Comparative experimental study of the survivability of a combined wind and wave energy converter in two testing facilities

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1. Abstract

Combining the offshore wind and wave energy on an integrated structure or in a farm configuration might be beneficial for cost reduction since they could share the infrastructure and the ocean space. The spar torus combination (STC) is a combined wind and wave energy converter concept, which is composed of a spar floating wind turbine and a torus-shape heaving-body wave energy converter (WEC). Numerical simulations have shown a positive synergy between the WEC and the spar floating wind turbine under operational conditions. However, in extreme sea states, it is challenging to maintain structural integrity due to severe wave loads. Three survival modes have been proposed to study the survivability of the STC, and two of them are selected for further study by model testing. Two model tests were performed to investigate the performance of the STC under the two survival modes in extreme conditions: one test is carried out in the CNR-INSEAN towing tank, and the other one is performed in the MARINTEK towing tank. The two survival modes considered are when the torus is fixed to the spar at the mean water level (the MWL mode) and when the torus is fixed to the spar at a submerged position (the SUB mode). In this paper, these two model tests are described first and then the measured responses are compared for each survival mode. In addition, the performance of the STC in the two survival modes is also compared for each model test. The focus of the model tests was wave-induced loads and responses, and the wind was also included to model the mean wind thrust on the wind turbine rotor. In the model tests, the six degrees of freedom of the rigid body motions, the mooring line tensions, and the forces between the spar and torus in three directions (X, Y and Z) were measured. The differences in the two model tests and therefore the differences in the measured responses are explained. Finally, validation of a numerical model against the model test measurements is also briefly discussed in this paper.

Key words: Spar Torus Combination, Wind Turbine, Wave Energy Converter, Model Tests, Survival Mode, Comparisons between Model Tests.

2. Introduction

Wind energy is becoming an increasingly important source of renewable energy. By June 2014, about 337 GW installed wind power capacity has been achieved in the world (The World Wind Energy Association, 2014). The installed offshore capacity in Europe has reached more than 8 GW by the end of 2014 (The European Wind Energy Association, 2015). Wave energy also represents an energy resource with a large potential and with a much higher power density than wind power. The worldwide overall resource which is around 2 TW is of the same order of magnitude as the world's electricity consumption (Cruz, 2008). The research on wind and wave energy has been rapidly developed these years. Many floating wind turbine (FWT) and wave energy converter (WEC) concepts have been proposed, built and tested at sea.

Commercial wind or wave farms usually occupy large ocean spaces. For this reason, combining the wind and wave energy converters in a farm configuration would be beneficial for utilizing more efficiently the ocean space. In the view of cost reduction, it would also be beneficial for the wind and wave energy converters to share the infrastructures such as support structure, power substations, mooring system and cables. In this case, the spar torus combination (STC) concept was proposed (Muliawan et al., 2012) through the EU FP7 Marine Renewable Integrated Application Platform project (MARINA Website, 2015). Other combined concepts were also proposed in that project, such as the semi-submersible flap concept (SFC) (Luan et al., 2014; Michailides et al., 2014) and the oscillating water column (OWC) array with a wind turbine installed.

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The STC concept as shown in Figure 1, is composed of a spar FWT and torus-shaped WEC. The wind turbine installed is the 5MW NREL reference turbine (Jonkman et al., 2009). In this concept, the torus can move along the cylinder of the spar to absorb wave energy through the relative heave motions. Roller and mechanical brake systems are incorporated to allow the relative heave motion and restrict the relative horizontal motion between the two bodies, and end stop systems are designed to limit the excessive relative heave motion under extreme conditions. To limit the yaw motion, a delta shape mooring system is deployed. The reference site for design is located 30 km off the west coast of Norway with the water depth of 200 m (Li et al., 2013).

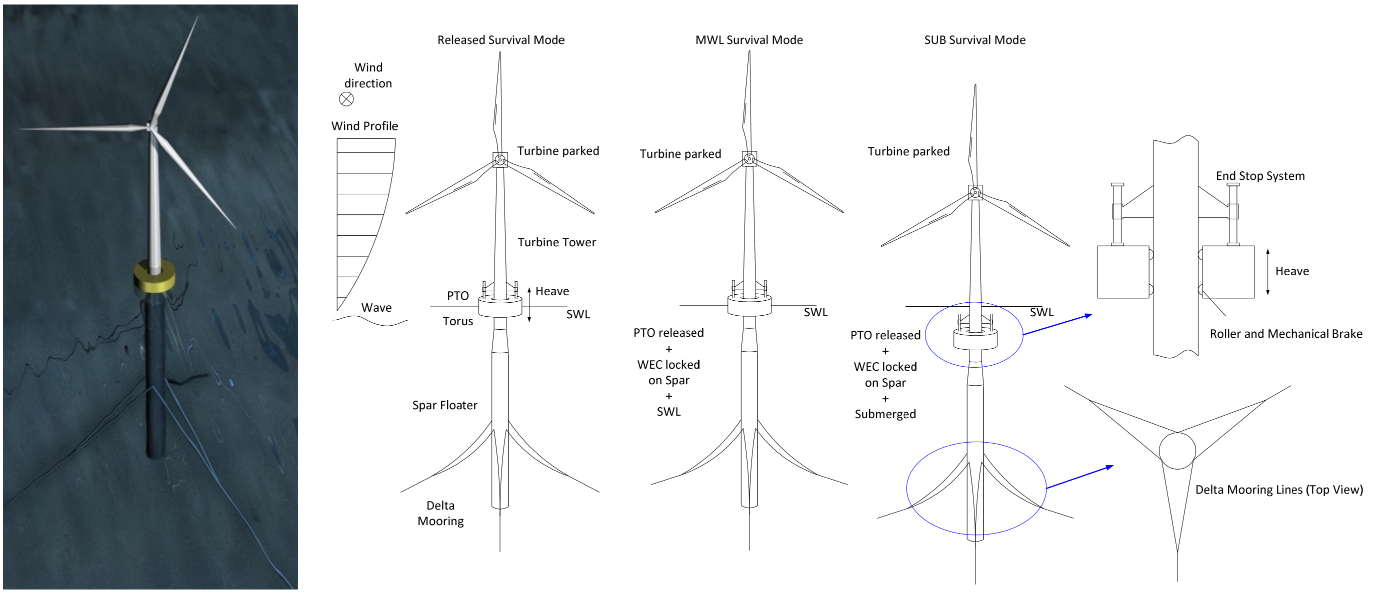

Figure 1. The STC concept and three proposed survival modes

Numerical simulations have demonstrated a positive synergy between the FWT and the WEC under operational conditions (Muliawan et al., 2013b): except for the good aspects from an economic point of view as mentioned before, the presence of the WEC would dampen the spar motions in particular in pitch, and at the same time produce more power. However, the structure is subjected to severe wind and wave loads under extreme conditions. For FWT concepts in extreme wind conditions, the wind turbine rotor will be parked and the blade can be feathered to the wind to reduce the extreme wind loads. For WECs, as the waves become larger, a transition from a state of efficient energy production to a survival condition is also required. For the STC, the WEC with a large structure close to the mean water level will especially suffer from the large wave loads during extreme sea conditions, which is a critical concern for structural integrity. Hence, three specific potential survival modes (Muliawan et al., 2013a) are considered for the STC concept, as shown in Figure 1:

- Mode I: the WEC PTO system is released, the wind turbine is parked, and the torus moves freely along the spar. The motion is only limited by the end stop system. This is referred to as the released survival mode. However, this mode will result in extremely large end stop forces (Muliawan et al., 2013a) and is not considered to be a feasible solution, so it is not selected as the case with further study.
- Mode II: the WEC PTO system is released, the wind turbine is parked, and the torus is locked mechanically to the spar at the mean water level (MWL). In this mode, the two bodies are locked and can move together. This is referred to as the MWL mode hereafter.
- Mode III: the WEC PTO system is released, the wind turbine is parked, and the torus is locked mechanically to the spar. By adding ballast to the torus or the bottom of the spar, the two bodies are submerged to a specified position. In this mode, the torus is totally submerged (SUB) in the water. This mode is referred to as the SUB mode hereafter.

To investigate the performance of the STC survival modes under extreme conditions, model tests were carried out with a particular focus on the investigation of the potential for the MWL and SUB modes as strategies for survivability. The model tests focused on the motions, the mooring forces and the interface forces between the spar and the torus. Wind was also included to model the mean wind thrust on the rotor. Model tests were performed in two different testing facilities to investigate the possibility to judge the experimental uncertainties and performance. One test is performed in the towing tank of MARINTEK, Trondheim, Norway; the other one is carried out in the towing tank of CNR-INSEAN, Rome, Italy,.

The test results in the towing tank of MARINTEK were presented in (Wan et al., 2014b). In this paper, the comparison of the results from the two model tests will be presented. In addition, the numerical model and its validation against the INSEAN test will be briefly discussed.

3. Physical testing model and setup in the INSEAN towing tank

The model in the tests was downscaled by Froude scaling (Chakrabarti, 2005) with a 1:50 geometrical scale factor. The scale factors for different variables are listed in Table 1. The results of the model tests were up-scaled and presented in full scale in this paper, unless specified otherwise. In recent years, research efforts have been made to develop a model scale wind turbine for testing offshore floating wind turbine system (Martin, 2011), in which, a model scale rotor following the Froude scaling law with downscaled rotor rotational frequency, rotor moment of inertia, tower bending moment was achieved. However, in the STC model test, the wind turbine was modelled by a simple drag disc, which was used in the Windfloat model test (Cermelli et al., 2009) previously.

In this paper, the focus is given to the testing facility and the test setup in the INSEAN towing tank, and the description of the test in the MARINTEK towing tank is referred to (Wan et al., 2014b). The same coordinate system was used in the two tests, which was set as follows: z direction is positive downward and x direction is positive in the upwind direction, which is indicated in Figure 2. The origin is at the intersection point of the still water surface and the central line of the cylinder.

Table 1. Froude scaling of the variables

Variables	Symbol	Scale factor	Value
Linear Dimensions	D	λ	1:50
Fluid or structure velocity	u	$\lambda^{1/2}$	1:7.07
Fluid or structure acceleration	a	1	1:1
Time or period	t	$\lambda^{1/2}$	1:7.07
Structure mass	m	λ^{3}	$1{:}1.25\times10^{5}$
Structure displacement volume	V	λ^{3}	$1{:}1.25\times10^{5}$
Force	F	λ^{3}	$1{:}1.25\times10^{5}$
Moment	M	λ^{4}	$1{:}6.25\times10^{6}$

Figure 2 shows the STC model used in the INSEAN test, and different components of the model as well as the coordinate system. The right top plot shows the MWL survival mode condition, while the right bottom plot shows the SUB mode condition. It should be mentioned that the wind disc size is chosen to produce the same wind force on the original wind turbine rotor for a given wind speed. Different components are described as follows:

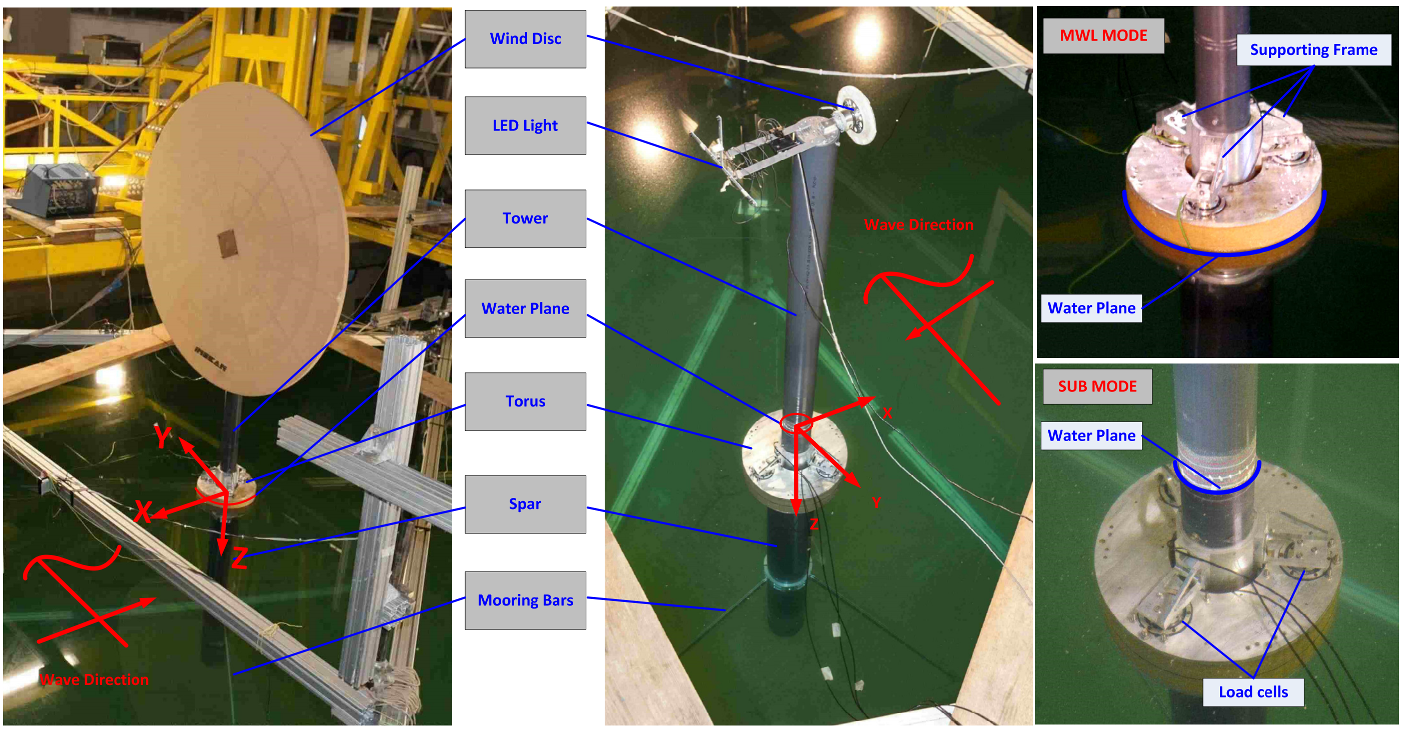

Figure 2. STC model, coordinate systems and various components in the two survival modes in the INSEAN test (right-top: the MWL mode condition, right-bottom: the SUB mode condition)

The tower and the main buoyant portion of the spar (lower part of the spar) are made of PVC, while the upper portion of the spar floater is made of aluminum alloy for fixing the load cells. The torus is made of two types of material, with a core of Dyvincell and aluminum alloy plates on the top and bottom of this core.

The load cells used in the INSEAN tests were three Kistler load cells, which are 3 directional load cells with load capacity ranges of approximately -1000 N to 1000 N for Fx and Fy and -2000 N to 2000 N for Fz in model scale. The three load cells were installed inside the Torus and were located 120 degrees apart with respect to the central line of the cylinder. The bottom of the load cells were connected to the aluminum alloy bottom plate and the top of the load cells were fixed to the rigid portion of the Spar through three triangular supporting frames as shown in Figure 2. Silicon sealant was used to waterproof the chambers for the load cells inside the torus.

In the model test, the mooring system was simplified as three rigid bars connected by three linear springs to model the catenary delta line mooring system deployed in the prototype as shown in Figure 1. This configuration can provide the desirable yaw stiffness and to limit the excessive yaw motion of the model. The LED lights were installed on the T-shape frame on top of the tower and the motions of the spar were tracked by cameras on the carriage through the KRYPTON system.

Wind effects on the rotor were considered in a simplified manner as a drag disc, which is installed on the top of the tower. The purpose is to mimic the mean thrust on the rotor. In the prototype, the mean wind thrust on the rotor varies with wind speed. The wind turbine thrust curve is shown in Figure 3. At rated wind speed of 11.4 m/s, the thrust force on the rotor reached the maximum value. When the wind speed is larger than 25 m/s, the wind turbine will be parked and the blades will be feathered to the wind, so there is only wind drag on the blade, and there are no centrifugal force and gyro moment. In the test, the wind velocity and wind thrust were downscaled by Froude scaling with a factor of $\lambda^{0.5}$ and λ^{3} respectively, then the diameter of the disk can then be calculated through $F_{wind} = 0.5\rho A C_d U_w{}^2$, where A is the disk area; C_d is the drag coefficient, which is assumed to be 1.9 according to the DNV rule (DNV, 2010); ρ is the density of the air, U_w is the model scale wind velocity, F_{wind} is the downscaled mean wind thrust. When the wind speed is in operational condition 11.4 m/s, a large disc should be used, while when the wind speed is in extreme condition, a small disc should be installed. It should be mentioned that, the model in the test is always in the survival mode even the sea states are the operational conditions.

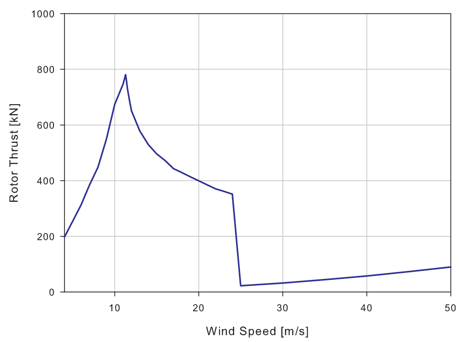

Figure 3. The thrust curve of the NREL 5MW wind turbine with different wind velocity in full scale

Two survival modes (the MWL mode and the SUB mode) were investigated. In the MWL mode, the torus is locked to the spar by load cells and the whole structure is floating at the still water plane with a target draft. In the SUB mode, the two bodies are still locked by the load cells and are submerged at a 19.5 m depth with the reference to the MWL mode by adding ballast to the bottom of the spar. The two survival modes are shown as the right plot in Figure 2.

The layout of the test at INSEAN is shown in Figure 4. The dimension of the tank is length=220 m, breadth=9.0 m, water depth=3.5 m. The wave maker is a one-side flap-type maker, and the wind was generated by an array of fans installed on the carriage. A honeycomb frame was installed in front of the wind generating system to reduce the lateral wind speed and the occurrence of large turbulent eddies. Five wave probes were installed, with one wave probe located far from the model in the direction towards the wave maker and the other four wave probes installed near the model. One extra Kenek wave probe was installed near Wave Probe 5, used as a reference. One large triangular prism frame was used to accurately fix the three mooring springs. Figure 5 shows pictures of the test setup.

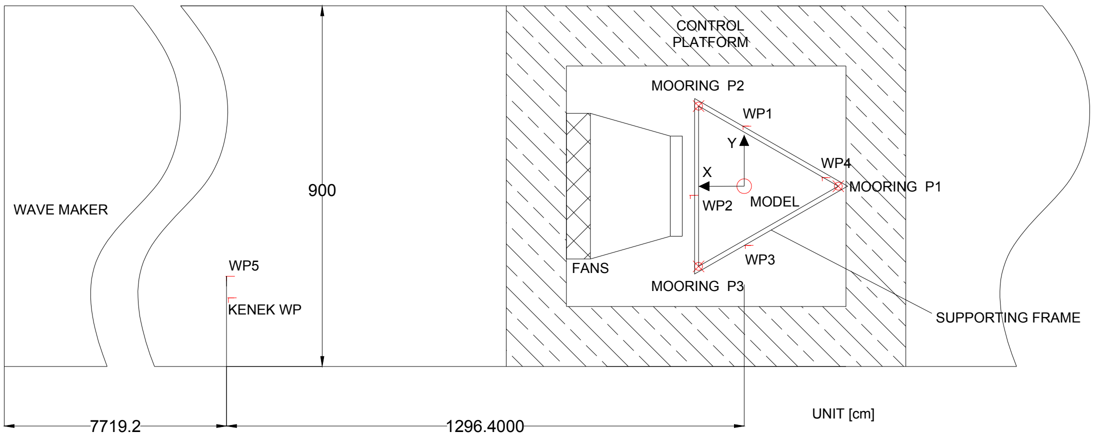

Figure 4. Horizontal layout of the test setup at INSEAN

Figure 5. Test setup at INSEAN

4. Physical testing model and setup in the MARINTEK towing tank

The model test of the same STC concept and survival modes was also performed in the towing tank of MARINTEK. The detailed setup in the MARINTEK test can be found in (Wan et al., 2014b). The physical model and different components are shown in Figure 6. In general, the designs of the two tests were quite similar, except for a few differences. The dimensions and mass properties of the models tested at MARINTEK and INSEAN are listed in Table 2 and Table 3. The main differences between the two test configurations are listed in Table 4. More detailed descriptions are as follows.

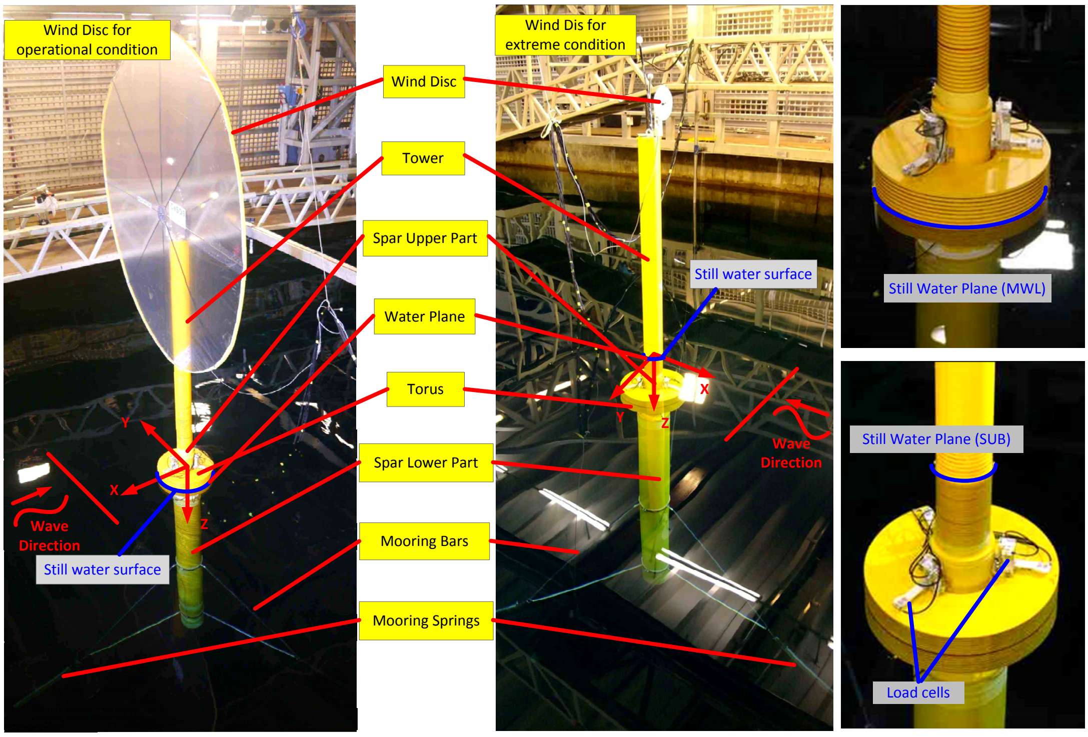

Figure 6. STC testing model and different components of the two survival modes in the MARINTEK test

The connecting part of the torus and spar, i.e., the load cell configurations differed considerably between the two tests. Different load cells were used in the two tests. They were located inside of torus for the INSEAN model, but they were placed on the top and bottom (outside) of the torus for the MARINTEK model. In this case, the hydrodynamic properties were slightly altered by the existence of the load cells in the MARINTEK model in the MWL mode and the impact forces on the bottom of the torus when it entered and exited the water were influenced by this layout.

As seen in Table 2, the dimensions of the two models are the same. In the SUB mode, the models were submerged by different depths, which were 26 m for the MARINTEK model and 19.5 m for the INSEAN model. The submerged depth is measured from the center of torus to the still water plane position in the SUB mode. Different depths of submergence will lead to different hydrodynamic forces.

Table 3 lists the information for the mass properties and the relative differences between the two models, using the MARINTEK model as the reference. The largest differences are associated with the radius of gyration with respect to the vertical central line of the model, i.e., Rzz. This difference is insignificant because yaw motion responses are not excited under the wave conditions considered and are thus not a concern. The mass of the load cells is included in the torus mass. For the MWL mode, the mass difference of the STC is 1.4%, but it produces a negligible draft difference because of the large water plane area in the MWL mode. For the SUB mode, there is a substantial draft difference in the STC with a relatively small weight change, which is attributed to the small water plane area of the tower. The center of gravity (C.O.G) differences for the MWL mode are approximately 2.2% for the entire STC model and 0.7% for the spar tower model, which are quite small. For the SUB mode, because there is a difference in the submerged depths, the relative difference in the C.O.G is larger. The reason why the models have the same geometry under the still water line in the MWL mode but with different total weights is, there are different buoyancies and weights of the mooring bars.

Table 2. Dimensions of the models tested at MARINTEK and INSEAN

	Dimension	MARINTEK model	INSEAN model
Spar lower portion	Diameter [m]	10	10
	Length [m]	108	108
Spar upper portion	Diameter [m]	6.45	6.45
	Length [m]	24	24
Tower	Diameter [m]	5.5	5.5
	Length [m]	77	77
Spar & Tower	Draft for MWL mode [m]	122	122
	Draft for SUB mode [m]	148	141.5

Torus	Height [m]	8	8
	Outer diameter [m]	20	20
	Inner diameter [m]	8	8
	Draft for MWL mode [m]	4	4
	Distance from Torus Center to SWL for SUB mode [m]	26	19.5

Table 3. Mass properties and the relative differences between the models tested at MARINTEK and INSEAN

		MWL mode			SUB mode		
STC		MARINTEK	INSEAN	Difference	MARINTEK	INSEAN	Difference
Total weight (including ballast) [ton]		10,036.25	10,179.00	1.4%	11,840.00	11,800.00	-0.3%
Ballast [ton]		4,276.25	5,123.75	19.8%	6,080.00	6,744.75	10.9%
C.O.G from WL [m]		67.50	69.00	2.2%	100.00	95.00	-5.0%
C.O.G from geometric center of Torus [m]		67.50	69.00	2.2%	74.00	75.50	2.0%
Radius of gyration with respect to water line [m]	Rxx	88.50	90.50	2.3%	114.00	110.50	-3.1%
	Ryy	88.50	90.50	2.3%	114.00	110.50	-3.1%
	Rzz	4.50	6.61	46.9%	4.50	6.61	46.9%
Spar, Tower & Wind turbine							
Total weight (including ballast) [ton]		8,891.25	9,124.00	2.6%	10,695.00	10,745.00	0.5%
Ballast [ton]		4,276.25	5,123.75	19.8%	6,080.00	6,744.75	10.9%
C.O.G from WL [m]		76.50	77.00	0.7%	108.00	102.50	-5.1%
Radius of gyration with respect to water line [m]	Rxx	94.50	95.50	1.1%	120.00	115.50	-3.8%
	Ryy	94.50	95.50	1.1%	120.00	115.50	-3.8%
	Rzz	4.00	6.50	62.5%	4.00	6.50	62.5%
Torus							
Total weight [ton]		1,145.00	1,055.00	-7.8%	1,145.00	1,055.00	-7.8%
Ballast [ton]		0.00	0.00	0.0%	0.00	0.00	0.0%
C.O.G from WL [m]		0.00	0.00	0.0%	26.00	19.50	-25.0%
Radius of gyration with respect to water line [m]	Rxx	7.00	6.50	-7.1%	26.50	21.00	-20.8%
	Ryy	7.00	6.50	-7.1%	26.50	21.00	-20.8%
	Rzz	7.00	7.50	7.1%	7.00	7.50	7.1%

The main differences in the test setup are listed in Table 4. They are mainly associated with the load cells, wind disc formation, mooring bar geometry and material, type of mooring springs and their installation, and wind generation system. None of the differences significantly influence the responses of the models except for the difference in draft in the SUB mode and difference in mooring spring type. Notably, the calibrated mooring stiffness is approximately 82500 N/m for the INSEAN test and 72500 N/m for the MARINTEK test. The mooring stiffness differences confer different horizontal resonant periods to the models, i.e., the surge natural period.

Table 4. The main differences between the setup of the two model tests

Different components	MARINTEK	INSEAN
Submerged depth in SUB mode with reference to the MWL mode	26 m	19.5 m
Load cells	18 bending Load cells (6 groups with each group consists of 3 load cells)	Three 3-directional load cells supported by the frame
Wind discs	Film supported by plastic frame (large disc), steel disc (small disc)	Dyvincell material manufactured by milling (large disc), steel disc (small disc)
Mooring bars	Long thin circular cylinders	Long flat bars
Mooring springs	Large and heavy, 6 springs with each spring weight approximately 0.4 kg (the mooring line 1 which is in the wave direction consists of 4 springs series-parallel connected, the other two mooring lines with 1 spring for each)	Small and light springs (each mooring line is modeled by 1 spring), mooring stiffness are slightly different with MARINTEK model
Connection point for mooring	One mooring connected to the carriage, the other two connected to side walls of the towing tank	3 mooring connected to the vertical bars of the large triangular prism frame
Wind generation	Array of fans, wind time series recorded	Array of fans, wind velocity calibrated, honeycomb frame was used
Wave probes	4 wave probes	5 wave probes

5. Test matrix

The test matrices at MARINTEK and INSEAN are described below. The testing procedures for the MWL and SUB modes are in general the same.

Hammering tests were conducted before and after installing the model in the water by hitting the model with a hammer at several locations on the spar and torus. The main purpose was to identify the structural eigen-frequencies.

Decay tests were then performed for the 6 D.O.F. of the rigid body motions. From the measured decay response curve, the natural period and damping level were identified.

To investigate the linear and nonlinear performance under each wave frequency, regular wave tests were performed to determine the RAOs of various response parameters, i.e., motions, interface forces between the spar and torus, mooring tensions and other parameters. The regular wave periods varied from 7 s to 23 s, and two sets of regular wave heights were tested (i.e., H=2 m and H=9 m) for the purpose of assessing the nonlinearity of the responses.

Then, tests of irregular waves with no wind were considered. Three sea states were selected based on the metaocean data for the western coast of Norway. One operational sea state with Hs=2.75 m, Tp=11 s and two extreme sea states with Hs=13.5 m, Tp=15 s and with Hs=15.3 m, Tp=15.5s were chosen as the designed sea states. One of the extreme sea states was selected based on the most probable maximum mean wind speed Uw at the 10 m height, and the other extreme sea state was selected by the most probable maximum significant wave height Hs (Li et al., 2013). All of the generated waves follow the Jonswap spectrum with the peakedness factor of 3. For each sea state, several tests were performed with different realizations.

Finally, wind tests and combined irregular wave/wind tests were performed. The mean wind speed was determined according to the sea state tested, and the corresponding wave conditions were the same as those considered in the pure irregular wave tests. For the tests with wind, two discs were used to produce representative mean thrusts under operational and survival conditions. Under operational wind conditions, a large wind disc was used, and a small disc was installed for extreme wind conditions. The wind velocities were downscaled by Froude scaling with the factor of $\lambda^{0.5}$.

The effective recording time in full scale for each irregular wave test at INSEAN was 70 min, compared to 100 min for MARINTEK tests. The steady state responses were considered for analysis.

6. Response obtained in decay and regular wave tests

6.1. Decay tests

Decay tests were performed in both tests. The identified natural periods and the differences between the two model test results are listed in Table 5. The largest differences are in the surge and in the sway, approximately 20% and 10%, respectively, which are mainly attributed to the difference in the mooring spring stiffness. The heave natural periods are very similar, and the differences are 3% for the SUB mode and 1% for the MWL mode. The differences in the pitch and roll natural periods are from 2% to 6%, which are caused by the difference in the moment of inertia and the difference in the hydrostatic restoring effect in pitch, and the pitch restoring effect is associated with the center of gravity, center of buoyancy and the model mass as well as the water plane area. Additionally, the heave natural period is greater than 40 s in the SUB mode, which is outside of the frequent wave region, compared to approximately 13 s in the MWL mode. The pitch and roll natural period for the SUB mode (approximately 26 s) is smaller than that for the MWL mode (approximately 36 s). The heave natural period of the torus in operational conditions is only approximately 6 s, while it increases to approximately 13 s when the spar and torus are locked together in the MWL mode. This natural period is just located in the region with the highest wave energy. Thus, large heave motion would be expected for the STC in the MWL mode under extreme sea states.

Table 5. The identified natural periods from the decay tests for the MARINTEK and INSEAN models

Natural Period [s]	SUB Mode			MWL Mode		
	MARINTEK	INSEAN	Difference	MARINTEK	INSEAN	Difference
Surge	101.9	80.0	-21%	98.0	76.9	-22%
Sway	92.5	81.9	-12%	93.1	80.7	-13%
Heave	47.2	45.5	-3%	12.8	12.7	-1%
Roll	25.6	26.6	4%	36.0	35.2	-2%
Pitch	25.7	26.6	4%	36.6	34.5	-6%

6.2. Regular wave tests

The regular wave tests were performed with wave periods from 9 s to 23 s and with wave heights of 2 m and 9 m. The same test conditions were applied to both the SUB and MWL modes. The response amplitude operator (RAO) which is the response amplitude divided by the input wave amplitude, is investigated in this section, with focus on the linear dynamic responses based on the steady state response time series from the regular wave tests. The pitch response amplitude is divided by the wave steepness parameters kA with k the wave number and A the wave amplitude. The motion is referred to the origin of the coordinate system. The test RAO results of the motions, the horizontal (Fx) and vertical interface forces (Fz) between the spar and torus as well as the mooring forces for the INSEAN and MARINTEK tests are plotted in Figure 7 and Figure 8 under the SUB mode and the MWL mode, respectively. All of the RAOs are based on cases with the input wave height H=2 m. It should be mentioned that under the MWL mode, there were water entry and exit phenomena observed in both tests in the heave resonant region, i.e., around wave period of 13 s.

The results for the SUB mode are shown in Figure 7. There are good comparisons between the two tests for the surge, heave and pitch motions under all the wave periods tested. For Fx and Fz, there are good agreements under wave periods larger than 13 s, while for wave periods smaller than 13 s, the MARINTEK results are smaller than the INSEAN results, mainly because the MARINTEK model submerged deeper, and there are smaller wave excitation forces on the torus. The mooring force RAOs are significantly larger for the MARINTEK model, this is due to the large spring mass, which make the mooring line inertia effect more prominent (Wan et al., 2014a).

For the MWL mode, the results are shown in Figure 8. The mooring line dynamic effect is also significant for the MARINTEK model. For the other response parameters, the comparisons have reasonable agreement except for the Fz under resonant region, i.e., about 13 s, when weak water entry and exit were observed. It can be seen that there are disturbance in all the response parameters at the resonant region.

By comparison of the two survival modes, in the SUB mode, the heave motion and the Fz are significantly reduced, which is of great importance for structural integrity. However, the surge and pitch motion are larger for the SUB mode to some extent. This is because the heave natural period is shifted out of the wave region, while the pitch natural period is closer to the wave region for the SUB mode compared to the MWL mode. The surge in the RAO is mostly induced by pitch motion.

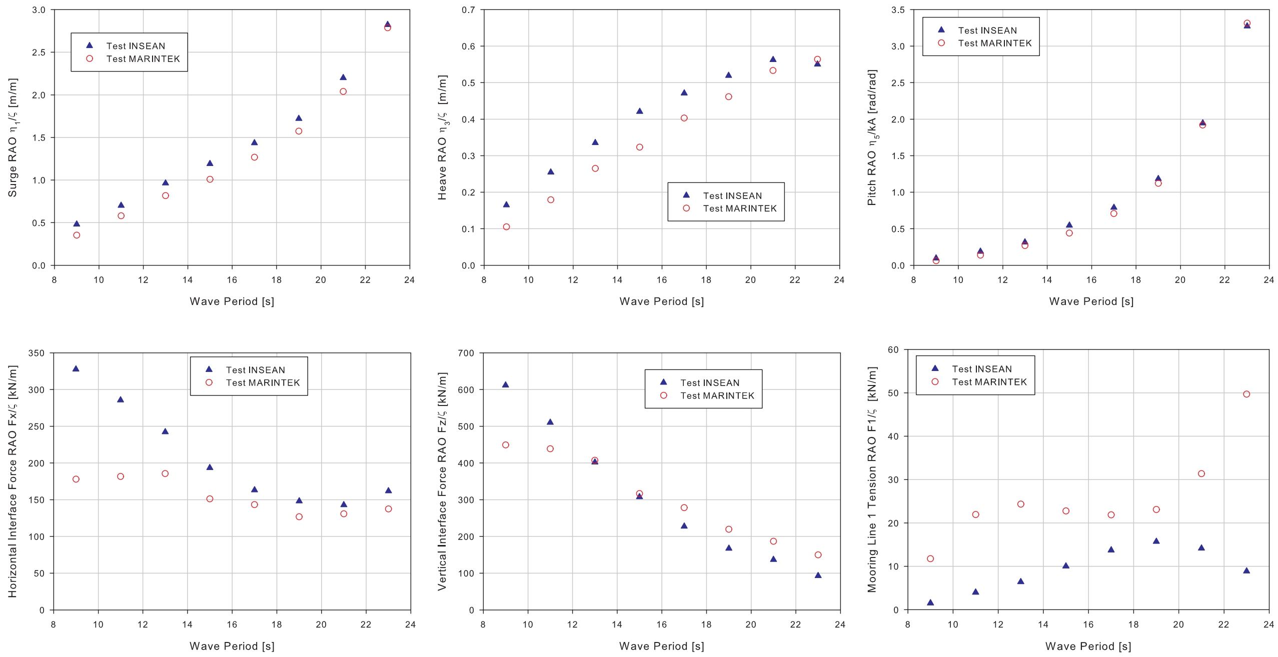

Figure 7. Comparison of RAOs of motions and forces for the MARINTEK and INSEAN tests under the SUB survival mode (Top, from left: surge, heave and pitch; Bottom, from left: Fx, Fz and Mooring line 1 tension F1)

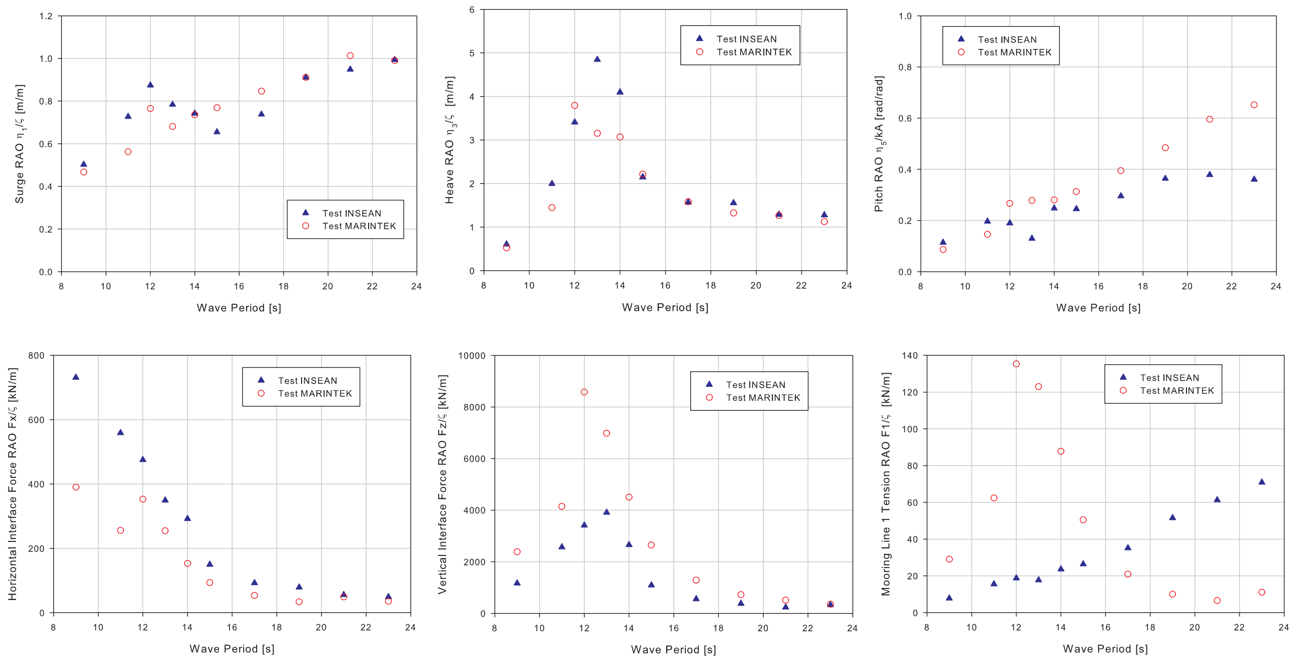

Figure 8. Comparison of RAOs of motions and forces for the MARINTEK and INSEAN tests under the MWL survival mode (Top, from left: surge, heave and pitch; Bottom, from left: Fx, Fz and Mooring line 1 tension F1)

7. Response obtained in irregular wave tests

In this section, the model tests for irregular wave conditions are presented, and the selected sea state is Hs=15.3 m, Tp=15.5 s.

7.1. Input wave

The waves generated in the model tests follow JONSWAP spectra. For the extreme sea state of Hs=15.3 m, Tp=15.5 s, six realizations were performed, and the statistics of each realization based on 1 hour steady state data are analyzed. Then the average of the six sets of mean, STD, maximum and minimum values are calculated and considered in the comparison to reduce the statistical uncertainty. The wave spectra are also averaged based on the six realizations. For the two model tests under both survival modes, the same method was applied to get the averaged data. The averaged wave statistics and wave spectra are plotted in Figure 9, in which the target wave spectrum is also presented.

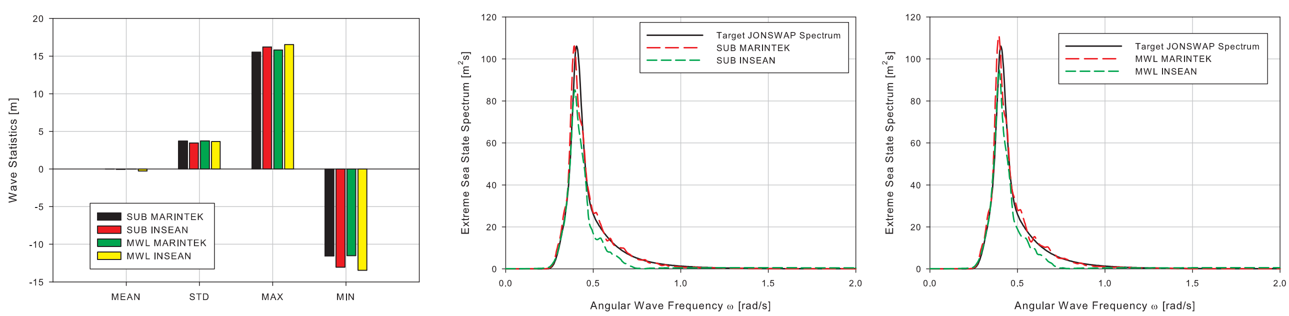

Figure 9. Averaged wave statistics and wave spectra of the generated waves under extreme sea state of Hs=15.3 m, Tp=15.5s

The comparisons of the input waves between the two model tests show good agreements. For the two survival modes in the same model test, the statistical properties of the generated waves are very close. In general, the waves generated in MARINTEK test have larger STD, but smaller peaks, which can also be reflected by the spectral comparisons. The uncertainties of the results might due to the insufficient times of realization and wave reflections. Quantitative analysis will be presented later.

7.2. Response statistics and spectra under extreme conditions

Under the extreme sea state of Hs=15.3 m, Tp=15.5s, six sets of data for the dynamic responses were recorded. The averaged values for the mean, STD, maximum and minimum values based on the same time window and the same analyzing method are calculated. The averaged statistics are shown in Figure 10 and the averaged response spectra are shown in Figure 11.

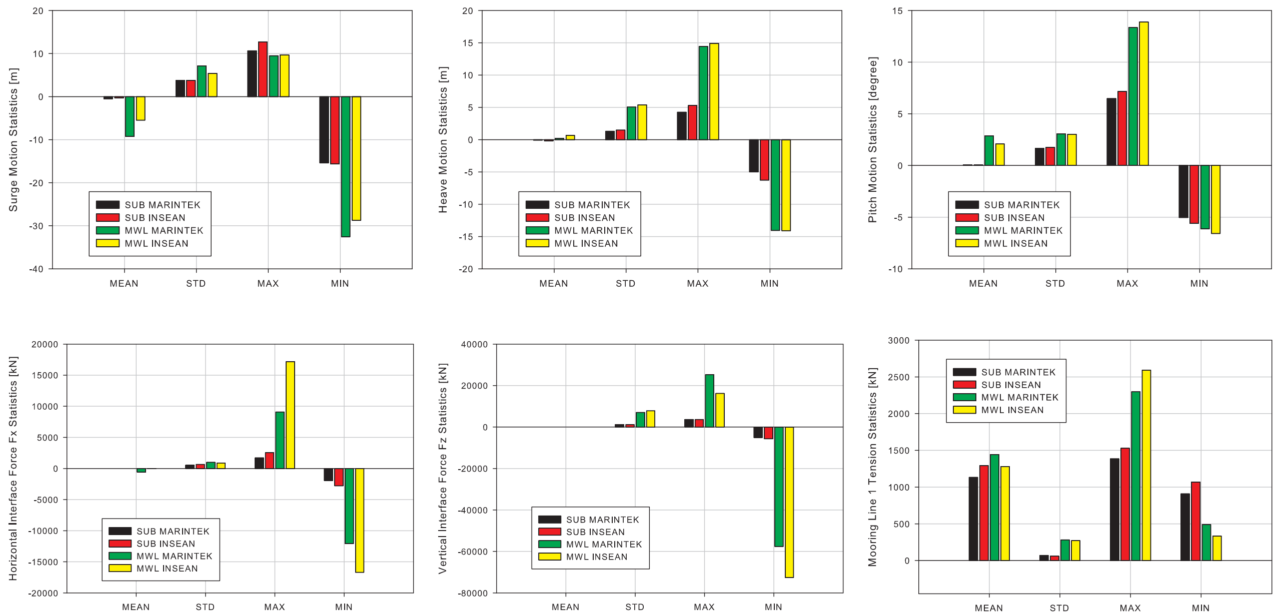

Figure 10. Averaged statistical values for the motion, interface force and mooring line tension responses under extreme sea state of Hs=15.3 m, Tp=15.5s (Top, from left: surge, heave and pitch; Bottom, from left: Fx, Fz and Mooring line 1 tension F1)

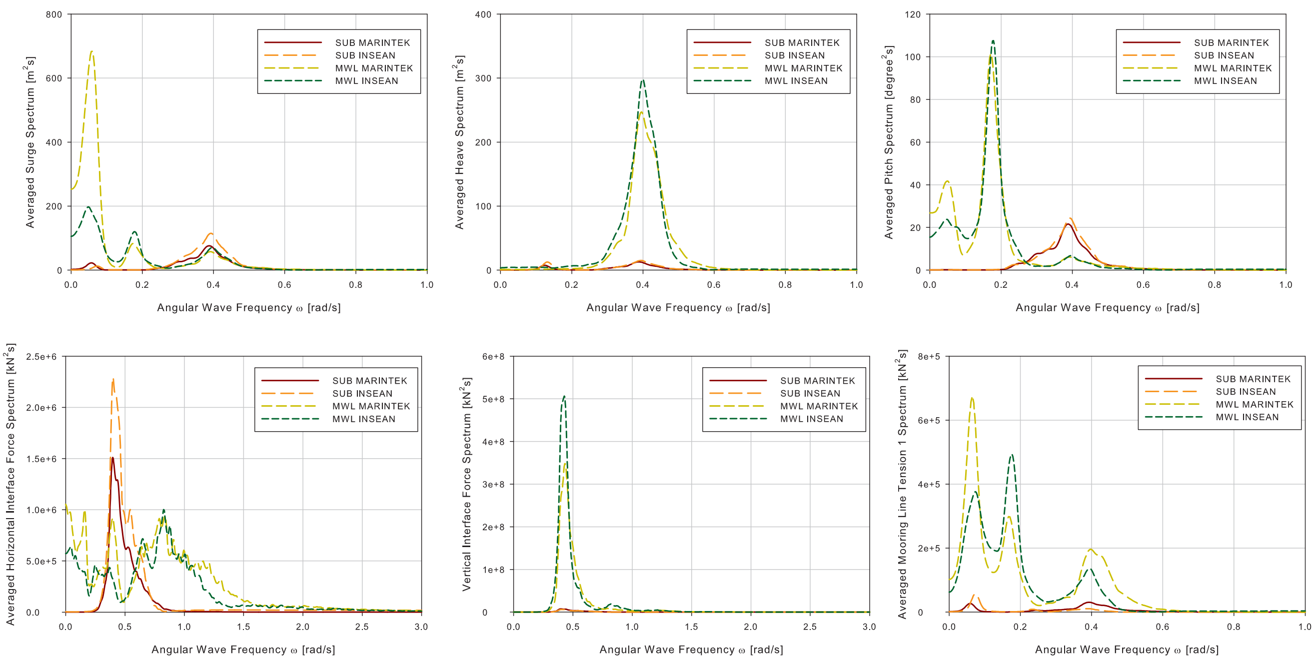

Figure 11. Averaged response spectra for the motion, interface force and mooring line tension under extreme sea state of Hs=15.3 m, Tp=15.5s (Top, from left: surge, heave and pitch; Bottom, from left: Fx, Fz and Mooring line 1 tension F1)

In Figure 10, there are some differences between the MARINTEK and INSEAN tests for both modes. In general, the responses for the MWL mode have larger STD, larger maximum values and smaller minimum values than the responses for the SUB mode, except for the surge positive maximum. It means that the responses under the MWL mode are larger than that for the SUB mode. By comparison of the same survival mode in two different model tests, there are relatively good agreements for all the response parameters, except for the maximum and minimum interface force responses under the MWL mode where a large difference is observed. This is because in the MWL mode, water exit and entry, i.e., wave impact was observed and it induced large impact forces. The impact force peaks are very sensitive to the impact velocity and deadrise angle of the torus bottom. Another reason could be the insufficient time of average based on six realizations of the sea state.

In Figure 11, the response spectra are presented. The wave frequency peak is about 0.4 rad/s, the surge, heave and pitch resonant frequency are about 0.06 rad/s, 0.49 rad/s and 0.17 rad/s for the MWL mode, and are about 0.06 rad/s, 0.14 rad/s and 0.24 rad/s for the SUB mode respectively. For the MWL mode, the surge and pitch resonance are dominant in the surge and pitch motions due to second order wave forces, and the heave resonance is observed in the heave motion due to the first order wave force, while for the SUB mode, the second order responses are significantly reduced compared with that for the MWL mode and the wave frequency responses are dominant. In the interface force spectral, there are wave frequency responses in Fx and Fz for the SUB mode; while the responses in Fx and Fz are under a large range of frequencies for the MWL mode, because of the strong wave impact, and the response peaks are much higher for the MWL mode compared with that under the SUB mode as shown in Figure 10. In the mooring line tension response, surge and pitch resonant components are dominant for the MWL mode, where wave frequency responses are also observed.

7.3. Comparisons between two model tests under extreme conditions

In this section, the comparisons between two model tests under the same survival mode, SUB mode or MWL mode are made quantitatively. The comparisons are based on the results of response statistics, and focus on the STD, maximum and minimum values for all the measured response parameters. The results from the MARINTEK test are taken as reference for the relative difference calculation. They are calculated as (INS.-MAR.)/abs(MAR.), in which the 'INS.' represents the results from the INSEAN test, and the abs(MAR.) means the absolute values of results from the MARINTEK test. The relative differences are presented in Figure 12.

The comparisons for the SUB mode are shown on the left plot in Figure 12. The input wave relative differences for the STD are smaller than 10% for the SUB mode, which means the input waves STD in the MARINTEK test is larger than that in the INSEAN test by less than 10%. The model submerged depths are different for the two model tests, the MARINTEK model was submerged by 26 m rather than the 19.5 m in the INSEAN test as shown in Table 4, which means the wave excitation forces on the torus would be reduced. In this case, the INSEAN test results are generally larger than that in the MARINTEK test, which can be also observed from Figure 10. The mooring line tension 1 for the MARINTEK model in the SUB mode has large STD due to the mooring line dynamics.

The comparisons for the MWL mode are shown in the right plot of Figure 12. The input wave STD difference is negligible. There is large STD difference in surge motion, because the slow drift motion is significant in the MWL mode, and there are different surge resonant periods for the two different tests. From the regular wave test results, the surge RAO under the SUB mode is larger than that under the MWL mode, but the RAO is based on the linear responses. In irregular wave tests, the STC has larger surge motion due to the slow drift effect under the MWL mode, which is caused by the large radiation of the torus according to Marou's formula (MAURO, 1960) and Pinkster's formula (Pinkster, 1975). For the Fx and Fz under the MWL mode, there are large difference in the force peaks, approximately 90% for Fx and 35% for Fz, which come from the wave impact. The heave motion difference due to the water exit and entry is relative small, which means the force responses are more sensitive than the motions when there are wave impacts.

In these comparisons, when the test statistics are small, the relative differences would be large even the absolute difference is not significant. But still, the significant differences can be observed through the comparisons and they may come from a variety of sources: the input waves are different; the mass properties have different values with a difference less than 10% (Table 3); and the natural periods of the two models are different, but with negligible relative difference except the 20% difference in surge (Table 5); there are different submerged depth for the two model tests (Table 4);

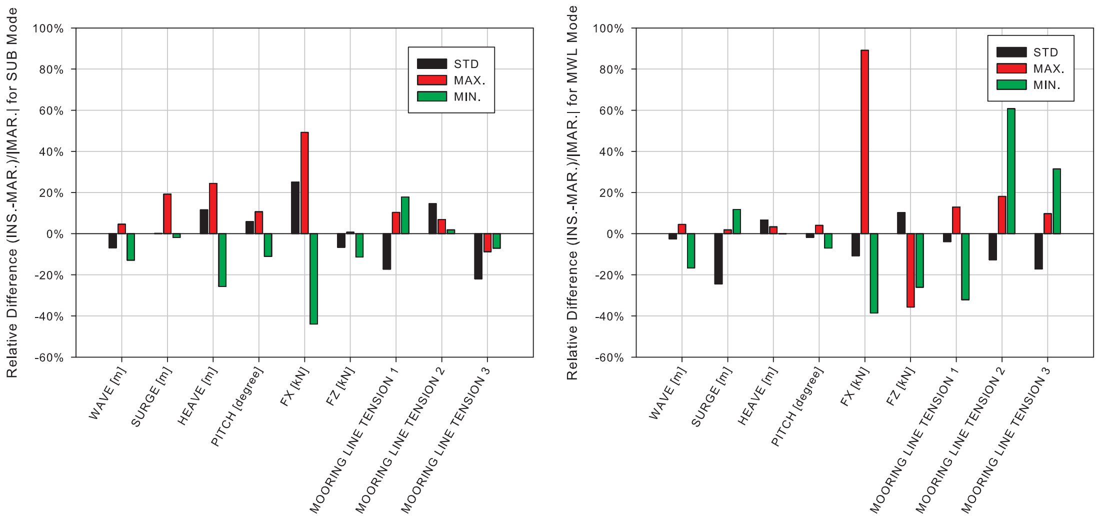

Figure 12. Relative differences of response statistics between the INSEAN and MARINTEK tests for all the parameters under the SUB mode (Left) and the MWL mode (Right)

7.4. Comparisons between the SUB and MWL modes under extreme conditions

In each testing facility, two survival modes were tested. In this section, the comparisons between the two survival modes in the MARINTEK test and in the INSEAN test are presented in Figure 13. The INSEAN test results are shown on the left plot, while the MARINTEK test results are shown on the right plot. The comparisons are based on the results of response statistics, and focus on the STD, maximum and minimum values for all the measured response parameters. The relative difference is calculated as (MWL-SUB)/abs(SUB), with the absolute values of the test results under the SUB mode as a reference.

Under the SUB survival mode, the STC performance is much better with smaller responses, especially the forces between the spar and the torus. Under the MWL mode, the heave motion STD increases about 300%, the Fx peaks about 500%, the Fz STD about 600%, the negative peak about 1100%, and the mooring forces also increase significantly as compared to those under SUB mode. The relative differences between the two survival modes are generally the same for the two different model tests, which shows that the consistent results are achieved in the two different testing facilities.

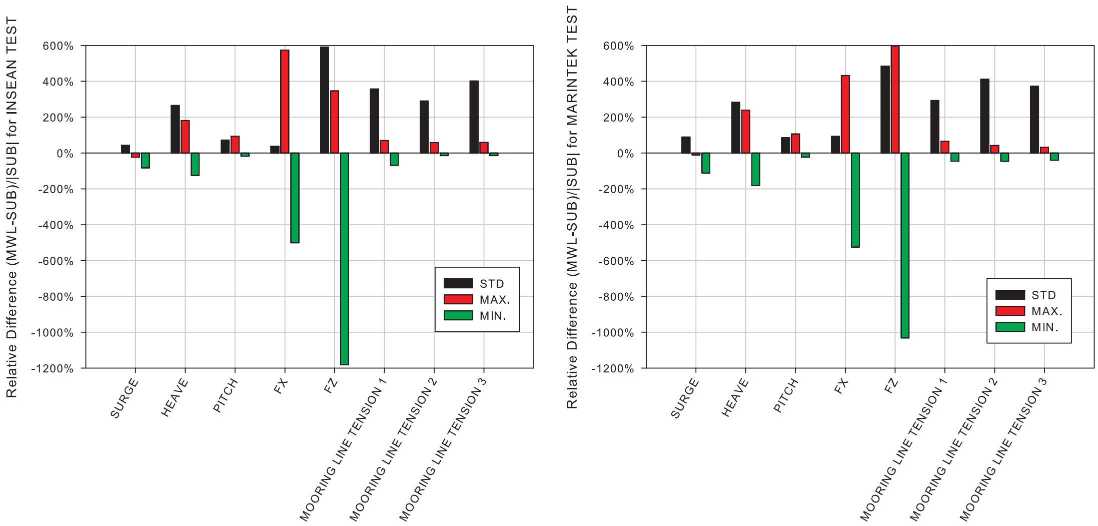

Figure 13. Relative differences of response statistics between the SUB mode and the MWL mode for all the response parameters in the INSEAN test (Left) or the MARINTEK test (Right)

8. Wind effect

Wind was generated in the model tests to model the correct wind thrust on the rotor of the prototype. In this section, the MARINTEK test results are presented. The wind speed is 38 m/s in extreme conditions, and the wind was generated corresponding to the extreme sea states. The sea states generated are the same with those in the irregular wave tests with no wind, and several realizations are performed. The statistical results for each realization are calculated, and average values based on all the realizations are derived and used in the comparison. The averaged statistical values of the dynamic responses for the extreme wave+wind conditions and for the extreme wave only conditions in the MARINTEK test under both survival modes are presented in Figure 14.

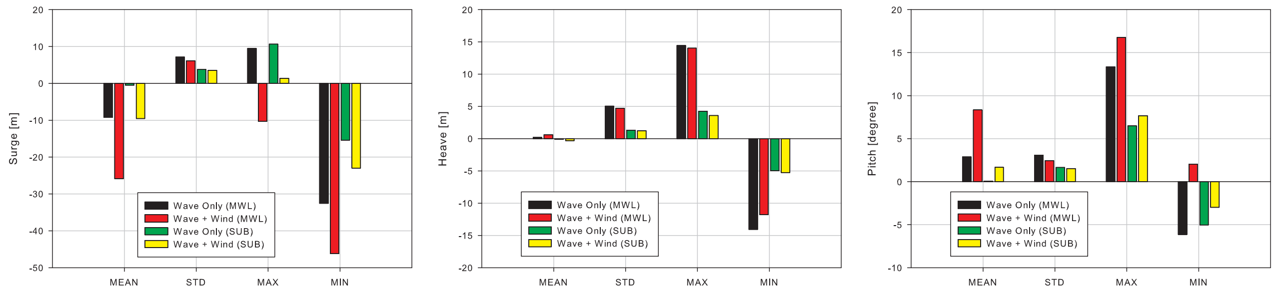

Figure 14. Dynamic responses under extreme wave+wind conditions in the MARINTEK test under the SUB and MWL modes compared to the irregular wave only cases (From left, surge, heave, pitch)

The surge and pitch motions are the most significantly affected by the extreme wind, and the mean, maximum and minimum values are mostly affected statistical values. Generally, the dynamic responses are affected more by the wind under the MWL mode rather than under the SUB mode due to the larger exposure area to the wind. The STD values are generally smaller with the presence of wind compared with those without wind.

9. Validation of a numerical model against the INSEAN test

In this section, a numerical model is briefly described and the validation against the INSEAN model test is presented. The numerical model is based on a hybrid frequency and time domain method (Naess and Moan, 2012) and is modeled and solved in SIMO (MARINTEK, 2007). Detailed numerical modelling methods can be found in the paper about the numerical and experimental comparisons of the MARINTEK test (Wan et al., 2014a). The same numerical methods are used in this paper for the comparison against the INSEAN model test results. The natural periods from the numerical model can be found in Table 6, a very good agreement can be seen in Table 5 as compared to the test results. The comparisons between the model test and numerical results for regular and irregular conditions under the SUB survival mode are presented in Figure 15 and Figure 16, respectively. It can be seen that the numerical model can predict the responses well under the SUB mode. In Figure 16, there is heave resonance (0.14 rad/s) due to the wave difference frequency in the model test, but this difference frequency effect is not taken into consideration for the heave mode in the numerical model, which is the reason that the numerical model underestimates the responses. Under the MWL mode, when there are strong nonlinear phenomena of water entry and exit, the numerical model failed to predict the responses. The results for the MWL mode are not presented here. The same conclusions were obtained in (Wan et al., 2014a) for the comparison of the MARINTECK test results.

Table 6. The natural periods from the numerical model

	SURGE	SWAY	HEAVE	ROLL	PITCH
SUB	77.6	77.6	44.3	25.6	25.6
MWL	76.6	76.6	12.5	34.7	34.7

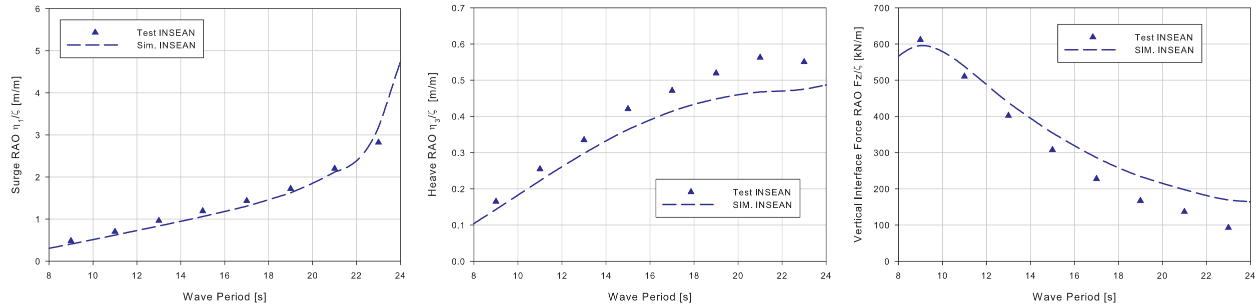

Figure 15. Comparisons between test and numerical RAO results under the SUB mode based on the INSEAN test (From left, surge, heave, Fz)

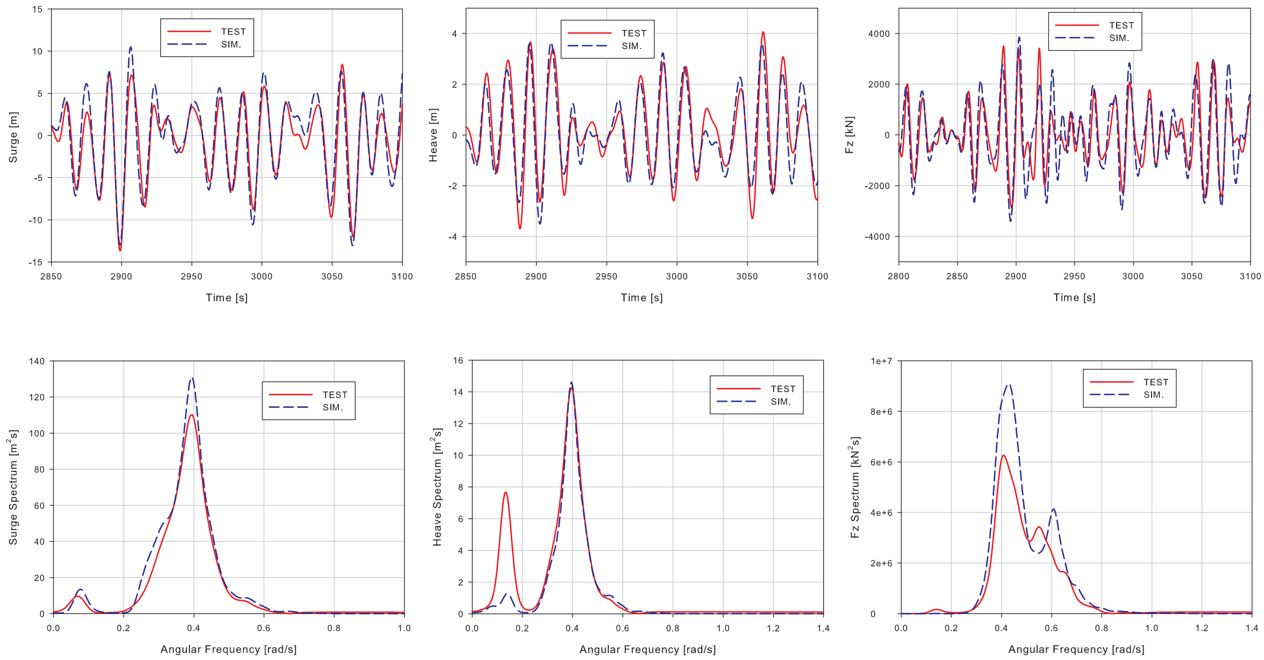

Figure 16. Comparisons of time series (Top) and spectra (Bottom) between test and numerical responses in extreme sea state under the SUB mode based on the INSEAN test (Top, from left, surge, heave, pitch; Bottom, from left: surge, heave, pitch)

10. Discussion and concluding remarks

In this paper, a combined wind and wave energy converter named spar torus combination concept are presented. The model tests of the STC concept under extreme conditions with focus on the two different survival modes were carried out. The STC model tests performed in the INSEAN towing tank are described in detail, and another test in the MARINTEK towing tank is briefly introduced. The common features and also the differences in the model properties and the test setups between the two tests are discussed.

The two model tests have similar geometries, but slightly different configurations, e.g., mooring stiffness, radius of gyrations and other parameters, which result in slightly different natural periods of rigid-body motions. The largest difference of about 20% occurs for the surge natural period. In addition, the two models have different drafts for the SUB mode, the submerged depth is 26 m for the MARINTEK model rather than 19.5 m for the INSEAN model. This leads to different wave excitation forces and therefore motion responses.

The regular wave test generally results in very similar RAOs between the two model tests. For the interface forces between the spar and the torus in the heave resonant region under the MWL mode, a large discrepancy is observed due to the water entry and exit problem which leads to a larger statistical uncertainty. In addition, the mooring line dynamic effects are significant for the MARINTEK test, and result in the discrepancies in the mooring line tension RAO.

Under irregular extreme conditions, the input averaged wave spectra for both model tests are very close to the target spectrum. The relative difference of the input wave STD between the two model tests are below 10%. The waves generated in MARINTEK test have a larger STD.

The INSEAN test results are generally larger than those in the MARINTEK test under the SUB mode, due to a smaller submerged depth and therefore larger wave excitation forces. There is also a large STD difference in surge motions between the two model tests under the MWL mode, due to the different surge natural periods and the significant slow drift motions. The water exit and entry problem under the MWL mode in the extreme sea states results in strong nonlinear phenomena, and large impact forces, which are very sensitive to the impact velocity and deadrise angle and result in a large difference between the two model tests. The interface forces are more sensitive than the motion responses in this case.

The averaged responses under the SUB mode are significantly smaller than that under the MWL mode because the heave natural period is shifted outside of the frequent wave period range and the wave excitation forces are significantly reduced by the total submergence of the torus. The increase of the responses under the MWL as compared to those under the SUB mode is listed as follows: the heave motion STD is about 300%, the Fx peak about 500%, the Fz STD about 600% and the negative peak is about 1100%.

The wind effects on the dynamic responses considering the mean wind speed are mainly on the surge and pitch motions. The dynamic responses are affected more by the wind under the MWL mode than under the SUB mode and the STD values of the responses are generally smaller with the existence of wind.

In the last section of the paper, a numerical validation work is carried out for the INSEAN model, similar conclusions from the validation of the numerical model with respect to the MARINTEK test (Wan et al., 2014a) are achieved.

Acknowledgements

The authors gratefully acknowledge the financial support from EU through the Marinet (Marine Renewables Infrastructure Network) project for the free access to the testing facility in CNR-INSEAN and through the MARINA Platform project (Marine Renewable Integrated Application Platform, Grant Agreement 241402) both in the Seventh Framework Programme. The financial support from both the Center for Ships and Ocean Structures (CeSOS), NTNU and the China Scholarship Council (CSC) is also acknowledged.

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