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

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ABSTRACT

Combining the offshore wind and wave energy on an integrated structure or in a farm configuration is 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, the two model tests are described and then the measured responses in the two model tests are compared for each survival mode. In addition, the performance of the STC in the two survival modes for each model test is also compared. The differences in the two model tests are explained in detail. The focus of the model tests was wave-induced loads and responses, and wind was also included to model the mean wind thrust on the wind turbine rotor. In the model tests, the rigid body motions in six degree of freedom, the mooring line tensions, and the forces between the spar and torus in three directions (X, Y and Z) were measured. Finally, validation of a numerical model against the model test measurements is also briefly discussed.

1. 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 great potential and with a much higher power density than wind power. The worldwide overall wave energy 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 the ocean space more efficiently. 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 under the project, such as the semi-submersible flap concept (SFC) (Luan et al., 2014; Michailides

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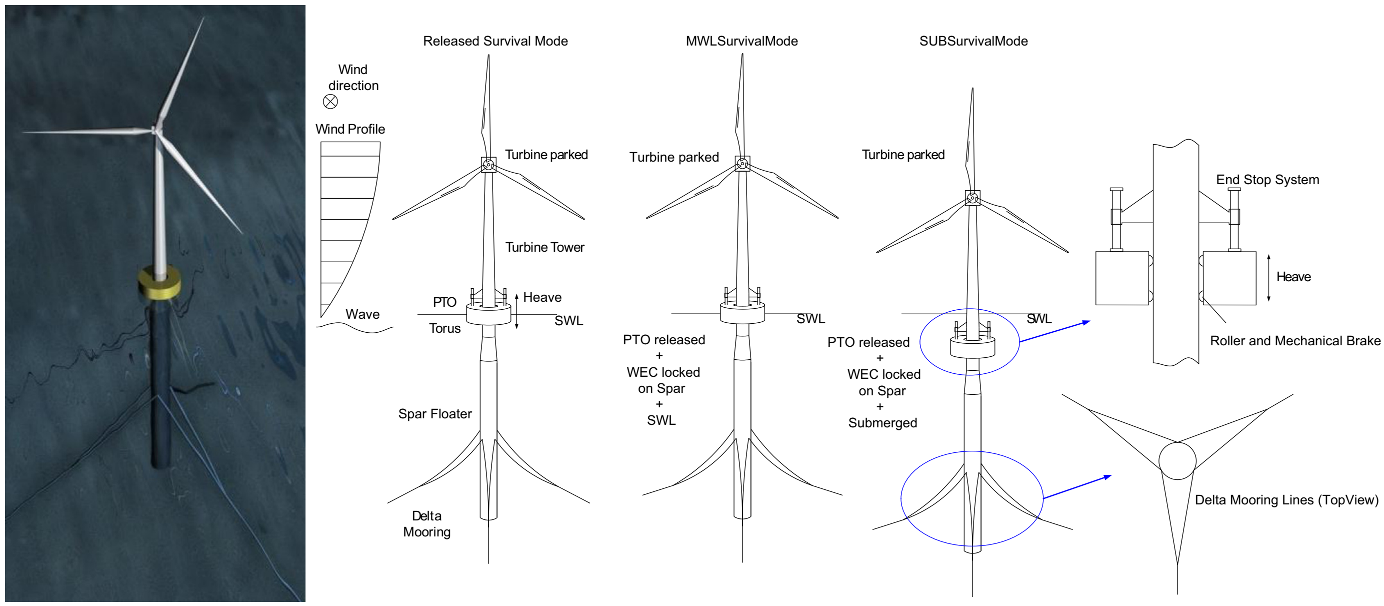

Fig. 1. The STC concept and three proposed survival modes.

et al., 2014) and the oscillating water column (OWC) array with a wind turbine installed.

The STC concept as shown in Fig. 1, is composed of a spar FWT and torus-shaped WEC. The wind turbine installed is the 5 MW NREL reference turbine (Jonkman et al., 2009), the WEC rated power is 0.5 MW. In this concept, the torus can move along the cylinder of the spar to absorb wave energy by the relative heave motions through a power take off (PTO) system. In the operational mode, the natural periods for the torus and the spar are 6 s and 32 s respectively. The PTO system induces coupling effect between the two bodies in the heave direction and makes the WEC work efficiently. The PTO damping should not be too large to prevent large heave motions of the spar. Roller and mechanical brake systems are incorporated to allow the relative heave motion and at the same time to restrict the relative horizontal motions between the two bodies. 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 the design is located 30 km off the west coast of Norway with the water depth of 200 m (Li et al., 2013).

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 pitch. 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 mode is also required. For the STC, the WEC with a relatively large water plane area 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 Fig. 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. (2014). 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.

2. 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 the STC model test, the wind turbine was modeled by a simple drag disc, which was used in the Windfloat model test (Cermelli et al., 2009) previously.