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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,

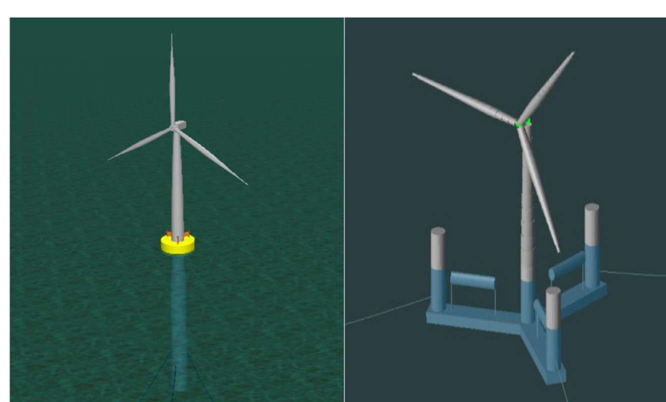

Fig. 1. The STC (left) and the SFC (right) concepts.