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Experimental study of the functionality of a semisubmersible wind turbine combined with flap-type Wave Energy Converters

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ABSTRACT

In the present paper the functionality of the Semisubmersible wind energy and Flap-type wave energy Converter (SFC) is examined experimentally. In order to study the functionality of the SFC, the focus is on operational environmental conditions. SFC is a combined concept that utilizes offshore wind energy and ocean wave energy for power production. Details are presented as far as the physical modelling of the wind turbine with the use of a redesigned small-scale rotor and of the Power Take-Off mechanism of the Wave Energy Converters (WECs) with the use of a configuration that is based on a mechanical rotary damper. Tests with quasi-static excitation, motion decay, regular and irregular waves without and with wind that is uniform are conducted on an 1:50 scale physical model. The experimental data are compared with numerical predictions obtained by a fully coupled numerical model using Simo/Riflex tool. A good agreement is observed between experimental and numerical predictions. The combined operation of WECs doesn't affect the tension of mooring lines nor the acceleration of nacelle and the bending moment in tower's base. The produced power of the WECs of the SFC and consequently the functionality of the SFC is estimated.

1. Introduction

The efficient harnessing and exploitation of the available enormous offshore (wind and wave) renewable energy resources can contribute significantly to the coverage of the increasing energy demands. Offshore renewable energy systems, namely Floating Wind Turbines (FWTs) and Wave Energy Converters (WECs), are expected to significantly contribute for the years to come to reach the energy security targets worldwide.

In recent years, offshore wind technology has been rapidly developed and commercially deployed in offshore wind farms with a trend towards larger scale wind turbines in larger water depths. For water depths larger than 100 m the use of FWTs is considered as the most appropriate from a cost-benefit point of view; FWT concepts for deep waters are still under development. Different floating support platform configurations are possible for use with FWTs [1]. One major type of support configuration is the semisubmersible platform consisting of columns that are connected with the use of braces [2,3]. Alternatively, the columns of the semisubmersible platform can be connected by pontoons with large dimensions and without braces [4–6]. In addition to offshore wind energy, ocean waves are an abundant and promising resource of alternative and clean energy; a large number of WECs has been proposed so far. The technology of WECs is currently under development but it is not mature yet for large scale commercial deployment. One major category of WECs is the rotating flap [7,8], usually this type of WECs is oscillating about a fixed axis close to the sea bottom. Hydrodynamic characteristics of such kind of devices are presented in Ref. [9] and [10,11] suggested the rotating flap to be fully submerged and to span vertically from the free surface about one third of the water depth. In general, WECs can efficiently deployed in multi-purpose offshore floating platforms [12,13].

In any case, the exploitation of the offshore wind and ocean wave energy resources should be realized in a sustainable manner,

Abbreviation: COG, Centre of Gravity; ECN, Ecole Centrale Nantes; EC, Environmental Condition; EU, European Union; FWT, Floating Wind Turbine; MWL, Mean Water Level; ML, Mooring Line; NREL, National Renewable Energy Laboratory; OWC, Oscillating Water Column; PTO, Power Take-Off; RAO, Response Amplitude Operator; SFC, Semisubmersible wind energy and Flap-type wave energy Converter; STC, Spar Torus Combination; WEC, Wave Energy Converter; WG, Wave Gauge.

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considering energy and cost efficiency. It might be beneficial to combine these energy systems of different technologies in one platform and investigate possible combined systems for simultaneous extraction of wind and wave energy. In order to evaluate the behaviour of the combined concepts, numerical models for the coupled dynamic analysis should be developed, while laboratory experiments in controlled environmental conditions for demonstrating the functionality of these concepts should be conducted.

Recently, EU research projects have been introduced to accelerate the development of combined offshore energy systems [14–18]. Several researchers [19–21] have studied combined concepts utilizing different floating support platforms and WEC types. In the EU project MARINA Platform three combined concepts have been selected and studied both numerically and experimentally under operational and survival conditions. The selection was based considering five simplified criteria, namely the cost of energy, constructability, installability, operation & maintenance and survivability. These combined concepts are the Semisubmersible wind energy and Flap-type wave energy Converter (SFC) [22] the Spar Torus Combination (STC) [23] and an array of Oscillating Water Columns (OWCs) in a V-shaped concrete large floating platform and one wind turbine combination [24].

The combined concept SFC consists of a braceless semisubmersible floating platform with four cylindrical shaped columns (one central column and three side columns) and three rectangular shaped pontoons with large dimensions that connect the side columns to the central column, a 5 MW wind turbine placed on the central column of the semisubmersible platform, three rotating flap-type WECs hinged at the pontoons of the semisubmersible through rigid structural arms and linear Power Take-Off (PTO) mechanisms, and three catenary mooring lines positioned at the three side columns of the semisubmersible. The upper point of the flap of WECs in its mean position is 2 m below the Mean Water Level (MWL) and the lower point of the flap is 15 m above the pontoon of the semisubmersible platform. In Fig. 1 a sea view of SFC is presented.

Experimental investigation of the functionality of either FWTs or WECs has been conducted and reported so far by various researchers. As far as physical model testing of FWTs with different type of platform (spar, semisubmersible and tension leg), one

Fig. 1. Artistic view of the SFC at sea.

particular uncertainty related to interpretation of the model test results is the scaling effect since it is not possible to scale simultaneously both the aerodynamic loads according to Reynold's law and the hydrodynamic loads using Froude's law [25]. Moreover there are different techniques for the rotor's thrust force physical modelling. The rotor may be simplified as a disk providing a drag force [3] or as a controlled fan providing an active force [26,27]. A geometrically scaled rotor would produce less corresponding thrust force at model scale as compared to a full scale rotor [28] and a redesign of the blades is necessary in order to the correct scaled thrust curve to be achieved [29]. During most of the tests the blade pitch angle is fixed but it can be manually adjusted [30] utilizing an active pitch control mechanism of blades similar as what is expected for the full scale wind turbine.

As far as the experimental investigation of WECs, the set-up of the PTO configuration can be considered as the most critical part [31] [32]. studied two different PTO configurations of two different types of WECs, namely an OWC and two rigid modules that are rotating relative to each other. For the latter WEC [33] presented details about the physical modelling of the PTO configuration that consists of a metal bar with an elongate hole, a wire that is welded at the two ends of the hole and a small electric engine with a wheel. As far as testing of fixed bottom rotating flaps [34], modelled the PTO configuration with an adjustable rotary viscous dashpot which is connected with a rotation shaft that is out of the water; this shaft is connected with a second shaft (that represents the axis of rotation of the WEC) through two thin pretensioned stainless steel wires. For the same type of WEC [35], tested the PTO configuration with the use of a magneto-rheological damper for applying resistance on the model. Alternatively [36] modelled the PTO configuration of the rotating flap with a gear transmission system and a piston-type air compressor. For the case of a floating rotating flap [37] modelled the PTO configuration with the use of a load adaptable friction wagon mounted on a rail, a potentiometer for measuring the displacement of the flap and a force transducer for recording the transmitted force.

So far experimental investigations of combined wind/wave concepts have been reported by Refs. [38–40] based on different physical model set-up strategies of different parts of the combined concepts.

In the present paper the functionality of the offshore combined wind/wave energy concept SFC is experimentally examined and the measured data are compared with predictions obtained by a numerical analysis model. Operational environmental conditions in specific offshore sites are considered. The development of the physical model set-up is initially presented. The physical model of the SFC has been built in an 1:50 scale. The PTO configuration of each of the WECs is physically modelled with the use of a shaft, two pulleys, a timing belt, two tensioners and a linear mechanical rotary damper that provides a constant damping level. The wind turbine is physically modelled with a redesigned small-scale rotor that rotates during the experiments. The wind turbine has the correct mass property and produces the equivalent thrust force in model scale for selected few examined cases with different wind speed as compared to the NREL 5 MW reference wind turbine. Quasi-static, motion decay, regular and irregular waves without and with aligned wind excitation tests have been conducted. The experimental data are compared with numerical predictions obtained by a fully coupled multibody numerical analysis model in Simo/Riflex tool. The examined response data are the motions of the semisubmersible support platform, produced power by one flap-type WEC, tension of mooring lines, internal loads of the arms that connect the rotating flap with the pontoon of the semisubmersible platform, acceleration of the nacelle and bending moment in wind turbines tower base. A very good agreement between experimental