This offset of tower top mass together with gravity force impose an increased tower bottom bending moment.

Issue 2 On pitch controlled turbine, the pitch controller will make the system unstable if not redesigned [7].

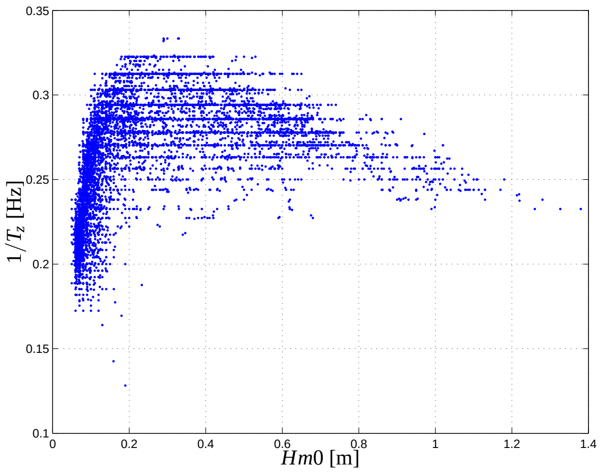

Figure 6: Zero crossing frequency $1/T_z$ of the waves as function of significant wave height $Hm0$.

This is because when the turbine tilts forward, it experiences a relatively higher wind speed and the pitch controller reduces the trust. When the tower tilts backward the relative wind speed decreases and the pitch controller increases the trust. All in all, this will result in a negative damped motion, if the pitch control doesn't disregard wind speed changes imposed by platform motion. This is not an issue for the turbines on the Poseidon demonstration platform, since these are fixed pitch stall regulated turbines.

Issue 3 Special for the turbines on the Poseidon demonstration platform is that they have a free yaw system, meaning that the nacelle is free to rotate 360 deg and the alignment with the wind is only insured by the aerodynamic forces. The center of gravity of the tower top mass is offset from the yaw bearing's center of rotation, as it is located between tower and rotor. When the tower is tilted this offset of center of gravity together with the gravity force will cause a turning moment on the nacelle. Since this turbine has a free yaw system, the turning moment can change the yaw settings and create a misalignment between wind and turbine.

4 The Wind Turbine

Three 11 kW Gaia wind turbines (Figure 7) will be mounted on the Poseidon platform. Table 2 shows a short list of specifications for the turbines. The Gaia

Rotor diameter	13 m
Tower hight	12 m
Tower top mass	900 kg
Rated power	11 kW
Cut in wind speed	3.5 m/s
Cut out wind speed	25 m/s
Rated wind speed	9.5 m/s
Rotation speed	56 rpm

Table 2: Specifications for the Gaia wind turbine.

Figure 7: Picture of a Gaia turbine, similar to the ones which will be mounted on the Poseidon platform.

turbine has two blades with a teetering hub[1] and a free yaw system. The turbine runs at a fixed speed, having a gearbox and an asynchronous generator. It has a fixed pitch and uses stall to limit the power production.

Table 3 shows the resonance frequencies of the turbine.

Description	Gaia	Meas.	HAWC2
rigid flap		0.75	0.76
rigid edge		1.5	1.61
lateral tower	3.06		2.94
longitudinal tower	3.06		3.37
1st flap (sym. Flap)		3	3.62
2nd flap		5.75	5.48
1st edge			6.69
3th flap		10.25	9.67
4th flap		15.75	15.65
5th flap			16.85
6th flap			18.56
7th flap			20.31
8th flap			21.06
2nd lateral tower	26		23.19

Table 3: Standstill resonance frequencies of the Gaia turbine. First column: data provided by Gaia, second column: measurements on blades only, third column: results from the HAWC2 model, all frequencies in Hz.

The yaw bearing has a friction resistance of 20 Nm. It is known that this friction has a large stabilizing effect on the yaw/teeter stability of the turbine, and therefore it is important to include that in the model. The teeter bearing is model with a linear stiffness of 5000 Nm/rad and a damping of 1000 Nms/rad. The stiffness is estimated from previous works done on a similar turbine at Risø

[1] The blades are fixed to each other but hinge in a bearing such that they can make rigid body rotation out of the rotor plane.

[8, 9] and the damping is estimated based on a measure of the damping of the teeter bearing rubber bushing.

4.1 Aeroelastic Wind Turbine Simulation

The turbine is modeled in the aeroelastic time simulation code HAWC2 [10]. The aeroelastic model is used to analyze the effect of the platform motion on the turbines. In this section, first normal operation conditions are simulated to create a basis for the comparison and then the effect of the platform motion on the tower bottom bending moment and the effect on the yaw and teeter motion are analyzed.

4.1.1 Normal Operation

Figure 8 and 9 show the response of tower bottom bending moment, teeter and yaw to normal operation in turbulent wind condition corresponding to SWT class I in the IEC-standard 61400-2. The tower bottom bending moment (Figure 8) increases monotonic with the wind speed, this is characteristic for a stall regulated turbine, as the Gaia, since the trust on the rotor continues to increase when the blades begin to stall. On a pitch regulated turbine the tower load is reduced at wind speed higher than rated wind speed ($\approx$ 11 m/s), since the blades pitch out of the wind and thereby reduce both the energy capture and the trust. At low wind speeds, the turbine experiences large yaw angle errors (Figure 9) with a mean yaw error on up to 25 deg and excursions up to 60 deg. The standard deviation is also high, indicating that there is a lot of yaw motion. The Gaia turbine has a free yaw system and therefor no active control of the yaw setting. Instead of a yaw control, the turbine is designed such that the aerodynamic forces will oriented the turbine correct in the wind. However, at low wind speeds the aerodynamic forces are low and therefore the turbine is less stable in yaw. The teeter excursions increase with wind speed and become relatively large for the higher wind speeds. The real teeter mechanisms have a teeter limit on 16 deg, so the largest teeter excursions will be limited by a stop mechanisms. Figure 10 shows the teeter angle for the simulation of normal power production at 17 m/s. It is only a few instances where the teeter angle exceeds the teeter limit (black line), not more than the teeter stop mechanisms can cope with.

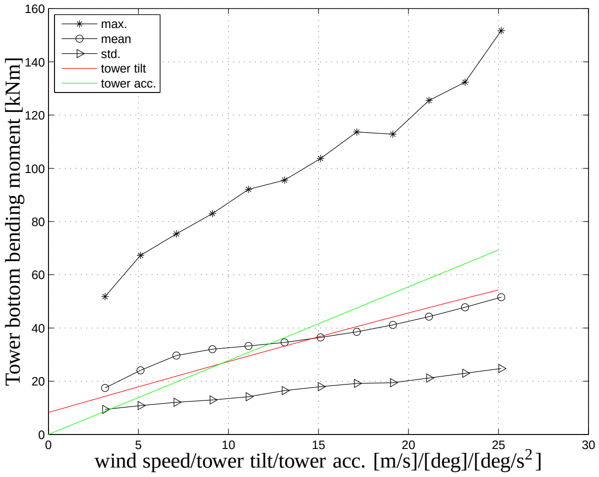

Figure 8: Statistics for tower bottom bending moment at normal operation. Red line shows the tower bottom bending moment caused by the offset of the center of gravity as a function of tower tilt angle. Green line shows the tower bottom bending moment caused by angular acceleration of the tower.

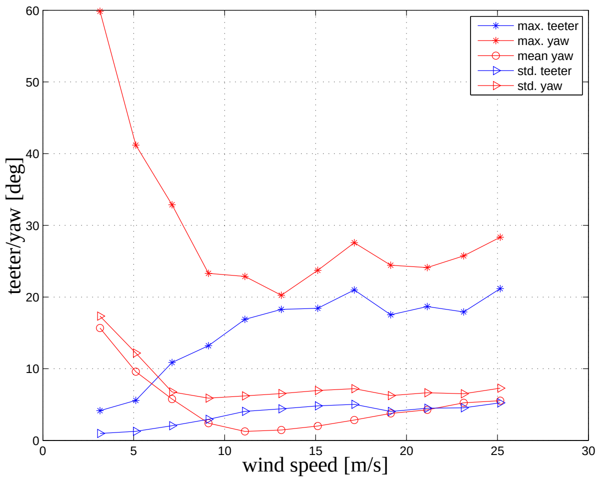

Figure 9: Statistics for teeter and yaw angle at normal operation.

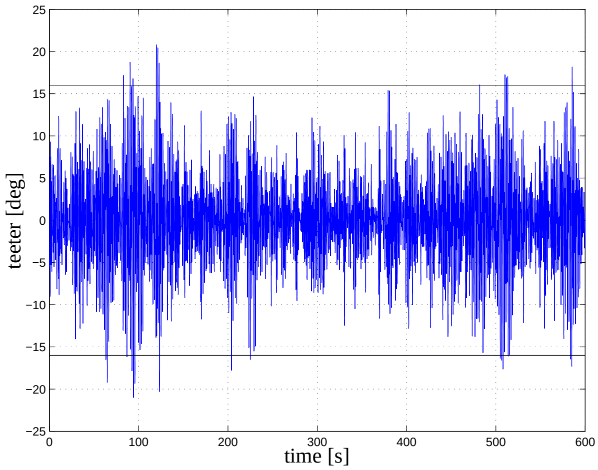

Figure 10: Teeter motion for time simulation at normal operation at 17 m/s

4.1.2 Turbine Response to Platform Motion

Together with the statistics for tower bottom bending moment figure 8 shows that the tower bottom bending moment contribution from tower top mass offset as function of static tower tilt (red line). The bending moment contribution is not zero at zero tower tilt, since the center of the gravity of the tower top mass is not located on the tower top, but between the tower and the rotor ($\approx$ 0.895 m from tower center).

For the Gaia turbine the contribution of bending moment at tilt angle values less than 5 deg is much smaller then the bending moment which occurs at normal operation, hence the tower tilt may not be a problem for the

Gaia turbine. However, if a turbine is linearly upscaled the tower top mass increase proportional to R^3 (where R is the rotor radius) and aerodynamic trust increases proportional to R^2. Hence the relative effect on tower bottom bending moment causes by tower top mass combined with tower tilt increases with the turbine size. For MW size turbines, the tower bottom bending moment will be dominated by the effect of tower tilt combined with the tower top mass at only a few degrees of tilt.

Figure 8 shows that the tower bottom bending moment caused by the angular acceleration of the tower, corresponding to roll or pitch acceleration of the platform. The measurements show roll and pitch accelerations on up to 3 deg/s^2, so the bending moment contributions for inertia forces are also much smaller than the bending moment under normal operation. Again this effect increases for larger turbines because of the uneven scaling of tower top mass and aerodynamic trust, but the acceleration is expected to reduce if the platform and turbines are up-scaled, so the effect of up-scaling is unclear.

The platform motion is modeled in the aeroelastic simulations by placing two bearings in the tower bottom, such that the tower can tilt in longitudinal and lateral directions. The bearings are controlled by a PI controller tracking the measured motion of the platform. The controller applies a moment to the bearing, instead of prescribe the angle, to insure a smooth motion of the tower and to avoid convergence problems in the simulation. Figure 11 shows the measured and the simulated roll and pitch of the platform. The measurements are from 6:00 AM the 5th Jan 2009 where the significant wave height was $Hm0 = 0.96m$, one of the largest measured wave height in the measurement campaign. Figure 12 and 13

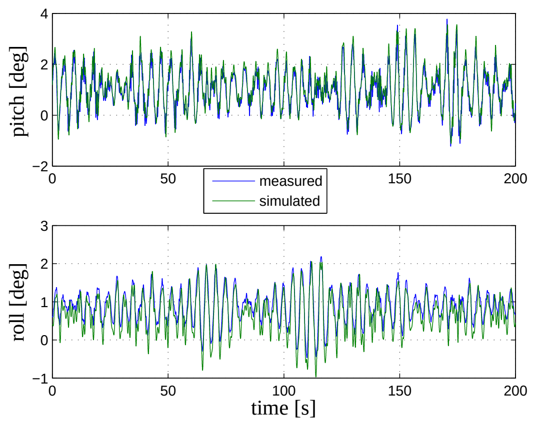

Figure 11: Measured and simulated platform pitch and roll at 6:00 AM 5th Jan 2009.

show the turbine's response to the platform motion at a mean wind speed of 5 m/s with a turbulent intensity of 0.225.

Figure 12 shows that the teeter motion exceeds the 16 deg limit only a few times, and that result is almost the same as the one found in the case with fixed turbine foundation (Figure 10). The yaw motion stays within acceptable limits and, most importantly, it doesn't rotate a full 360 deg. The longitudinal tower bottom bending mo-

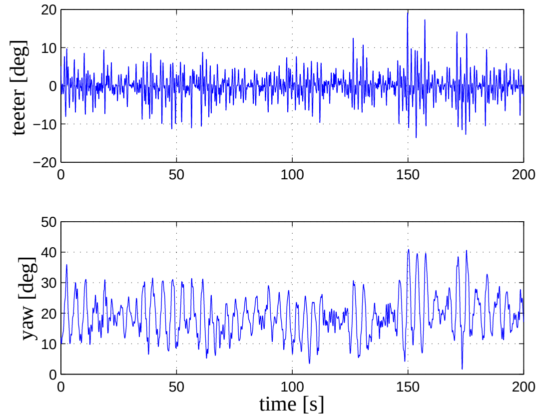

Figure 12: Teeter and yaw response to the platform motion shown in Figure 11

ment increases slightly and that doesn't create any critical conditions. The lateral tower bottom bending moment increases a lot and become the dominating tower load. The results indicate that there will be a higher tower load on a turbine mounted floating foundation.

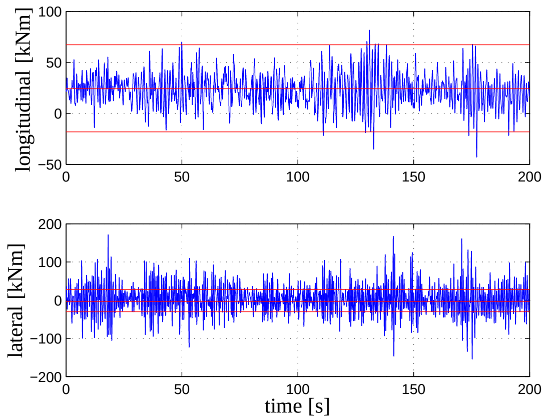

Figure 13: Tower bottom bending moment responses to the platform motion shown in Figure 11. The red lines indicates the minimum, mean and maximum for the simulations without platform motion.

4.1.3 Effect of Turbines on the Platform

Figure 14 shows the average work done by the controller on the turbine to realize the measured platform motion shown in figure 11. This work corresponds to the damping effect of the turbine on the platform motion. It is seen that the turbine adds most damping in the lateral direction (platform roll), which is unexpected, since normally turbines are low aerodynamically damped in the lateral direction. The reason to that is the free yaw, which changes the characteristic behavior of the turbine. The damping for a similar turbine with a fixed yaw is also shown in figure 14. The damping for the fixed yaw turbine is seen to be completely different from the one with free yaw. If a pitch regulated turbine is used, the

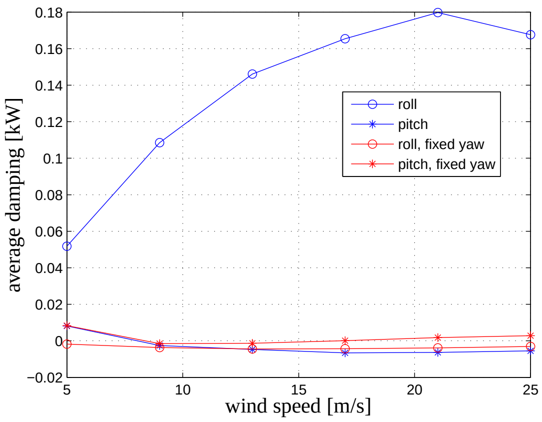

Figure 14: Average work done to make the tower follow the platform motion.

pitch controller can be used actively to change the damping of the platform.

5 Conclusion

This paper presents the results of an application of combining wave and wind energy technologies together. The basis of the application is a floating power plant called Poseidon which consists of offshore wind turbines that are mounted on a wave energy plant. Tests related to wave energy part have been realized at the sea and a comprehensive measurement campaign has been carried out to measure the platform motion together with the environmental conditions (wave, current and wind characteristics). The measurements formed the basis for the aeroelastic simulations of a wind turbine mounted on the platform. The turbine, which will be mounted on the Poseidon platform, is modeled in HAWC2 (Risø's aeroelastic code developed for modeling wind turbines) and the measured platform motion is imposed at the tower bottom. The aeroelastic simulations indicate that wind turbines can be mounted on the floating wave energy platform, but the tower bottom bending moment has increased, and extra considerations has to be taken in turbine tower construction.

The specific turbine is found to damp the roll motion of the platform, however other turbine concepts will give different damping effect on the floating platform.

Three instrumented turbines will be mounted to the platform in the beginning of May. Once the turbines are installed, the platform will be operated as a combined wave and wind energy conversion system and a second measurement campaign will be carried out, measuring on both platform motion, wave energy system and wind turbines. The measurements will be used as a validation basis for developing simulation tools which can model a combined energy platform, such as Poseidon. The results will also be used to clarify the synergy effects of having a combined wave and wind energy conversion plant.

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