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Experimental investigation of floating wave energy converters for coastal protection purpose

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ABSTRACT

Coastal areas are vital economic hubs already affected by erosion, flood risk and long-term habitat deterioration. The growth of economy coupled with the acceleration of climate change draws the attention to sustainable coastal defence plans. Near-shore floating wave energy converters may be an innovative way to defend the coast with low environmental and aesthetic impact together with the secondary benefit of energy production. This contribution specifically addresses the use of devices of the Wave Activated Body type for coastal protection, based on 3D laboratory results. New experiments were carried out on a single device in 1:30 scale and on three devices of the same type in 1:60 scale in the deep-water wave tank at Aalborg University. Wave transmission, wave reflection, mutual interaction among the devices and device efficiency are assessed under a variety of conditions by changing wave steepness and water depth. Experiments allow a first outline of design guidelines for these kinds of combined installation for wave energy production and coastal defence.

1. Introduction

At present, erosion and flood are serious threats for coastal areas and the set-up of defence technologies able to cope with sea level rise and increased storminess induced by climate change represents a great challenge (Zanuttigh, 2011).

Due to their adaptability to sea level changes and to the absence of piling-up, near-shore floating structures can be a smart solution for attenuating incident waves and therefore reduce littoral erosion. Until now, only floating breakwaters were used for coastal protection purposes, limitedly to mild wave climates (Martinelli et al., 2008).

An innovative and sustainable way to combine coastal protection and energy production may be the installation of farms of floating wave energy converters (f-WECs).

Research devoted to the changes of the wave field around single and multiple f-WECs is fairly limited. A detailed experimental study on a single f-WEC, a model of the Wave Dragon (www.wavedragon.net), was performed by Nørgaard and Poulsen (2010).

Contributions dedicated to arrays of WECs are usually focused at providing data for modelling the device motions, power recovery and mooring components (for oscillating water columns, Bryden and Linfoot, 2010; for floating point absorbers, Vicente et al., 2009). To our knowledge only Beels et al. (2010) analysed the hydrodynamics around multiple f-WECs through numerical simulations.

The aim of this contribution is to experimentally examine the feasibility of using f-WECs for coastal protection by analysing the hydrodynamic performance of a single and multiple DEXA devices (www.dexawave.com). DEXA is a f-WEC that belongs to the Wave Activated Body (WAB) type, where the energy production is based on the relative movements of its components.

Preliminary tests of DEXA in 1:30 scale showed that for device length to peak wave length ratio l/L_p close to 1, the obtained wave transmission coefficient is in the range 0.7–0.8 for one single device (Kofoed, 2009; Martinelli et al., 2011; Ruol et al., 2010; Zanuttigh et al., 2010).

Specific objectives of this paper are:

- to fully describe the wave field around the device/s, with specific focus on wave transmission;
- to verify the dependence of wave transmission and device efficiency on l/L_p, in order to provide guidelines for the optimal device design (i.e. device length with respect to typical wave climate);
- to examine the effects of wave steepness;
- to investigate the sensitivity of such f-WECs to climate change by varying water depth at installation;
- to assess the interactions – if any – among the devices and therefore provide design guidelines for the optimal layout of the wave farm (i.e. mutual distances among the devices);
- to assess scale effects and measurement uncertainties.

Section 2 describes the facility and the tests, including the models, the mooring system and the equipment. The tested irregular wave conditions and the types of measurements are also provided.

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Main outcomes of the tests are summarised in Section 3, focusing on wave transmission, wave reflection, changes of wave direction induced by the device and mutual interactions among the devices. Guidelines on the design of the device and of the farm are derived based on the 1:30 and 1:60 scale tests respectively.

The performance of f-WEC installation for coastal protection purposes is discussed in Section 4 with respect to devices of similar geometry but different scopes, such as floating breakwaters, and with respect to interventions characterised by similar purpose (i.e. multi-purpose, limited environmental impact) but different structures, such as low crested breakwaters.

Conclusions are finally drawn in Section 5.

2. Description of the tests

The purpose of this section is to fully describe the tests, including: the basin and the wave maker; the concept of the DEXA device and the characteristics of the two models used in the tests in 1:30 and in 1:60 scale; the type of mooring system adopted; the 3D irregular wave conditions and the measurements performed in the basin.

2.1. The facility

The hydrodynamic tests were performed in the deep-water directional wave basin of the Hydraulics and Coastal Engineering Laboratory at Aalborg University, DK. The basin is 15.7 m long (wave direction), 8.5 m wide and 1.5 m deep.

The wave generator is a snake-front piston type composed of 10 actuators with stroke length of 0.5 m, enabling generation of short-crested waves. The software used for controlling the paddle system is AwaSys developed by the same laboratory (Aalborg University, 2007a). Regular and irregular long and short crested waves with peak periods up to approximately 2.5 s, oblique 2D and 3D waves can be generated with good results.

Passive wave absorption is carried out. A 1:4 dissipative beach made of concrete and gravel with average diameter $D_{50} = 5$ cm is placed opposite to the wave maker. The sidewalls are made of crates (1.21 × 1.21 m, 0.70 m deep).

2.2. The device and the physical models

The DEXA device (see Fig. 1) consists of two rigid pontoons with a hinge in between, which allows each pontoon to pivot in relation to the other. The draft is such that at rest the free water surface passes in correspondence of the axis of the four buoyant cylinders. The Power Take-Off (PTO) system consists of a low pressure power transmission technology and is placed close to the centre of the system, in order to maximise the stabilisation force (Kofoed, 2009).

In the 1:30 scale tests, one DEXA model (Fig. 2) was examined.

The model is 2.10 m long cross-shore and 0.81 m wide long-shore (scheme in Fig. 3), and totally weighs 33 kg, being of about 10 kg the weight of the PTO system.

The device brings on board a PTO system to examine power production (Fig. 4). The PTO consists of a metal bar with an elongate-shaped hole, a wire welded at the two ends of the hole and a small electric engine with a wheel. The bar is connected to one half of the device and the wheel to the other, via a load cell (strain gauge equipped "bone"). The wire is rolled up around the wheel that is forced to rotate while translating along the bar hole. The rigidity R of the PTO was modified by varying the resistance of the wheel to rotation and therefore the current in the engine. It is out of the scope of this paper to show the tuning process of R, however it is relevant to say that R was kept constant during all the tests; its value was selected to achieve the best compromise between power production and device efficiency.

In 1:60 scale, three DEXA models 0.95 m long and 0.375 m wide (perpendicularly to wave propagation) were adopted (Fig. 5).

Each wooden model is composed by two parts: two cylindrical floaters and two legs, perfectly scaling down the size of the 1:30 model. An elastic resistant strip is placed in between the pontoons in order to connect them. The total weight of each model is 3.30 kg. These models did not carry PTO systems or measurement instrumentations on board.

2.3. Mooring systems

Both in 1:30 and 1:60 the models were moored with a realistic mooring system of the "spread type" (Harris et al., 2004). It consists of four steel chains – respectively 1.5 m and 3.0 m long, 0.25 kg/m and 1.0 kg/m in 1:60 and in 1:30 scale – fixed to the bottom with – respectively 5 kg and 30 kg heavy – anchors and linked to the device at the fairlead point in the middle of the legs by means of a resistant plastic strip (scheme for the 1:30 tests in Fig. 6). Chains were designed based on the catenary equations (Esmailzadeh and Goodarzi, 2001), being the length of the chain portion raised from the bottom about 1/3 of the total chain length.

2.4. Tested wave conditions

Tested wave attacks were selected to assess more in depth the dependence of the wave transmission coefficient K_T on the device length to peak wave length ratio l/L_p for a wide variety of significant wave heights H_s so that results may be useful for applying the device to different climate conditions. Wave state (WS) parameters were also chosen to investigate the effects of wave steepness s_p and of the water depth h.

Wave state (WS) parameters are reported in 1:1 scale in Table 1. Tests 1 and 2 were performed in 1:30 scale only due to limitations of the wave maker to reproduce so small waves in scale 1:60.

Two water depths were examined in 1:60 scale ($h_1 = 0.3$ m, $h_2 = 0.35$ m), whereas a single water depth was used in 1:30 scale ($h = 0.6$ m, i.e. up-scale of the water depth h_1) due to limitations of the basin depth.

Fig. 1. Two 3D rendering images (www.dexawave.com) showing a single DEXA device full scale (to the left) and a DEXA wave energy farm (to the right).