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Comparative numerical and experimental study of two combined wind and wave energy concepts

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Abstract

With a successful and rapid development of offshore wind industry and increased research activities on wave energy conversion in recent years, there is an interest in investigating the technological and economic feasibility of combining offshore wind turbines (WTs) with wave energy converters (WECs). In the EU FP7 MARINA Platform project, three floating combined concepts, namely the spar torus combination (STC), the semi-submersible flap combination (SFC) and the oscillating water column (OWC) array with a wind turbine, were selected and studied in detail by numerical and experimental methods. This paper summarizes the numerical modeling and analysis of the two concepts: STC and SFC, the model tests at a 1:50 scale under simultaneous wave and wind excitation, as well as the comparison between the numerical and experimental results. Both operational and survival wind and wave conditions were considered. The numerical analysis was based on a time-domain global model using potential flow theory for hydrodynamics and blade element momentum theory (for SFC) or simplified thrust force model (for STC) for aerodynamics. Different techniques for model testing of combined wind and wave concepts were discussed with focus on modeling of wind turbines by disk or redesigned small-scale rotor and modeling of power take-off (PTO) system for wave energy conversion by pneumatic damper or hydraulic rotary damper. In order to reduce the uncertainty due to scaling, the numerical analysis was performed at model scale and both the numerical and experimental results were then up-scaled to full scale for comparison. The comparison shows that the current numerical model can well predict the responses (motions, PTO forces, power production) of the combined concepts for most of the cases. However, the linear hydrodynamic model is not adequate for the STC concept in extreme wave conditions with the torus fixed to the spar at the mean water level for which the wave slamming on the torus occurs and this requires further investigation. Moreover, based on a preliminary comparison of the displacement, the PTO system as well as the wind and wave power production, the STC concept will have a lower cost of energy as compared to the SFC concept. However, the cost of energy of either the STC or the SFC concept is higher than that of a pure floating wind turbine with the same floater.

Keywords: Combined wind and wave energy concept; Floating wind turbine; Wave energy converter; Numerical analysis; Model test.

1. Introduction

Offshore wind technology has been rapidly developed in recent years and led to large-scale commercial deployment of offshore wind farms with an average annual increase in installed capacity about 30% since 2010. The total installed capacity around the globe by end of 2013 is 6.59 GW, with Europe as the main contributor [12], accounting for about 93%. Most of the offshore wind turbines today are deployed on bottom-fixed structures, such as monopile, tripod and jacket, since the water depth in most of the commercial wind farms today is limited, up to 40–50 m. However, there exists an increasing interest in developing floating wind turbines for deep water in particular in Scotland, Japan and US. Research work has been carried out worldwide considering different types of floaters, such as spar, semi-submersible and TLP. There

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are no commercial wind farms based on floating structures yet, but prototypes have already been tested at sea. Statoil installed the world´s first floating wind turbine, Hywind with a 2.3 MW Siemens turbine, in 2009 [37]. A semi-submersible floating wind turbine, WindFloat with a 2 MW Vestas turbine, was launched in 2011 [34]. Two floating wind turbines were installed in late 2013 in Japan, a semi-submersible developed by Mitsui with a Hitachi 2 MW downwind turbine [5], and a hybrid spar developed by a Kyoto University and Toda Corporation with a Hitachi/JSW 2 MW turbine [8].

The technology of wave energy conversion is also being actively developed in recent years, but it is not mature yet for large-scale commercial deployment. In contrast to offshore wind turbines, wave energy converters span a wide range of different concepts and do not converge to a particular concept for commercialization. According to the principle of wave energy conversion [4], different concepts can be categorized as oscillating bodies, oscillating water column, overtopping device or others (such as cycloid turbine wave absorber, submerged pressure differential device). According to IEA [13] a number of prototypes of wave energy converters at various scales have been tested or are being tested at sea with the total installed and approved-for-installation wave energy power around 125 MW (76 MW in Europe, 43 MW in Oceania, 4 MW in Asia and 1.5 MW in North America).

Commercial wind or wave farms are expected to occupy a large ocean space. It might be beneficial to combine these devices of different technology in a farm configuration or even into one platform. Individual WTs or WECs, either bottom-fixed or floating, can be placed or connected in a farm configuration and the possible synergy in view of cost reduction will be related to the share of ocean space as well as infrastructure of the farm (such as power substation, power cable, anchors, etc.). Furthermore, WTs and WECs can be combined on one platform and increased power production might be achieved due to the coupling effect between WT and WEC motions. The EU FP7 MARINA Platform project [21] is one of such projects that have addressed the integration of wind and wave energy devices on a single platform with focus on floating concepts for deep water application. Other EU-supported projects that develop offshore multi-purpose renewable energy conversion platforms are ORECCA [32], TROPOS [38], H2Ocean [11] and MERMAID [26].

In the MARINA project, three combined concepts, namely the spar torus combination (STC) [30], the semi-submersible flap combination (SFC) [27] and the oscillating water column array with a wind turbine [7], were selected as final concepts for detailed numerical and experimental studies. It should be noted that these studies were carried out based on a preliminary design of the two combined concepts and no engineering work for detailed design was made. More research work needs to be done in order to bring any combined concept into the market. One of the tasks in the MARINA project is to develop numerical methods and tools as well as experimental techniques that have generic value for modeling, analysis and assessment of any combined wind and wave concept, rather than to develop and recommend a specific design of combined concepts for commercial deployment. The numerical and experimental study is also the focus of this paper.

This paper starts with a brief description of the two combined concepts (STC and SFC), and the methods for numerical modeling and analysis. Then the model tests of the two concepts and in particular the experimental techniques that were used for modeling of WT rotors and WEC PTO systems in labs, are presented, followed by a comparison between the numerical and experimental results of selected responses (such as motions, PTO forces and power production). Finally, we conclude our study and make recommendations for future work.

2. Combined wind and wave energy concepts

Among the three combined concepts studied in the MARINA project, the STC and SFC concepts are basically the floating wind turbine concepts with add-on WECs, while the third concept (the OWC array) represents a concept of adding one WT on a large-size floater accommodating multiple WECs. The same 5 MW NREL wind turbine [14] is considered for the three concepts, but the type of floaters and WECs are different.

The STC concept [30] (Fig. 1, left) consists of a spar floater to support a 5 MW wind turbine and an axisymmetric wave energy converter (torus) that heaves along the spar to extract energy from waves through a hydraulic PTO system. It is moored by a three-line catenary system. In addition to the operational modes, two survival modes of the WEC (the MWL and the SUB modes) were studied for this concept considering extreme wind and wave conditions in which the WEC PTO system is disconnected. In the MWL mode, the torus WEC is locked to the spar at the mean water level, while in the SUB mode, the torus WEC is locked to the spar at a submerged position. This can be achieved by adding ballast water to the spar or to the torus. For the operational modes, the spar and the torus have the same ballast conditions as those of the MWL survival mode.

The SFC concept [27] (Fig. 1, right) is a combined concept of semi-submersible wind turbine with three flap-type wave energy converters. It consists of a semi-submersible floater,

Fig. 1. The STC (left) and the SFC (right) concepts.

Table 1
Main properties of the STC and the SFC concepts.

	STC	SFC
Platform		
Width (m)	9.4	83.3
Height (m)	130	50
Draft (m)	120	30
Displaced volume (m^3)	8674 (MWL) 9317 (SUB)	10,470
Mass (ton)	8194 (MWL) 9998 (SUB)	11,322
WEC		
Rated power (kW)	500	350 (including the 3 WECs)
Number of WECs	1	3
Width (m)	20	20
Displaced volume (m^3)	1117 (MWL) 2234 (SUB)	384 (each of the 3 WECs)
Mass (ton)	1145 (MWL) 1145 (SUB)	100 (each of the 3 WECs)
Wind turbine (NREL 5 MW)		
Rated power (kW)	5000	
Rotor diameter (m)	126	
Total mass (ton)	697	
Nacelle height (m)	90 above mean water level	

with one central column to support a 5 MW wind turbine and three side columns that are connected to the central column by three pontoons, and three rotating flaps considered as wave energy converters that are hinged at the three pontoons, respectively. The flaps have an elliptical cross section and are fully submerged below the free surface. The wave energy is absorbed via rotation of the flaps and is converted into electricity through a hydraulic PTO system. The SFC is also moored by a three-line catenary system. In both operational and survival modes, the ballast conditions of the semi-submersible and the WECs are kept the same. The WEC PTO system is disconnected for survival conditions.

The main properties of the two concepts are listed in Table 1. Both concepts support the same NREL 5 MW wind turbine. The STC concept has a smaller total displacement as compared to the SFC concept and the spar structure with less welding work is cheaper to build as compared to the semi-submersible floater. Moreover, the STC concept applies only one WEC PTO system, while the SFC concept has three. These indicate that the cost of the STC would be smaller than that of the SFC. On the other hand, the STC produces more wave power although the wave power is only 5–10% of the total power production. As a result, the cost of energy of the STC is expected to be smaller than that of the SFC.

3. Numerical modeling of combined concepts

The main purpose of numerical analysis of combined concepts is on one hand to estimate the power absorption of both WTs and WECs, and on the other hand to predict the external aerodynamic and hydrodynamic loads and induced-motion and structural responses of the WT and WEC system and components for ULS (ultimate limit state) and FLS (fatigue limit state) design check. After solving the dynamic responses of a combined concept in wind and waves, power production of WTs or WECs can be obtained straightforward based on the characteristic power curve of WT generator or WEC PTO system. The focus of this paper is the global dynamic response analysis of combined concepts for design of structural components (including WT rotor, tower, floater, WECs and mooring lines). Design of mechanical components (such as drivetrain in WTs) or hydraulic components (such as WEC PTO systems) usually requires a hierarchical analysis method in which a global analysis is performed first using a simplified model (normally with one degree of freedom) of such components, followed by analysis with a detailed multi-body model or finite element model of these components. This will not be discussed in the present paper, but the reference is made to Xing et al. [40] and Yang et al. [41].

Depending on the purpose of analysis, aerodynamic and hydrodynamic loads might be modeled as integrated force/moment, distributed force/moment or distributed pressure, and structural components might be modeled as rigid bodies, flexible beam or shell finite elements for structural response analysis, respectively.

For wind turbine aerodynamics, the BEM (Blade Element Momentum) theory [10] is normally used with engineering corrections for dynamic wake, dynamic stall, tip loss, etc. Typically, aero-elasticity is considered since the flexible eigen-modes of blades and tower are normally excited by wind loads. More advanced analysis methods, such as Navier–Stokes solvers (CFD (Computational Fluid Dynamics)) [10], can be used to estimate the pressure distribution on a 3-D blade structure, but it is too time-consuming for design analysis of wind turbines. If the wind turbine is simplified as a disk for example in model tests, the drag force can be modeled by considering a proper drag coefficient of the disk.

Hydrodynamic loads on floaters or WECs might be estimated using potential flow theory or the Morison's formula. When applying the potential flow theory, hydrodynamic coefficients of added mass and potential damping as well as 1st- and 2nd-order wave excitation loads are obtained in frequency domain using a panel code for example WAMIT [19] and then applied in time domain simulations of dynamic motions of the floater in which viscous effect can be included as drag forces on the structure components. Fully nonlinear potential flow models or CFD [20] can be used to capture wave breaking and other highly nonlinear phenomena for extreme wave conditions.

Although there are no numerical tools that are developed specifically for analysis of combined wind and wave concepts, WT analysis tools and to some extent WEC analysis tools do exist. Integration of the onshore wind technology and the offshore oil and gas technology has resulted in a significant development of numerical tools for analyzing offshore wind turbines. In general, these tools [15] are developed

Table 2
Basic features of the STC and SFC numerical models.

Components	STC		SFC	
	Structural model	External load model	Structural model	External load model
WT	Rigid disk	Gravity, wind drag force	Rigid rotor (beam elements)	Gravity, aerodynamics (blade element momentum theory)
WEC	Torus, rigid body	Gravity/buoyancy, 1st- and 2nd-order (Newman's approx.) wave loads, drag force	Three flaps, rigid bodies	Gravity/buoyancy, 1st- and 2nd-order (Newman's approx.) wave loads, drag force
Tower	Rigid body	Gravity, wind drag force	Flexible tower (beam elements)	Gravity, wind drag force
Floater	Spar, rigid body	Gravity/buoyancy, 1st-order wave loads, drag force	Semi-submersible, rigid body	Gravity/buoyancy, 1st- and 2nd-order (Newman's approx.) wave loads, drag force
Mooring system	Linear springs	No external load	Flexible mooring lines (beam elements)	Gravity/buoyancy, Morison-type hydrodynamic loads

Table 3
Modeling of different parts of the STC and SFC concepts for lab testing.

Components	STC		SFC	
	Functionality test (operational conditions)	Survivability test (survival conditions)	Functionality test (operational conditions)	Survivability test (survival conditions)
WT	Disk, wind turbine thrust force represented by drag force	Disk, wind turbine thrust force represented by drag force	Redesigned small-scale rotor, blade pitch angle manually adjustable, but fixed for each test case	Redesigned small-scale rotor, blade pitch angle adjusted to zero for parked condition
WEC	Rigid, PTO modeled using pneumatic damper, PTO force measured, contact forces between torus and spar measured	Torus locked to spar, forces between torus and spar measured	PTO modeled as hydraulic rotary damper, forces in structural arms measured	Flaps free to rotate, forces in structural arms measured
Tower	Rigid, force at tower top measured	Rigid, force at tower top measured	Flexible, forces at tower top and base measured	Flexible, forces at tower top and base measured
Floater	Rigid	Rigid	Rigid, cross-sectional loads on one pontoon measured	Rigid, cross-sectional loads on one pontoon measured
Mooring system	Springs, tension measured	Springs, tension measured	Scaled mooring lines, fairlead tension measured	Scaled mooring lines, fairlead tension measured

based on either a numerical code for onshore wind turbines by adding hydrodynamic modules, such as FAST, HAWC2, Bladed, 3DFloat, or a hydrodynamic and response analysis code coupled to a wind turbine aerodynamic module, such as SIMO-RIFLEX-AeroDyn [33]. Floating wind turbines differ from bottom-fixed wind turbines by their large rigid-body motions and strong coupling effect between wind- and wave-induced loads and responses. Typically, numerical analysis is performed in time domain in order to capture nonlinear effects from aerodynamic or hydrodynamic loads, nonlinear geometrical effects due to large motions, and automatic control. These developed numerical tools have been extensively used to study the dynamic behavior of different type of floating wind turbines supported by spar, semi-submersible, TLP, barge, etc. [2,3,16–18]. For analysis of WECs, tailor-made numerical codes or some commercial codes (such as ANSYS-AQWA, OrcaFlex) can be used. Hydrodynamic analysis of WECs is normally based on potential flow theory with hydrodynamic interaction considered for multi-body problems. PTO system is usually simplified as damper (and spring) in the dynamic model for WEC motion analysis.

The numerical models for the STC and SFC concepts in this paper were established using SIMO-RIFLEX-AeroDyn [33], developed by MARINTEK and CeSOS/NTNU, which is capable of analyzing combined floating wind turbines and wave energy converters. SIMO [23] is used to model the time-domain hydrodynamic loads on rigid-body floating structures (floater and WECs), including the first-order and second-order wave loads. RIFLEX [24] is a nonlinear time domain program with a finite element formulation that can handle large displacement and rotations. It is used to model hydrodynamic loads on slender structures (mooring lines) based on the Morison's formula and model aerodynamic loads on wind turbine blades using the code AeroDyn [29]. Structural models of the complete system are dealt with in RIFLEX and the equation of motion is solved in the time domain in RIFLEX.

Table 2 shows the structural and external load modeling of different parts in the STC and SFC concepts. The numerical models were established based on the actual configuration used in the model tests of the two concepts.

For the STC concept, the spar, torus, tower and WT disk are generally considered as rigid bodies, while mooring lines are modeled as linear springs. Aerodynamic loads on the WT disk and tower are modeled as drag force, while hydrodynamic loads on the spar and the torus were modeled considering the 1st-order wave loads and the drag force. In addition, the 2nd-order wave loads based on the Newman's approximation were considered for the torus, while the 2nd-order loads on the spar were negligible and not included. The WEC PTO system (pneumatic damper) is modeled as a quadratic damper for low velocity and a linear damper for high velocity for operational conditions. As mentioned above, the WEC PTO system is disconnected for survival conditions and the torus is locked to the spar either in the MWL mode or in the SUB mode.

For the SFC concept, the semi-submersible and the three flap-type WECs are considered as rigid bodies. WT blades are modeled as rigid beams as in the model tests, while tower and mooring lines are modeled as flexible beams. Aerodynamics on the WT was modeled using the blade element momentum theory. Hydrodynamic loads, including the 1st-, 2nd-order wave loads and drag forces, are considered for the semi-submersible and three WECs, while the loads on mooring lines are based on the Morison's formula. A hydraulic rotary damper is attached to the structural arm of each WEC at the position of connection to the pontoon to model the PTO system for operational conditions. In survival conditions, the PTO system is disabled and the WEC can rotate freely along its axis.

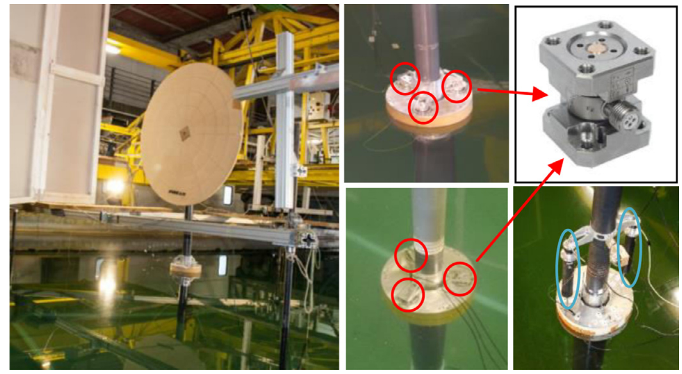

Fig. 2. The STC test model at INSEAN (left: overview of the test setup; middle-top: the MWL survival mode with three load cells (marked by the red circles) that measure the forces between the spar and the torus; middle-bottom: the SUB survival mode; right-top: one of the load cells; right-bottom: the operational mode with the torus connected to the spar by two pneumatic cylinders (marked by the blue ellipses) to model the WEC PTO damping).

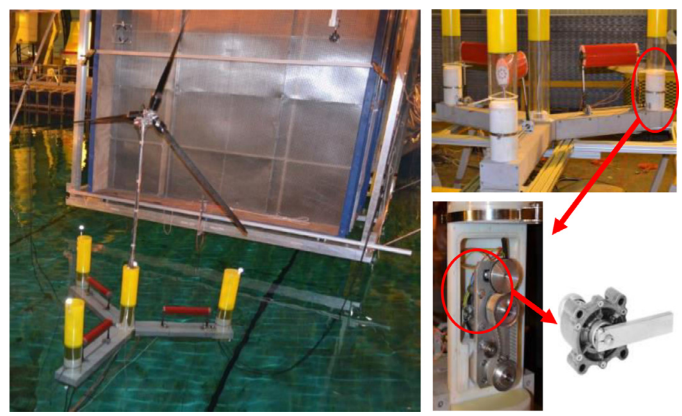

Fig. 3. The SFC test model at ECN (left: overview of the test setup; right-top: the three flap-type WECs connected to the pontoons; middle-bottom: the hydraulic rotary damper (marked by the red circles) inside one column; right-bottom: the hydraulic rotary damper to model the WEC PTO damping).

4. Model tests of the two combined concepts

Model tests under controlled environmental conditions in laboratories are important steps to study the dynamic behavior of offshore wind turbines and wave energy converters, and to validate numerical methods and tools. Our focus here are model tests performed at relatively small scales (1:30–1:100) in wave tanks or ocean basins.

A number of model tests have been conducted by other researchers for offshore wind turbines and in particular for floating wind turbines with different type of floaters (spar, semi-submersible and TLP). One particular uncertainty related to interpretation of the model test results is the scaling effect, since it is not possible to simultaneously scale both the aerodynamic loads according to the Reynolds law and the hydrodynamic loads using the Froude law [31]. Most of the tests of floating wind turbines apply the Froude scaling law since hydrodynamic loads are the most important loads for rigid-body motions which were the primary focus of such tests. Then, there are different methods for modeling a wind turbine rotor and its thrust force. The rotor may be simplified as a disk providing drag force [35] or a controlled fan providing active force [1] to mimic the thrust force. A geometrically-scaled rotor would produce less corresponding thrust force at model scale as compared to a full-scale rotor [6] and a re-design of the rotor blade is necessary to achieve the correct thrust curve [25]. Blade pitch angle in most of the tests was fixed for each test case, but can be manually adjusted for different runs. A recent test in MARIN utilized an active pitch control mechanism of blades, similar as what we can expect for a full-scale pitch-regulated wind turbine [9].

Model tests for wave energy converters typically follow the Froude law for scaling hydrodynamic loads. One of the difficulties is to model the WEC PTO system. Geometrically similar modeling of the PTO system is not generally appropriate because it is very difficult to achieve at very small scale [36]. The PTO system is often simplified as linear or quadratic damper.

For combined wind and wave energy concepts, model tests can also be used to investigate the coupling effect between the WT and WEC motions, which are of great importance for power production and structural design. Under the MARINA Platform project, functionality and survivability model tests of the SFC concept were performed in the ocean basin at ECN, France. The model tests of the STC concept were performed

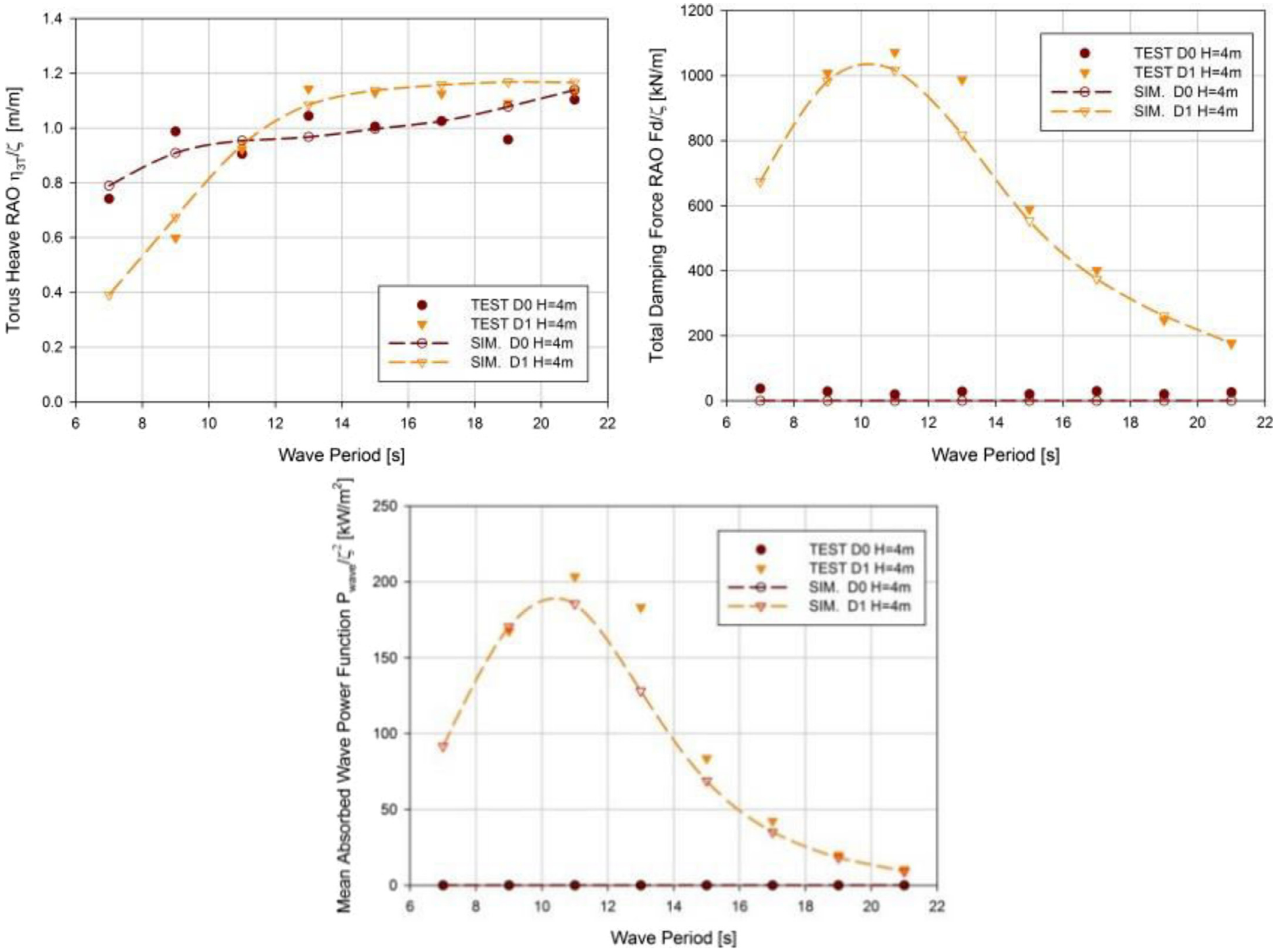

Fig. 4. Numerically and experimentally obtained RAOs of selected response parameters of the STC concept under the operational mode for regular wave conditions with $H = 4$ m (left-top: torus heave motion; right-top: WEC PTO damping force; middle-bottom: mean absorbed wave power).

in the towing tank of INSEAN, Italy, under the MariNet support [22]. A scale factor of 1:50 was considered for testing of both concepts. Table 3 summarizes how the different parts of the two combined concepts were simplified and modeled in the lab tests. Figs. 2 and 3 show the STC test model at INSEAN and the SFC test model at ECN, respectively.

In particular, depending on the purpose of testing as well as the dominance of the wind or wave loads, WT can be modeled as a scaled and redesigned rotor in the SFC test to represent the correct thrust force as function of wind speed, or a disk in the STC test to provide drag force to mimic the WT thrust. WEC PTO systems were chosen considering the principle of wave energy conversion, i.e. as a hydraulic rotary damper to represent the flap-type WEC in SFC and a pneumatic damper to represent the heaving-buoy WEC in STC. The primary objective is to model the damping effect due to wave power absorption. For survivability tests, the PTO system is not activated, and the WEC can either rotate freely as in the SFC concept or is locked to the floater as in the STC test.

As for the measurements, in addition to the wave elevation and the wind speed, the response signals of spar and torus motions, force at the tower top, PTO force of the pneumatic damper, forces between the spar and the torus and tension in mooring springs were measured in the STC test. While in the SFC test, motions of the semi-submersible and the three WECs, forces at the tower top and base, forces in the WEC structural arms, cross-sectional forces and moments at one location on one pontoon and mooring line tension at fairlead were measured.

More details about the model tests of the two concepts can be found in Wan et al. [39] and Michailides et al. [28], respectively.

5. Comparison of the numerical and experimental results for operational conditions

In the following, numerical simulations were performed at model scale and then both the numerical and experimental results were up-scaled to full scale according to the Froude law

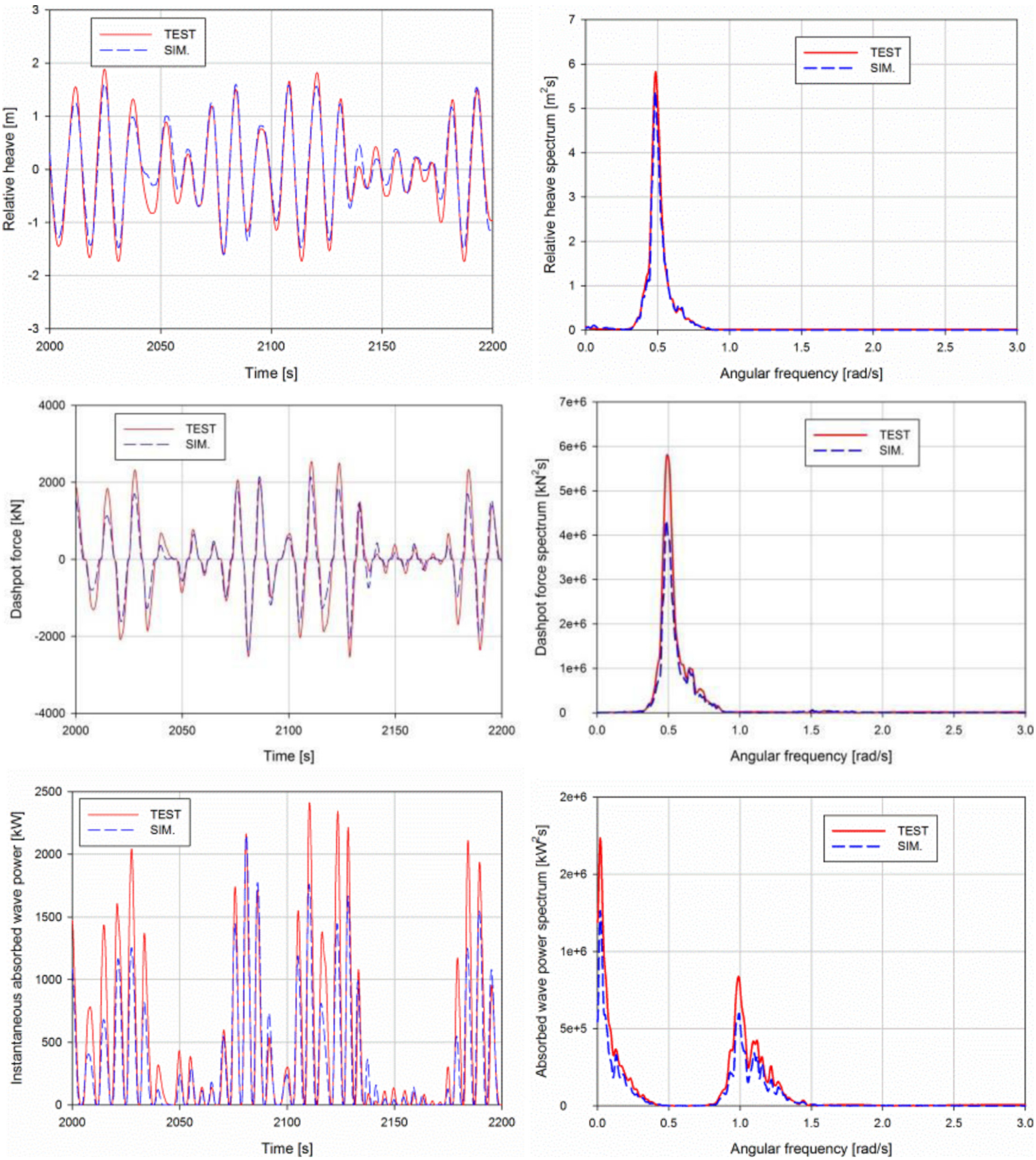

Fig. 5. Numerically and experimentally obtained time series (left) and spectra (right) of selected response parameters of the STC concept under the operational mode for an irregular wave and constant wind condition with Hs = 4 m, Tp = 13 s, Uw = 17 m/s (top: relative heave motion between the torus and the spar; middle: WEC PTO damping force; bottom: instantaneously absorbed wave power).

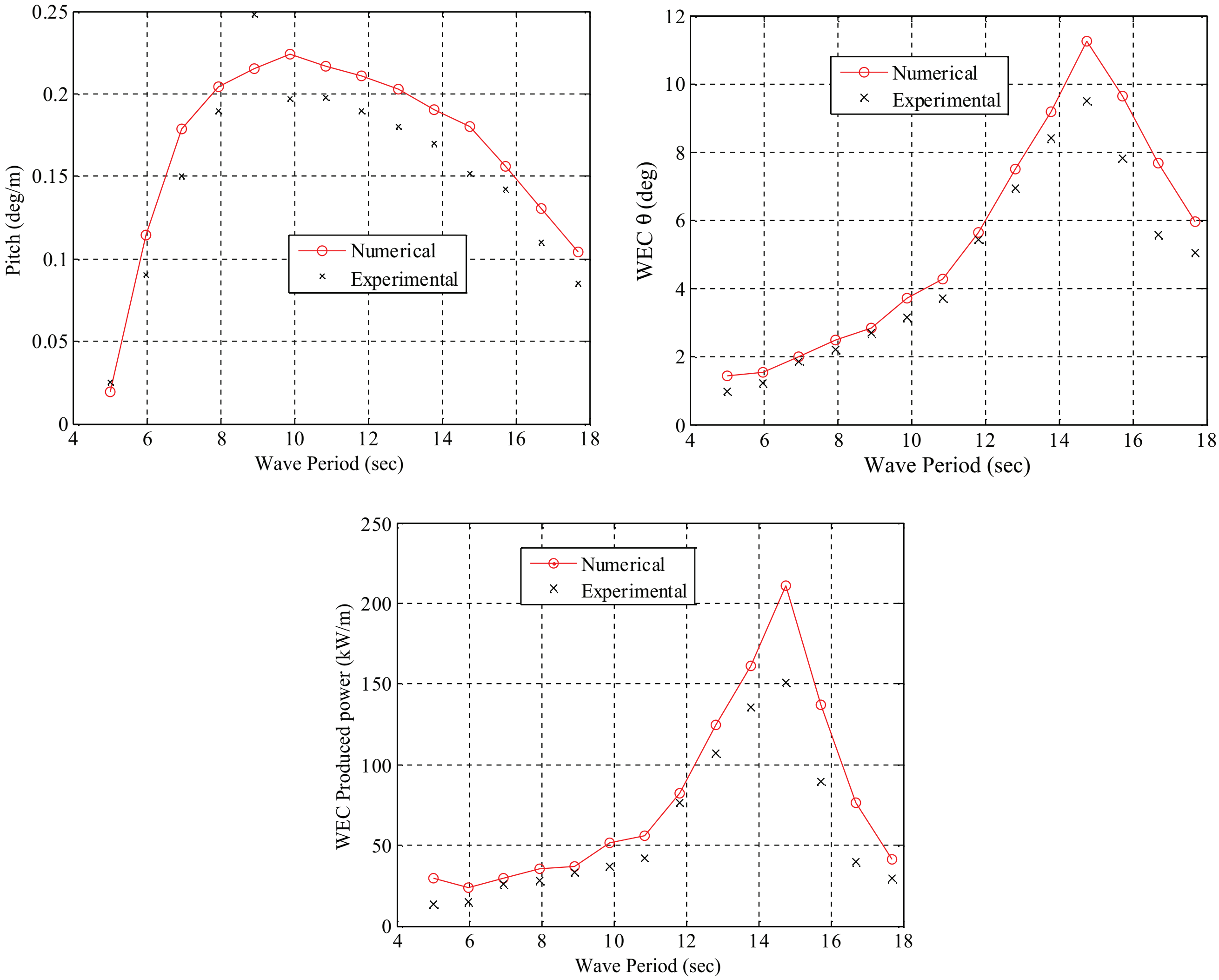

Fig. 6. Numerically and experimentally obtained RAOs of selected response parameters of the SFC concept under the operational mode for regular wave conditions with $H = 2$ m (left-top: semi-submersible pitch motion; right-top: WEC rotational motion with respect to the semi-submersible; middle-bottom: mean absorbed wave power of one WEC) (WEC PTO linear damping coefficient = 528 kNms/deg).

and compared. For irregular wave and turbulent wind cases, the measurements of wave elevation and wind speed from the model tests were used as input to the corresponding numerical analyses. In this section, a comparison of the numerical and experimental results for functionality tests of the STC and the SFC concepts will be provided for representative response parameters and selected wind and wave cases. In the papers Wan et al. [39] and Michailides et al. [28], more results of the comparison can be found for the STC and the SFC concepts, respectively.

5.1. Results of the STC concept for operational conditions

Regular wave tests with a wave height of 4 m at full scale have been performed in the functionality tests of the STC with different WEC PTO damping levels. The test results with no PTO damping and with a PTO quadratic damping coefficient of 3125 kNs^2/m^2 at full scale were compared in Fig. 4 with the numerical results for the response parameters of torus heave and WEC PTO damping force. Response Amplitude Operators (RAOs) of these parameters were compared. In addition, the mean absorbed wave power, which is the product of the PTO damping force and the relative velocity in heave between the torus and the spar, was also considered in the comparison and normalized by wave amplitude squared.

In general, a good agreement between the numerical predictions and the experimental measurements was observed for most of the response parameters. Fig. 4 also indicates that the WEC produces the maximum power for a wave period around 10 s and this is a result that the WEC was designed to have a natural period in heave around 8–10 s. Moreover, the PTO damping force also reaches its maximum under these conditions.

Fig. 5 compares the time series and spectra of the relative heave motion between the torus and the spar, the PTO damping force and the instantaneously absorbed wave power for

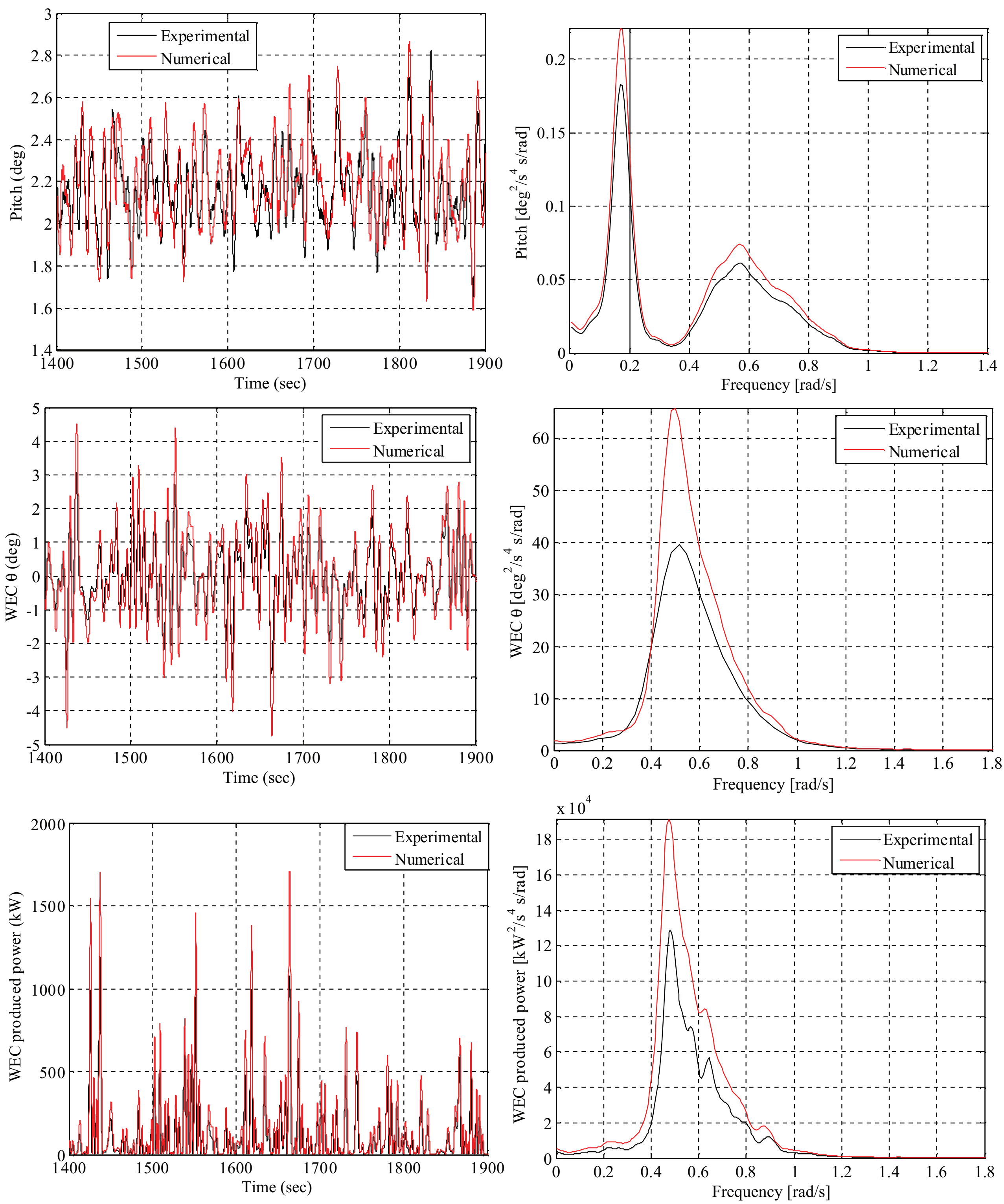

Fig. 7. Numerically and experimentally obtained time series (left) and spectra (right) of selected response parameters of the SFC concept under the operational mode for an irregular wave and constant wind condition with Hs = 3 m, Tp = 12 s, Uw = 9.4 m/s (top: semi-submersible pitch motion; middle: WEC rotational motion with respect to the semi-submersible; bottom: instantaneously absorbed wave power of one WEC) (WEC PTO linear damping coefficient = 528 kNms/deg).

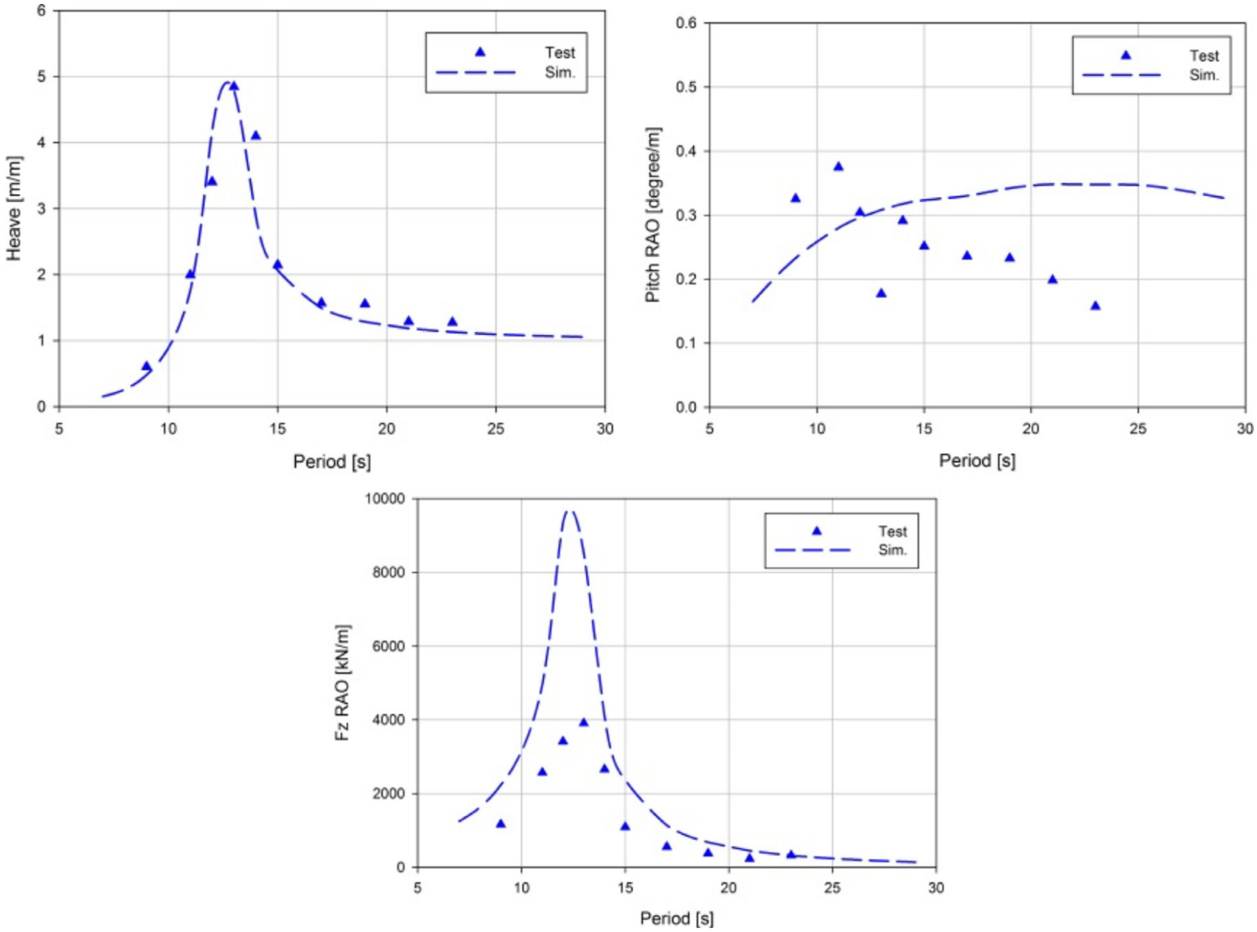

Fig. 8. Numerically and experimentally obtained RAOs of selected response parameters of the STC concept under the MWL survival mode for regular wave conditions with H = 9 m (left-top: STC heave motion; right-top: STC pitch motion; middle-bottom: vertical force between the torus and the spar).

an irregular wave and constant wind condition with significant wave height Hs = 4 m, spectral peak period Tp = 13 s and mean wind speed at nacelle height Uw = 17 m/s, obtained by the numerical analysis and the model test. A very good agreement was also obtained for the comparison of both the time series and the spectra.

5.2. Results of the SFC concept for operational conditions

Similarly, the RAOs of pitch motion of the semi-submersible and WEC rotational motion with respect to the semi-submersible, obtained from the SFC functionality test under regular wave conditions with a wave height of 2 m are presented in Fig. 6. It can be seen that the motion of the semi-submersible is quite small, while the WEC rotational motion with respect to the semi-submersible is large due to resonance since the natural period of the WEC rotational motion was designed close to 15 s. In general, the numerical results compare reasonably well with the experimental data. The numerical analysis overestimates the rotational motion of the WEC around the resonance with the wave periods from 13 s to 17 s. The comparison of the wave power from one WEC (also shown in Fig. 6) with a PTO linear damping coefficient of 528 kNms/deg gives a similar conclusion.

Fig. 7 shows the comparison of time series and spectra for the same response parameters in an irregular wave and constant wind condition (Hs = 3 m, Tp = 12 s, Uw = 9.4 m/s). The same conclusions as those drawn from the comparison of RAOs can be obtained. As compared to the experimental measurements, the numerical method seems to accurately predict the pitch motion of the semi-submersible, while it slightly over-predicts the WEC rotational motion and therefore the instantaneously absorbed wave power.

6. Comparison of the numerical and experimental results for survival conditions

6.1. Results of the STC concept for survival conditions

As mentioned, in the survivability test of the STC concept, two survival modes were considered, as shown in Fig. 2, namely the MWL and the SUB modes. The RAOs of heave and pitch motions of the STC considering regular waves with a wave height of 9 m are presented in Figs. 8 and 9 for the MWL and the SUB modes, respectively. In these tests, the torus was connected to the spar by three load cells which by combination gave the total forces in three directions between

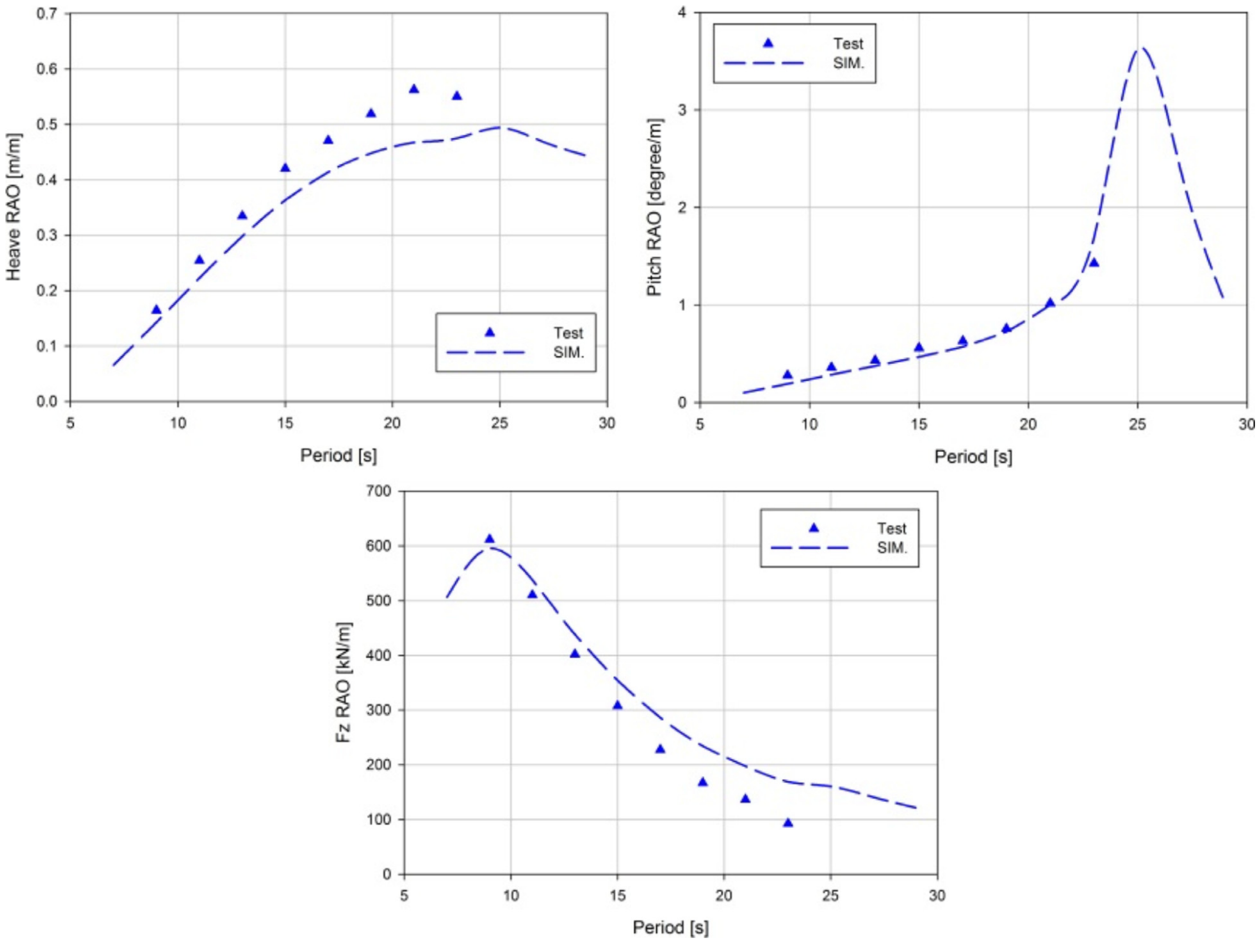

Fig. 9. Numerically and experimentally obtained RAOs of selected response parameters of the STC concept under the SUB survival mode for regular wave conditions with $H = 9$ m (left-top: STC heave motion; right-top: STC pitch motion; middle-bottom: vertical force between the torus and the spar).

the two bodies. The RAOs of vertical force between the torus and the spar are also presented in the figures.

Fig. 8 indicates that the STC motions in the MWL mode are governed by heave resonant motions for wave periods from 10 s to 15 s and the heave natural period is about 13 s. This is because the torus WEC was designed to have resonant heave motions in operational conditions to maximize the wave power absorption. However, when it is fixed to the spar at the mean water level, leading to an increase in the restoring stiffness for heave motion of the spar, the heave natural period of the spar reduces from 47 s for the SUB mode to 13 s for the MWL mode.

This is not a good survival mode from the structural integrity point of view. It also leads to a significant increase in the vertical contact force between the torus and the spar, as compared to that in the SUB mode in Fig. 9. In general, the agreement between the numerical and the experimental results becomes worse for the MWL mode. The current numerical model cannot accurately predict the vertical contact force under the heave resonant motions due to the presence of water exit and entry problem which causes a large variation of the buoyancy force and induces wave slamming loads on the torus. Further development of the numerical model is needed to take into account these nonlinear hydrodynamic loads.

On the other hand, it can be seen from Fig. 9 that the current numerical method predicts reasonably well for most of the response parameters for the SUB survival mode. It is also noted in the numerical results that the natural period of pitch motion under this mode is around 25 s. However, regular wave tests were not performed for wave periods larger than 23 s, which are out of the typical period range of main waves.

The numerical and the experimental results of the STC concept under the SUB mode for an extreme condition of irregular waves with Hs = 15.3 m, Tp = 15.5 s and constant wind with Uw = 30 m/s are compared in Fig. 10 in terms of time series and spectra. In general, the numerical simulations agree reasonably well with the experimental results for the responses of pitch motion and vertical force between the spar and the torus, for which the wave frequency responses dominate. However, the numerical model under-predicts the pitch resonant motions caused by the second-order wave loads in heave since it applies the Newman's approximation for modeling the second-order wave loads and it does not include such loads corresponding to the vertical motion modes (heave, pitch and roll).

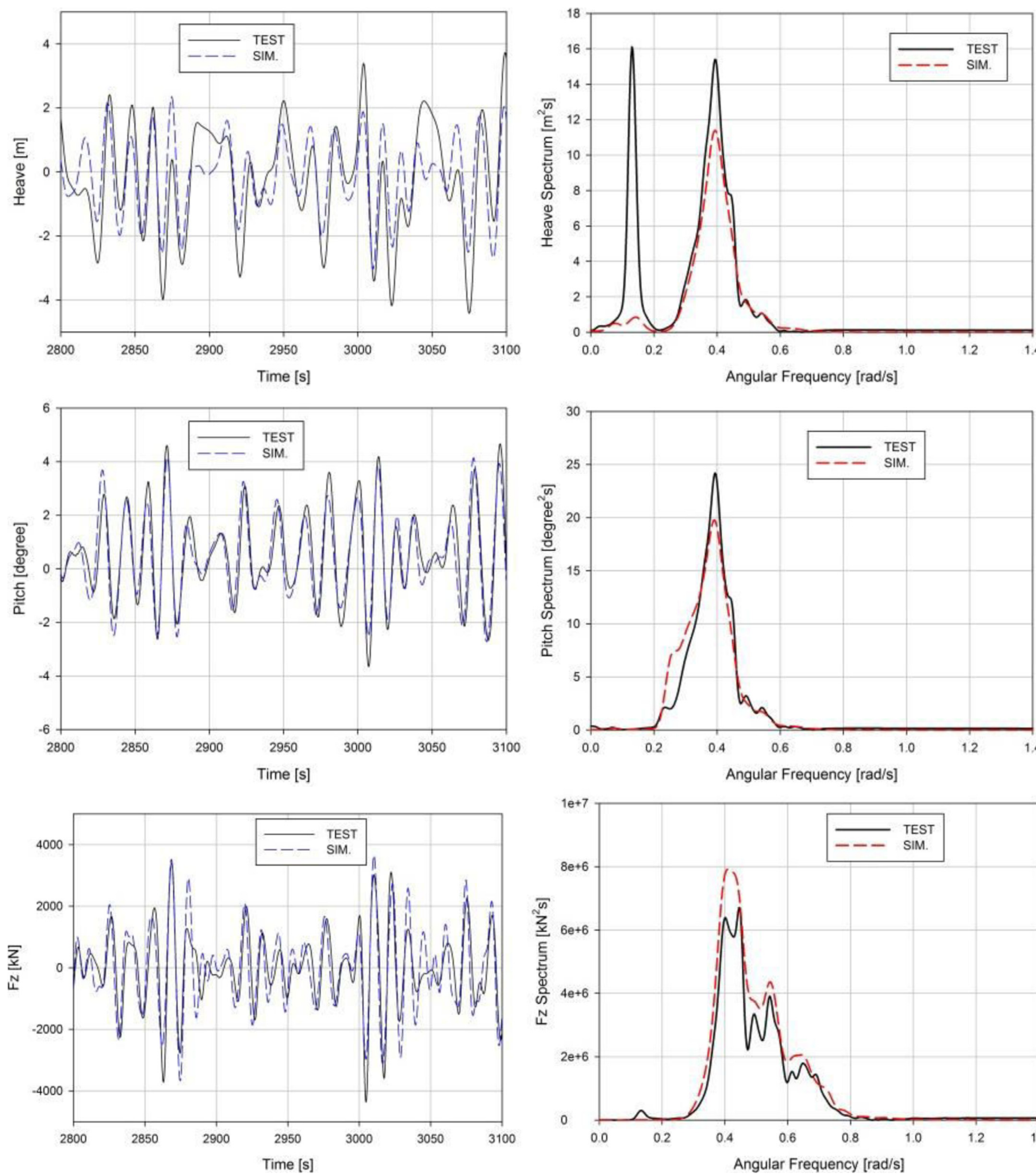

Fig. 10. Numerically and experimentally obtained time series (left) and spectra (right) of selected response parameters of the STC concept under the SUB survival mode for an irregular wave and constant wind condition with Hs = 15.3 m, Tp = 15.5 s, Uw = 30 m/s (top: STC heave motion; middle: STC pitch motion; bottom: vertical force between the torus and the spar).

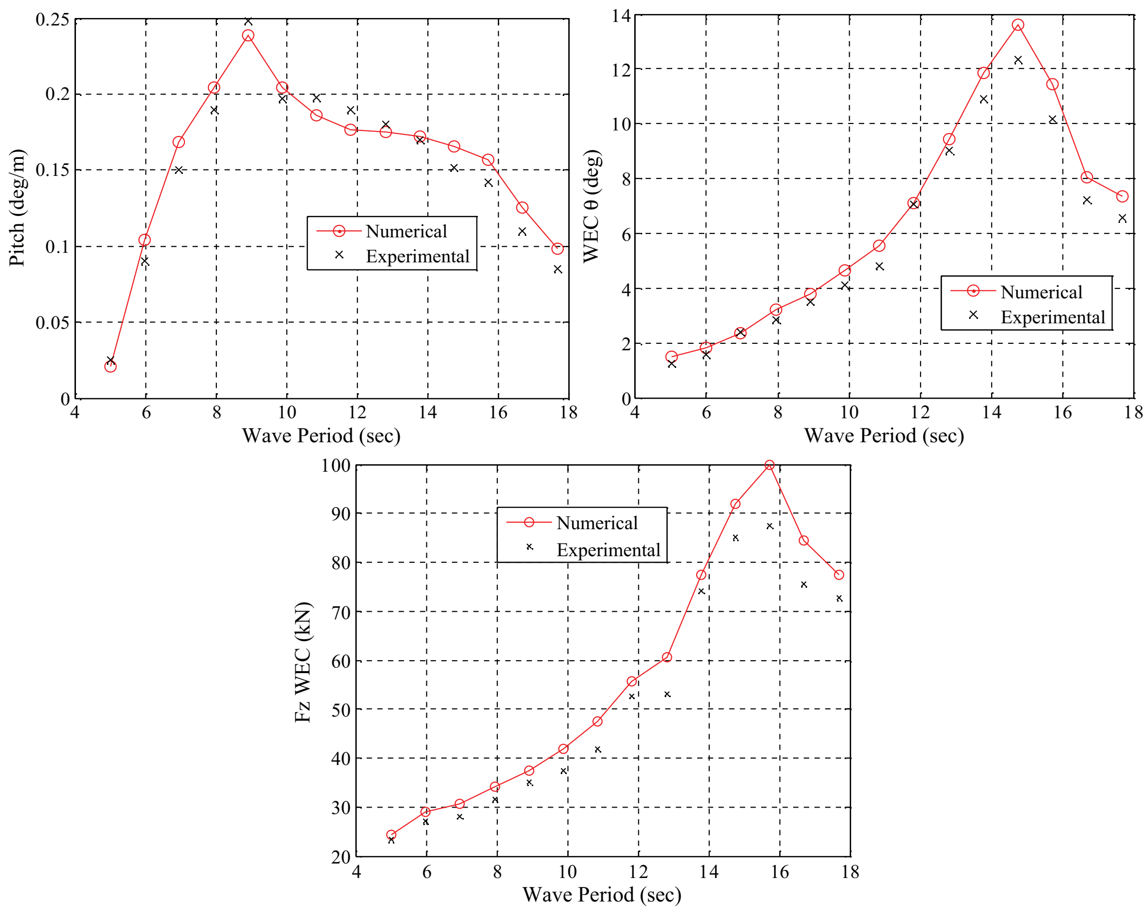

Fig. 11. Numerically and experimentally obtained RAOs of selected response parameters of the SFC concept under the survival mode for regular wave conditions with $H = 2$ m (left-top: semi-submersible pitch motion; right-top: WEC rotational motion with respect to the semi-submersible; middle-bottom: axial force in one WEC structural arm).

6.2. Results of the SFC concept for survival conditions

Fig. 11 shows the regular wave test results of the SFC concept under the survival mode in which the flap WECs can rotate freely along the axes at the pontoons of the semi-submersible. In addition to the pitch motion of the semi-submersible and the rotational motion of one WEC, the response parameter of the axial force in the structural arm of the WEC is selected for comparison. The obtained RAOs are very similar as those of the operational mode in Fig. 6, except that the rotational motion of the WEC is slightly larger under the survival mode since there is no PTO damper connected. The numerical model agrees very well with the experimental results and this is also the conclusion from the comparison of the time series and spectra of these response parameters in Fig. 12 for an extreme condition of irregular waves and constant wind with Hs = 15.3 m, Tp = 15.5 s, Uw = 31.4 m/s.

7. Comparison of the two combined concepts with respect to functionality and survivability

Both the STC and the SFC concepts represent a category of combined wind and wave energy concepts with wind power dominating and wave power accounting for only 5-10% of the total power output. According to Muliawan et al. [30] and Michailides et al. [27], the STC seems to produce more wind power than the SFC, since there is a positive synergy for wind power absorption of the STC concept due to the presence of the torus WEC [30], while the motions and therefore the wind power absorption of the SFC are not influenced by the additional three flap-type WECs [27]. On the other hand, the wave power produced by the STC is larger than those from the SFC.

The dynamic motions and therefore the structural responses of the SFC under the wave and wind loads are smaller than those of the STC for the same operational or survival conditions. In particular, the STC has strong resonant heave motions under the MWL survival mode in extreme waves, which induce significant structural responses. However, the responses reduce dramatically if the SUB survival mode is applied. Overall, as mentioned in Table 1, the SFC has a larger displacement, a more complex geometry and more WEC PTO systems, which is expected to have a higher fabrication cost.

Combing these two aspects, it is concluded in the MARINA project that, the cost of energy, defined as the cost in Euro per kWh of produced electricity, of the STC concept

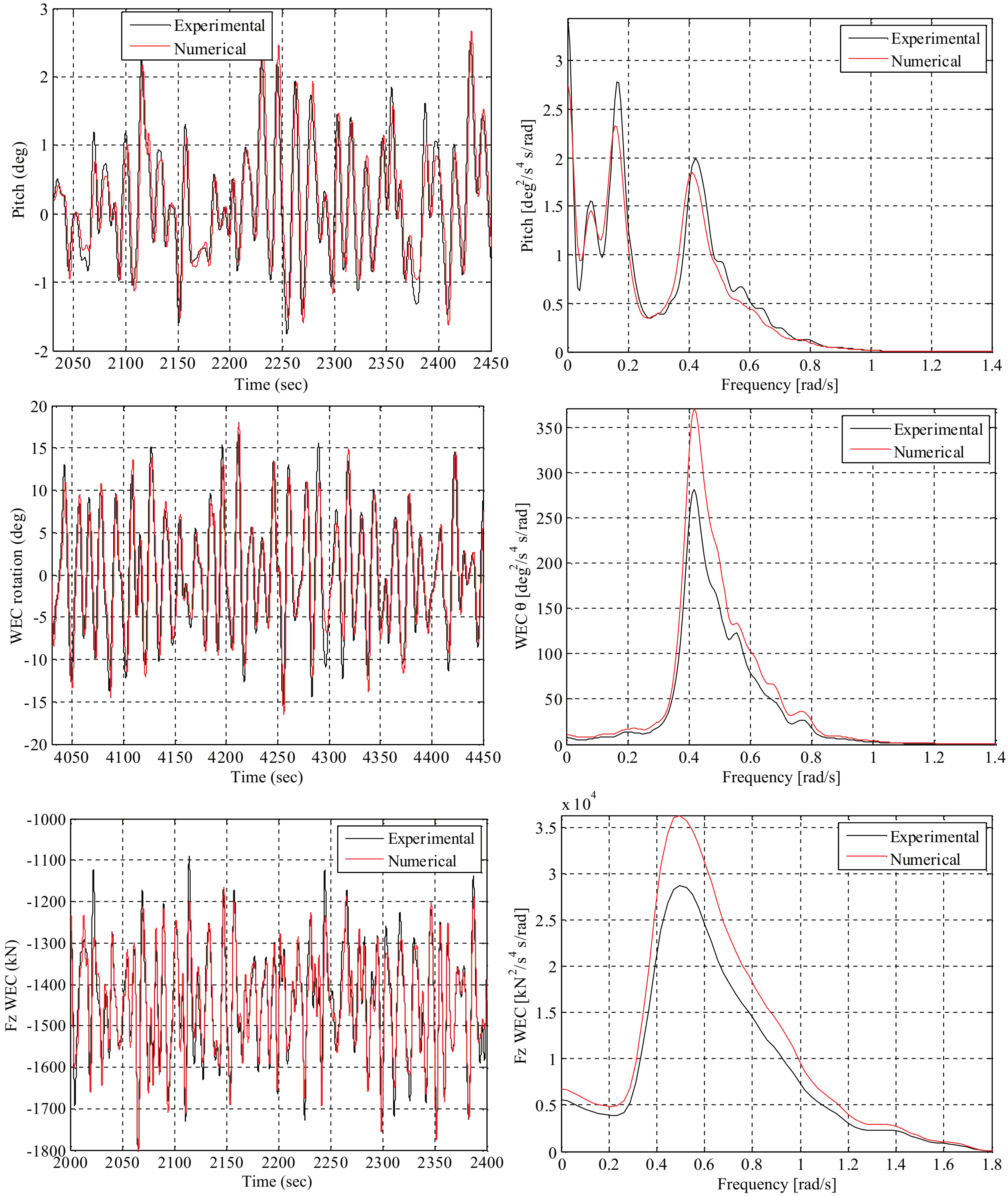

Fig. 12. Numerically and experimentally obtained time series (left) and spectra (right) of selected response parameters of the SFC concept under the survival mode for an irregular wave and constant wind condition with Hs = 15.3 m, Tp = 15.5 s, Uw = 31.4 m/s (top: semi-submersible pitch motion; middle: WEC rotational motion with respect to the semi-submersible; bottom: axial force in one WEC structural arm).

will be slightly smaller than that of the SFC concept. Moreover, since the wave energy is much more expensive than the offshore wind energy, the combined concept will have a higher cost of energy as compared to that of a pure floating wind turbine.

8. Conclusions

In this paper, a numerical model for global dynamic analysis of combined concepts of floating wind turbines and wave energy converters was established and exemplified for analysis of the two combined concepts (STC and SFC) developed in the MARINA Platform project using the code SIMO-RIFLEX-AeroDyn. It was discussed in detail how the external (aerodynamic and hydrodynamic) loads on different parts of the two concepts are modeled and how these structural parts are modeled in the global response analysis.

The corresponding model tests of the two concepts with respect to functionality and survivability were introduced with a detailed discussion on the different techniques for modeling of the WT rotor and WEC PTO system for lab testing. The focus of the STC model test was on the hydrodynamic aspects in particular in extreme conditions considering two alternative survival modes (SUB and MWL), while the model test of the SFC studied the dynamic behavior of this concept for both operational and survival conditions with simultaneous wave and wind actions. As compared to the STC, the SFC behaves well with less dynamic motions and therefore smaller structural responses in extreme conditions.

In order to validate the numerical models against the experimental results, numerical analyses were performed considering the exact models that were used in the tests. The numerical and the experimental results were then up-scaled to full scale and compared. In the case of irregular waves and turbulent wind, the measured wave elevation and wind speed were used as input to the numerical models in order to reduce the modeling uncertainty for the comparison.

The numerical models of the STC for the functionality test and under the SUB mode for the survivability test can predict reasonably well most of the response parameters as compared to the experimental measurements, including motions of the spar and the torus, absorbed wave power, contact force between the spar and the torus as well as tension in mooring springs. However, the STC under the MWL mode in extreme conditions exhibits strong heave resonant motions, causing water exit and entry problem for the torus and leading to a significant variation in the buoyancy force and large wave slamming forces on the torus. The current numerical model does not take into account these nonlinear hydrodynamic loads and therefore cannot accurately predict the corresponding motion and structural responses. In a future paper, the numerical model will be improved with an inclusion of a simplified model for nonlinear buoyancy and wave slamming forces.

The comparison of the numerical and the experimental results for the SFC concept with respect to both the functionality and survivability tests indicates that the current numerical model can accurately predict all of the response parameters that were considered in the comparison, i.e. motions of the semi-submersible and the WECs, axial force in the WEC structural arm and mooring line tension.

Based on a preliminary comparison of the total power production, displacement and WEC PTO system, the STC concept with the SUB survival mode seems to have a lower cost of energy as compared to the SFC concept. On the other hand, a combined wind and wave energy concept is more expensive than a pure wind energy concept of the same floater due to the immaturity of the wave energy technology.

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