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DEVELOPMENT OF A POINT ABSORBER WAVE ENERGY CONVERTER FOR INVESTIGATION OF ARRAY WAKE EFFECTS IN LARGE SCALE EXPERIMENTS

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Abstract

Wave energy from ocean waves is absorbed by using Wave Energy Converters (WECs). In order to extract a considerable amount of wave power at a location, in a cost-effective way, large numbers of WECs have to be arranged in arrays using a particular geometric configuration. Interactions between the individual WECs ("near field effects") affect the overall power production of the array. In addition, the wave height reduction behind an entire WEC array ("far field effects") may affect other users in the sea, the environment or even the coastline. Several numerical studies on large WEC arrays have already been performed, but large scale experimental studies, focussing on "near-field" and "far-field" wake effects of large WEC arrays are not available in literature. Within the HYDRALAB IV FP7 European programme, the WECwakes research project has been introduced, in order to perform

experiments on large arrays of point absorber WECs, using different geometric configurations and inter-WEC spacings. The selected facility is the Shallow Water Wave Basin of the Danish Hydraulic Institute (DHI), in Denmark. The results from the WECwakes experimental tests will be useful in the validation and extension of the recently developed numerical models, as well as in providing insight to optimizing the geometric configurations of WEC arrays for real applications. The latter, also, aims at cost-effective configurations of WEC arrays for power production, and at quantifying the related environmental impact. The present paper focuses on the preparation of the WECwakes project and the development of the used WEC models.

1. Introduction

The shrinking reserves of fossil fuels in combination with the increasing energy demand have enhanced the interest in sustainable and renewable energy sources, including wave energy. In order to extract a considerable amount of wave power, large numbers of Wave Energy Converters (abbreviated as WECs) will have to be arranged in arrays (or “farms”) using a particular geometric layout. The operational behaviour of a single WEC may have a positive or negative effect on the power absorption of the neighbouring WECs in the array (so-called “near-field” effects). As a result of the interaction between the WECs within an array, the overall power absorption is affected. Finally, the wave height behind a large array of WECs is modified which may influence neighbouring farms, other users in the sea or even at the coastline (so-called “far-field” effects). In Fig. 1, the importance of the geometric lay-out of WEC arrays is illustrated.

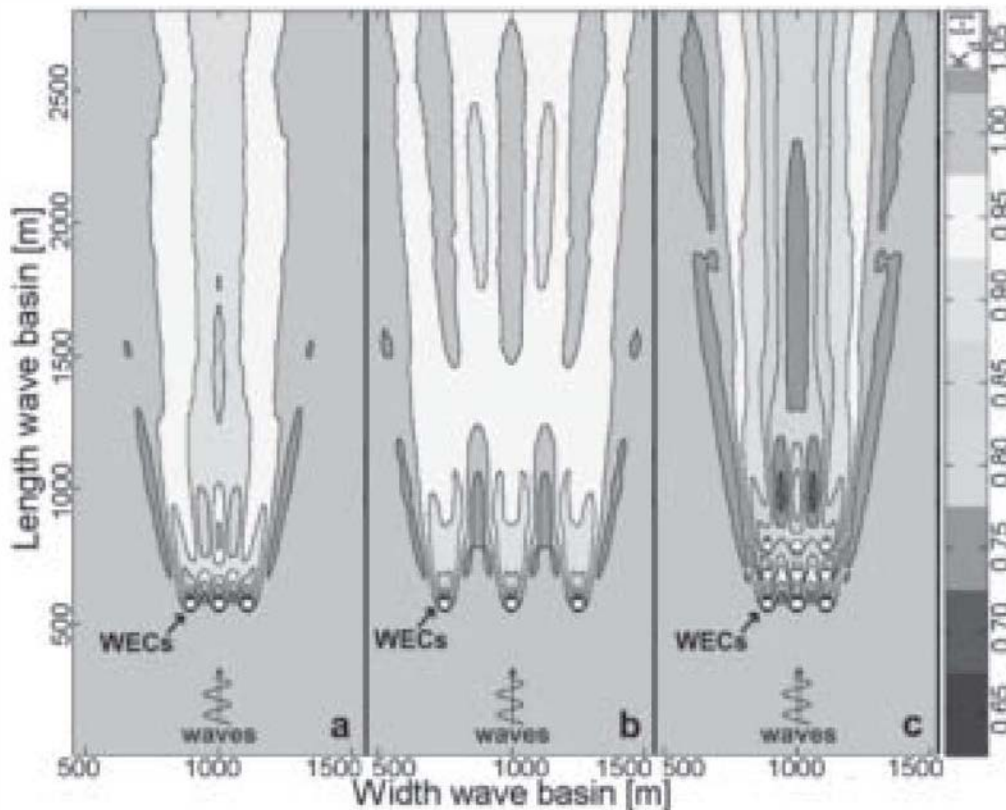


Figure 1. Wake effects behind WEC arrays (WECs of the overtopping type). Wave height reduction behind the WECs is visualized by the reduction of the disturbance coefficients k_d (=local H_s /incident H_{sCb}). WEC arrays of: a) 3 WECs, b) 3 WECs with larger inter-WEC distances, c) 9 WECs (Troch et al. 2010).

Using the wave propagation model MILDwave (Troch 1998), wake effects have been modelled behind wave energy converters, by using a sponge layer technique developed at Ghent University (Troch et al., 2010). In Fig. 1, wakes can be easily visualized for an example of devices of the overtopping type. Results are presented in terms of the disturbance coefficient k_d ($=H_s/H_{sGB}$, with H_s the local significant wave height and H_{sGB} the wave height at the wave generation boundary). Waves are propagating from the bottom to the top of Fig. 1, while the 'white squares' simulate generic wave energy converters with a certain power absorption. The wake in the lee of the WEC arrays is clearly visible, with areas of reduced k_d values, represented by variable contour lines. When the geometric layout and the number of devices of the WEC array changes (Fig. 1a-b-c), the wake behind the WEC array changes as well.

Several numerical studies on large WEC arrays have already been performed (e.g. Troch et al., 2010; Child, 2011; Borgarino et al., 2012), but large scale experimental studies on near-field and far-field wake effects of large WEC arrays are not available in literature. Within the HYDRALAB IV FP7 European programme, the research project WECwakes (Stratigaki et al., 2011; 2012) has been introduced to perform experiments on large arrays of point absorbers for different geometric configurations and inter-WEC spacings. The aim is to validate and further develop the applied numerical methods (Folley et al., 2012), as well as to optimize the geometric layout of WEC arrays for real applications. A scale model of such a point absorber WEC has been developed and optimized experimentally. The model has been constructed in the workshop of Ghent University. Its geometry, construction and operational behaviour is simple, allowing the production of the model in large numbers for experiments on large scale in the Shallow Water Wave Basin of the Danish Hydraulic Institute (DHI), in Denmark.

2. Characteristics of the WEC model

A generic point absorber (buoy) has been developed with a total height of 60.0 cm, a hemispherical bottom and a cylindrical PVC prefabricated upper part (see Section 3.1). The buoy's draft is 31.5 cm, equal to its diameter, with a total mass of 20.545 kg. The WEC has only one degree of freedom: it is restricted to heave motion along a vertical, square, hollow stainless steel axis that is anchored in a square 50.0 x 50.0 cm base. The axis passes through a slightly larger shaft bearing inside the WEC, which continues over the total height of the buoy to avoid water infiltration. The square form of the axis hinders rotation. The movement of the WEC buoy in the horizontal plane, due to the margin between axis and shaft bearing, is prevented by two PTFE (PolyTetraFluorEthen) bearings at the top and bottom of the buoy, selected for its low friction coefficient on steel surfaces.

The power take-off (abbreviated as PTO) is simulated by a mechanical brake, through which the extracted energy from the incident waves is dissipated by friction. Specifically, the PTO consists of 4 springs, exerting a normal force on two PTFE-blocks on top of the buoy, which are pressed against the steel WEC axis. In (Stratigaki et al. 2013; Stratigaki, 2013) the developed WEC is described in detail.

3. Developing the point absorber WEC model

For the preparation of the large scale experiments at DHI, experiments with WEC models have been performed in the wave flume of Ghent University (Fig. 2), in the wave basin of Queen's University Belfast (Fig. 3) and in the large wave flume of the Flanders Hydraulics Research laboratory (Fig. 4). The testing of the WEC models prior to the WECwakes project, allowed not only the removal of structural/operational problems of the WEC models, but also the

development of appropriate measurement techniques for the WEC's heaving motion and the surge forces on the WEC.

The WEC model has been tested under the action of regular and irregular long- and short-crested waves, for four different test cases: a) without the presence of the WEC, in an empty wave basin/flume; b) with the WEC buoy fixed, as obstacle, under wave action; c) with a heaving WEC buoy, but without any damping applied through the PTO; and d) with a heaving WEC buoy and with varying damping applied through the PTO.

Operational wave conditions, representative for several European Countries (e.g. Belgium, France, Germany, Portugal, Denmark, The Netherlands) have been tested.

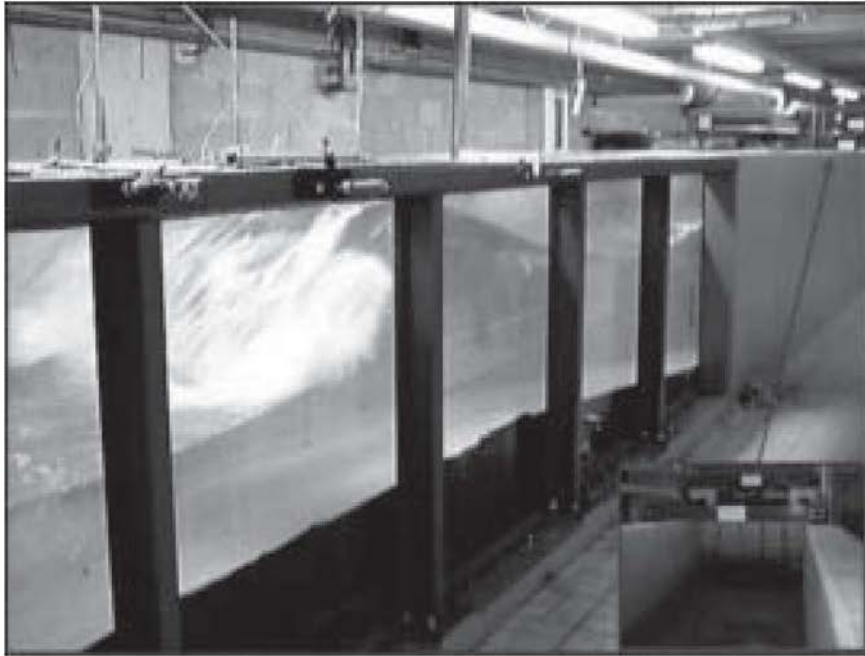


Figure 2. Front view of the wave paddle (down-right) and side view of the large wave flume of Ghent University, Belgium.



Figure 3. Side view of the wave paddles in the basin of Queen's Univ. Belfast.



Figure 4: Side view of the wave paddle (up-right) and front view of the large wave flume at Flanders Hydraulics Research, Belgium.

3.1 Experiments in the 2-D wave flume of Ghent University, Belgium

The first series of experiments has been carried out in the wave flume at the laboratory of Ghent University (Fig. 5), which has a width of 1.0 m and a water depth of 0.7 m. The operating software and hardware of the flume has been developed at Ghent University (Troch, 2000; Troch and Versluys, 2001; 2004).

Those experiments aimed at:

1. The structural testing of the model, comprising: testing of the rigidity of the vertical WEC axis, stability of the WEC base for different installation techniques in the wave flume bottom, solving/identifying internal friction issues of the WEC model, etc.;
2. The comparison between different measurement techniques for the heaving motion of the WEC buoy, in order to select the most appropriate one, using: a) an optical method (camera); b) two types of draw-wire potentiometers; and, d) an LVDT (linear variable differential transformer);
3. The measurement of horizontal motion of the vertical WEC axis using an optical method (camera).

In addition, tests regarding the non-lubricated (dry) and lubricated (wet) static μ_s and dynamic μ_d friction coefficient have been performed, in order to determine friction characteristics between the PTFE-bearings/PTFE-blocks of the PTO-system and the steel WEC axis. The experimental set-up shown in Fig. 6 has been used, in which the WEC is mounted to an electromechanical INSTRON 5800R tensile testing machine with a FastTrack 8800 digital controller.

The horizontal movement of the vertical WEC axis was found to be limited, indicating sufficient bending stiffness of the WEC axis, with the best results achieved when the base was clamped both on the wave flume bottom and at the top of the WEC axis. This installation technique was therefore selected for further testing with the WEC models.

The influence of the measuring techniques used for the heaving motion of the WEC buoy has also been determined. Specifically, the draw-wire potentiometer has been selected for its sufficient accuracy and feasibility/ease of use in large numbers (25 potentiometers, necessary for the WECwakes project).

In this experimental setup, the reflection from the sidewalls does not allow thorough investigation of the WEC buoy heave motion and of the water surface elevations around the WEC (wake effects), as the WEC buoy diameter (0.315 m) is quite large compared to the width of the wave flume (1.0 m).

Moreover, friction characteristics have been identified, important for the PTO-system and the calculation of the absorbed wave power of the WEC.

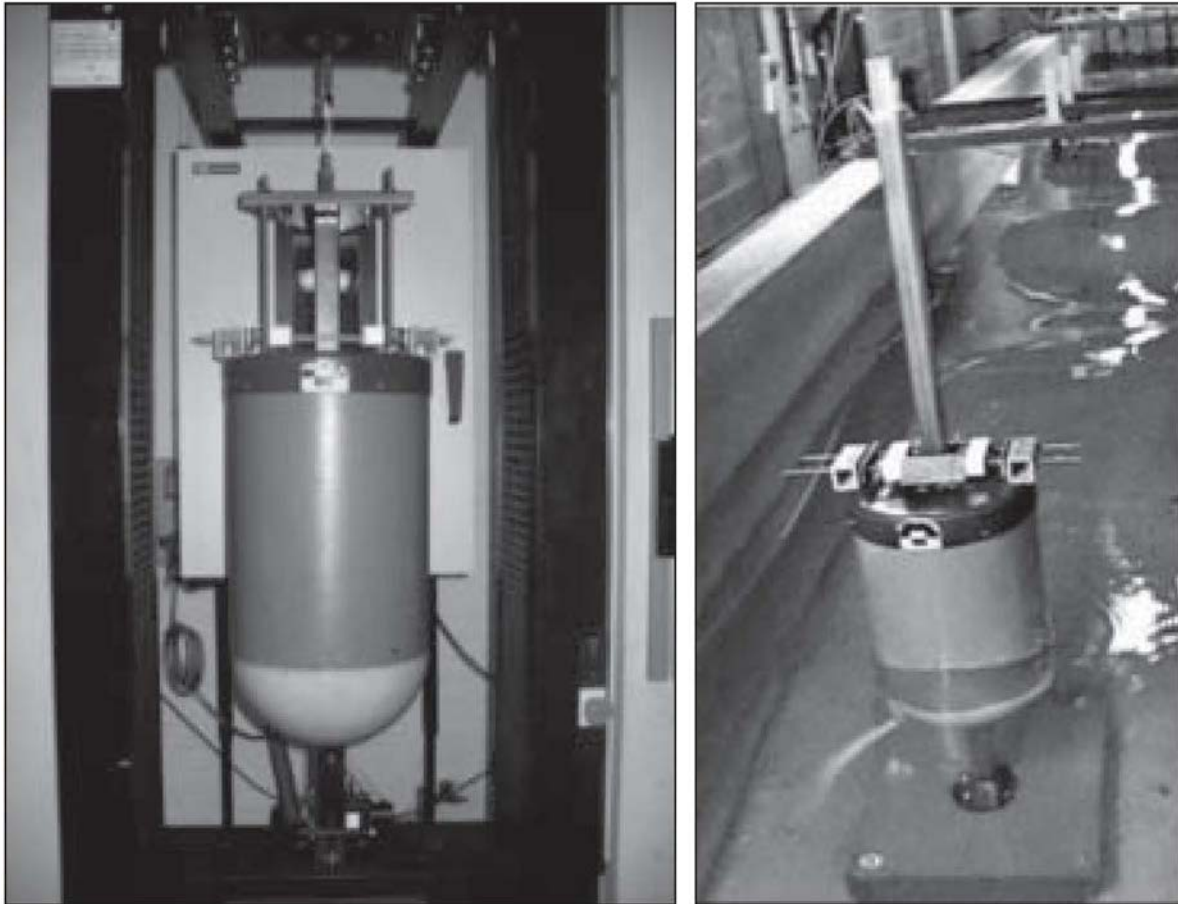


Figure 5. The developed generic point absorber WEC during tests at Ghent University, Belgium: Front view of the WEC buoy in the experimental setup in the electromechanical tensile testing machine (left); Rear view of the WEC during experiments in the wave flume (right). The waves are propagating from the rear of the photo toward the WEC.

3.2 Experiments in the 3-D wave basin of Queen's University Belfast, Northern Ireland, UK

A similar test series has been performed in the wave basin of Queen's University Belfast, which is 15.0 m wide and 17.0 m long, using a water depth of 0.61 m (Fig. 6).

The experiments in the wave basin aimed at:

1. The tuning of the PTO-system for the target wave conditions for the large scale experimental testing at DHI. Specifically, the tuning of the PTO-system has focussed on the experimental determination of the optimum power absorption of the WEC model;

2. The influence of the WEC model on the wave field (wake effects and wake dimensions) and the investigation of the appropriate distances between the resistive wave gauges used to capture wake effects around the WEC models;
3. Recording the WEC model's heaving motion which was not possible in the wave flume. Measurements of the heaving motion of the WEC buoy have been taken using the type of draw-wire potentiometer, which has been selected as a result of the flume tests.



Figure 6. Side view of the developed generic point absorber WEC in the experimental set-up of the wave basin of Queen's University Belfast, Northern Ireland (UK). Resistive wave gauges are installed upwave, downwave and at the sides of the WEC.

During the tests in the wave basin, the repeatability of the (un)damped WEC buoy motion has been confirmed, ensuring the effectiveness of the developed PTO-system composed by friction brakes. Moreover, optimum power absorption through the developed PTO has been estimated experimentally, for use in the large scale experiments at DHI.

3.3 Experiments in the 3-D wave flume of Flanders Hydraulics Research, Belgium

Similar test characteristics for regular waves used during the testing in the wave flume of Ghent University and in the wave basin of Queen's University Belfast, have been reproduced in the large wave flume of Flanders Hydraulics Research (Fig. 7). The wave flume is 4.0 m wide with water level set to 0.7 m, such that the test region comprises a flat bed of 13.25 m followed by 1:35 bed-slope over 24.5 m. Waves are generated on one side of the wave flume along a 4.0 m wide wave paddle. Measurements of water surface elevation have been taken using a network of 15 resistive wave gauges.

The objective of these experiments is to:

1. Tune in detail the PTO-system for the used wave conditions, by aiming at optimum power absorption of the WEC, using potentiometer measurements of the heaving motion of the buoy and surge force measurements on the WEC;

2. Test thoroughly the developed technique for measuring the surge force on the WEC, using load cells at the top and bottom of the WEC buoy.

The measurements of the heaving motion of the WEC buoy are used to calculate power absorption of the WEC, since energy is extracted from the waves by the power take-off system damping the WEC's motion. For measuring the heaving motion of the WEC buoy, a rotary potentiometer connected to the buoy is used (Fig. 8, left). The potentiometer consists of a wire which can wind and unwind following the heaving motion of the WEC buoy.

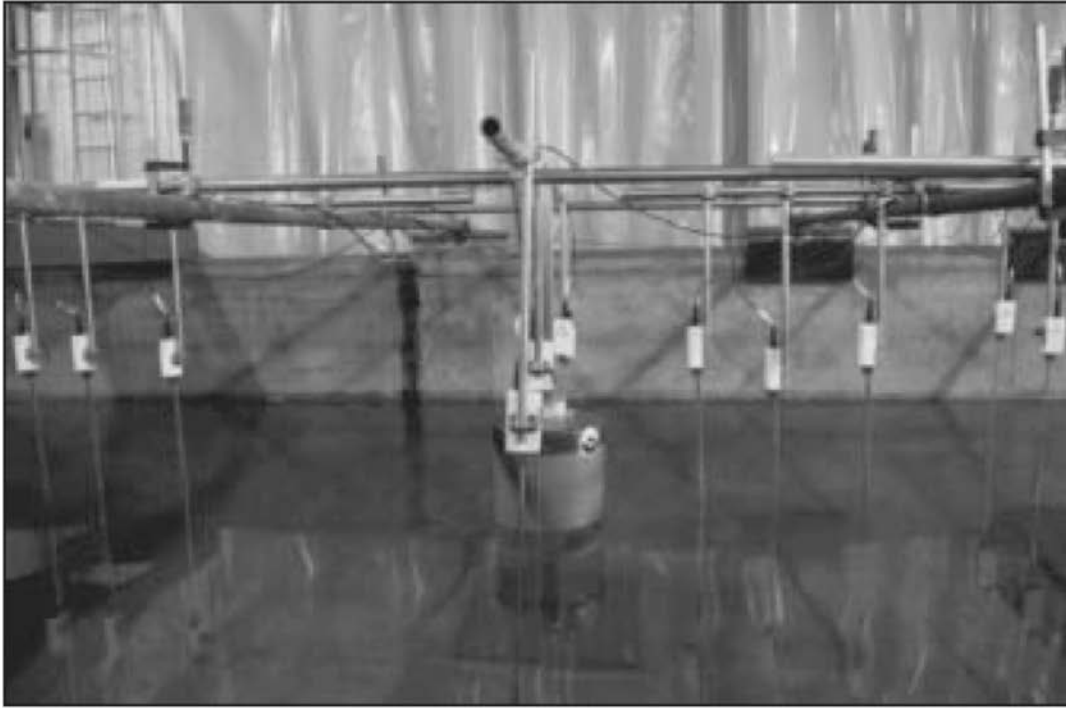


Figure 7. Side view of the developed generic point absorber WEC and resistive wave gauges installed upwave, downwave and at the sides of the WEC, in the experimental set-up of the wave flume of Flanders Hydraulics Research (Antwerp, Belgium).

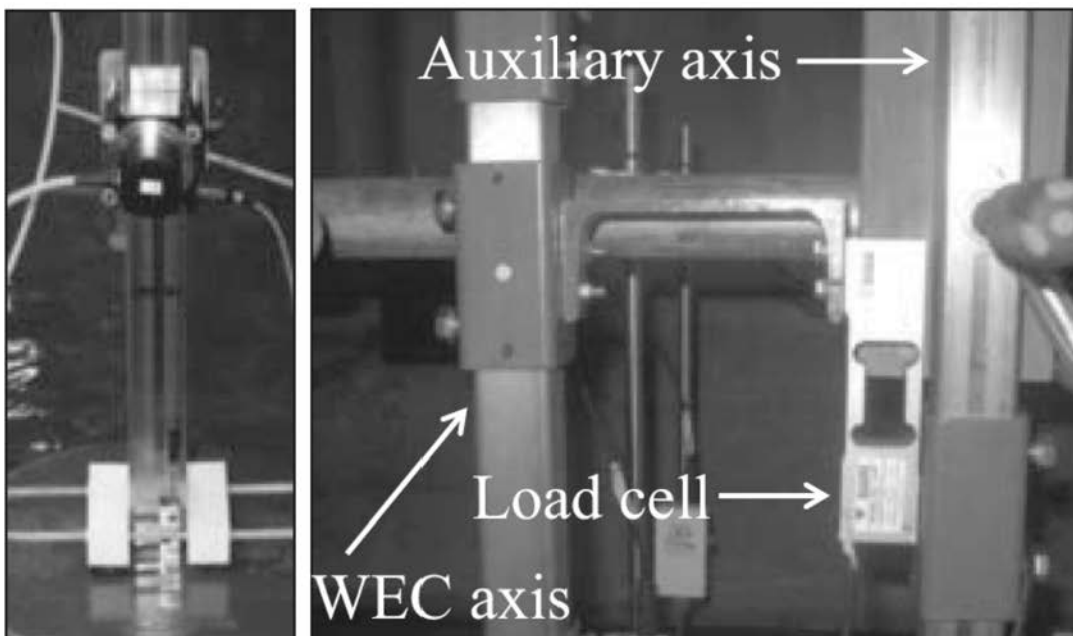


Figure 8: Rotary potentiometer (left); Load cell (right), both installed at the top of the WEC axis.

The surge (horizontal) force that the incident waves exert on the WEC buoy is measured using two load cells attached both at the top and at the bottom of the WEC axis and to an auxiliary axis, parallel to the direction of 0° wave propagation (Fig. 8, right). In a similar way, a second load cell is installed at the bottom of the WEC axis, just above the WEC base. The set-up for measuring forces on the WEC buoy has been developed by Ghent University for specific application in the WECwakes project.

4. Summary

A point absorber WEC model has been developed, suitable for use in the WECwakes HYDRALABIV project. The WEC model and the necessary measurement techniques have been tested prior to the large scale experiments at DHI for the WECwakes project in the wave flume and tensile testing machine of Ghent University (Ghent, Belgium), in the wave basin of Queen's University Belfast (Northern Ireland, UK) and in the large wave flume of the Flanders Hydraulics Research laboratory (Antwerp, Belgium).

The WEC model has been tested under the action of regular and irregular long- and short-crested waves, for four different test cases: a) without the presence of the WEC, in an empty wave basin/flume; b) with the WEC buoy fixed, as obstacle, under wave action; c) with a heaving WEC buoy, but without any damping applied through the PTO; and d) with a heaving WEC buoy and with varying damping applied through the PTO. Operational wave conditions, representative for several European Countries (e.g. Belgium, France, Germany, Portugal, Denmark, The Netherlands) have been tested.

This detailed testing of the WEC models, allowed not only the removal of structural/operational problems of the WEC models, but also the development and optimization of appropriate measurement techniques of parameters important for the investigation of the behaviour of the WECs and for the calculation of their wave power output. Specifically, for the WEC's heaving motion a rotary potentiometer has been selected, after testing different techniques. For recording the surge forces on the WEC a set-up has been developed at the workshop of Ghent University, 'cut out' for the WECwakes applications. Finally, the detailed testing of WEC models lead to the construction, at the workshop of Ghent University, of 25 identical WEC models with the necessary instruments attached, ready for direct use in the wave basin of the Danish Hydraulics Institute, in Denmark, in the WECwakes research project.

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