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Long-term performance estimation of the Spar–Torus-Combination (STC) system with different survival modes

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ABSTRACT

This work addresses a combined wind and wave energy concept called the Spar–Torus-Combination (STC) system. Two additional survival modes for the original STC system (in a survival mode with the tours locked to the spar) have been proposed, namely the submerged mode and the low power take-off (PTO) damping mode. The performance of the STC system with different modes has been investigated based on a coupled analysis of wind–wave-induced stochastic response using the SIMO-TDHMILL code in the time domain. The energy production, structural fatigue damage and extreme responses of the STC system have been estimated based on the long-term wind–wave joint distribution at two selected sites in European waters. The hydrodynamic loads on the spar and torus were estimated using potential theory by accounting for the hydrodynamic interactions. The aerodynamic loads of the rotor were calculated by a validated simplified thrust model (TDHMILL). The annual wind and wave power production have been obtained using the hourly mean output power of each short-term condition and its occurrence probability. The annual fatigue damage of both mooring lines and the tower has been calculated based on the *S–N* curve approach and the Palmgren–Miner's linear damage hypothesis. The extreme responses of the STC system have been investigated by assuming that the largest values in each short-term case follow the Gumbel distribution. The results show that the new proposed survival strategy can significantly reduce the long-term fatigue damage and extreme responses of the original STC system without sacrificing power production by avoiding the possible heave resonance effect when the torus is locked to the spar at the mean water level (MWL). Furthermore, considering the fact that long-term analysis with all sea states is time consuming, the contour line method has also been applied to effectively estimate the extreme responses of the original STC system and has been validated by a comparison with the full long-term analysis method.

1. Introduction

Among available ocean renewable energy resources, offshore wind energy has been the most rapidly growing in the last decade. As offshore wind farms are moving into deeper water to utilize more and better wind energy resources, the support structure of large offshore wind turbines has changed from fixed-bottom to floating types from a cost-benefit point of view when the water depth is deeper than 60 m.

In fact, ocean wave energy may also be considerable where the offshore wind energy resource is rich, due to natural correlation. The combined concept of wind turbine (WT) and wave energy converter (WEC) systems makes it possible to utilize both wind and wave energy simultaneously while sharing the same supporting structure system and cables, as well as using the area of the ocean more efficiently. The EU project, MARINA Platform, was dedicated to establish a set of integrated platforms for the multi-purpose utilization of marine renewable energy as well as to develop design and analysis tools for new multi-purpose renewable energy floating platforms (MARINA, 2014). In the MARINA Platform project, several possible combined WT and WECs concepts based on floating platforms have been investigated. One combination of an oscillating-water-column-type WEC or a point-absorber-type WEC with a semi-submersible type floating wind turbine (FWT) 'WindFloat' has been studied using both numerical and laboratory models (Aubault et al., 2011; Peiffer et al., 2011). A study of the power produced by a combination of a WT on a semi-circular-shaped barge with a surge-type WEC has been reported in Soulard and Babarit (2012). A combined concept consisting of a 5 MW WT and three point absorber WECs with a single column tension leg platform has also

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been proposed, and its main dynamic responses have been examined for both operational and extreme sea conditions (Bachynski and Moan, 2013). A combined semi-submersible wind turbine and rotating flap type wave energy converters (SFC) system has been proposed and investigated by the coupled tool Simo-Riflex-Aerodyn. It was found that the rotating flaps could result in an increase of the power production without significantly affecting the behavior of the semi-submersible platform (Michailides et al., 2014). Another combined concept, denoted as the STC (Karimirad and Moan, 2012), which involves a combination of a spar-type FWT and a torus-shaped point absorber-type WEC, has also been introduced and studied both in operational and extreme sea conditions (Muliawan et al., 2012, 2013a, 2013b, 2013c). It was found that the STC system could increase total power production compared to the segregated FWT and WEC concepts. However, based on the contour line method, the mooring line force and tower bending moment of the STC system under extreme sea conditions were found to be much higher than those of the pure spar FWT concept, and there are some new challenges regarding both the ultimate limit state (ULS) and fatigue damage state (FLS) design of the STC structure system. In addition, the possible slamming and green water effects of the STC system have been observed in laboratory tests (Wan et al., 2014). Choung et al. (2011) analyzed the fatigue damage of mooring lines for two floating type combined ocean renewable energy platforms by neglecting the aerodynamic load on the wind turbine. So far, there is limited information about the long-term performance in terms of annual power production, structural fatigue damage, and extreme responses of the combined WT and WEC floating systems.

The present work, therefore, addressed the long-term performance of the promising STC system by carrying out a coupled wind and wave-induced stochastic response analysis using the SIMO-TDHMILL code in the time domain, based on the long-term wind–wave joint distribution at two selected deep water sites in European waters (Li et al., 2015). Two additional survival modes (one with torus fully submerged and the other with low power take-off (PTO) damping) for the original STC system have been proposed to reduce both the structural fatigue damage and extreme responses of the original STC system, and their effects on the performance of the STC system have been investigated. Annual wind/wave energy production was calculated using hourly mean output power for each short-term condition and its probability of occurrence. The annual accumulated damage of the mooring line and the tower was obtained based on the *S–N* curve approach and the Palmgren–Miner's linear damage hypothesis. The long-term extreme responses of the STC system have been investigated by assuming the largest peak values in each short-term case follow the Gumbel distribution (Agarwal and Manuel, 2009; Saha et al., 2014), and the simplified contour line method has also been applied to estimate the 50-year extreme responses of the original STC system.

2. Numerical model of the STC system

2.1. Description of the Spar–Torus Combination system

The combined concept 'Spar–Torus Combination' (STC) system considered in this study is inspired by spar-type FWTs, such as the 'Hywind' (Statoil, 2011) developed by Statoil in Norway, and the two-body axi-symmetric floating WEC, such as the 'Wavebob' (2010) developed in Ireland. The STC system is illustrated in Fig. 1. The Power-Take-Off (PTO) system and the connection between the torus and the spar in this concept are described in detail in Ref. Muliawan et al. (2012). The torus slides vertically along the spar to extract energy from the waves, whereas the wind turbine generates power from the wind. The present STC concept has been based on the spar-type FWT with a NREL 5 MW wind turbine (Jonkman et al., 2009) and the torus properties used in Muliawan et al. (2013a). A detailed description of the STC system can be found in Muliawan et al. (2013c). The mooring system properties are summarized in Table 1 (Muliawan et al., 2013c). The system consists of three sets of mooring lines, each of which contains a clump weight and four line segments. The purpose of the delta lines is to provide sufficient yaw stiffness for the system (Fig. 1).

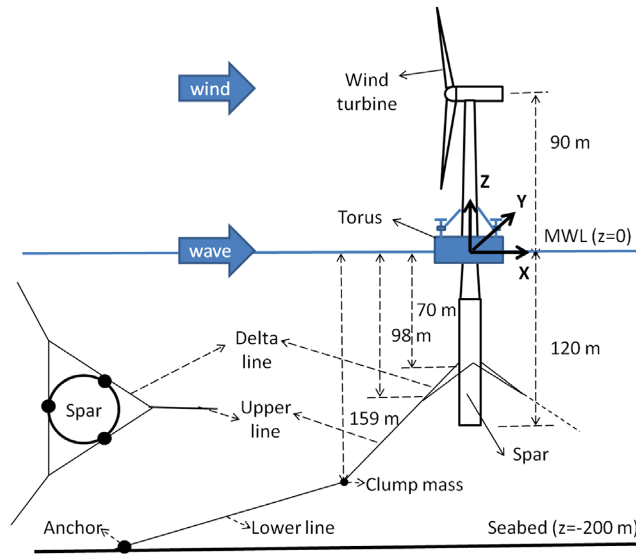

Fig. 1. Conceptual sketch of the STC system.

Table 1
Properties of the mooring system components (Muliawan et al., 2013c).

Property	Delta line	Upper line	Lower line	Clump mass
Length (m)	50	115	275	–
Diameter (m)	0.09	0.09	0.09	–
Nominal section area (m^2)	0.0063	0.0063	0.0063	
Mass per length (kg/m)	42.5	42.5	42.5	–
Axial stiffness (kN)	384,243	384,243	384,243	–
Total weight (kN)	–	–	–	338.2

2.2. Numerical modeling of the STC system

In the numerical study, the STC system is modeled as two rigid bodies, a spar FWT and a torus, connected by mechanical couplings at their interfaces. Hydrodynamic interaction coupling is also considered. The modeling of the two-body system used for the present analysis is similar to the modeling method explained in detail in Muliawan et al. (2013a). Therefore, the present paper includes only a brief overview of this method.

A coupled stochastic response analysis of the STC system subjected to wind and wave loads has been performed using the SIMO-TDHMILL code in the time domain. SIMO (Marintek, 2008) provides a tool for modeling multi-body systems and can accommodate the introduction of both mechanical and hydrodynamic couplings between the bodies. Wave loads in SIMO are generated based on a frequency-domain hydrodynamic analysis using WAMIT, which includes first-order wave loads (considering the two-body hydrodynamic coupling) and second-order wave forces, whereas the viscous forces are modeled in the form of the Morison drag force. The aerodynamic loads on the wind turbine rotor are considered as thrust forces and are calculated by the validated simplified thrust force model TDHMILL code (Karimirad and Moan, 2012). The drag force on the tower due to wind is also considered. Considering the relative wind speed at each time step of the simulation, the thrust force and output power are estimated by the ideal thrust force and output power curves of the NREL 5-MW WT (Jonkman et al., 2009), which are shown in Fig. 2.