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A coupled hydrodynamic–structural model of the M4 wave energy converter

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ABSTRACT

A method is developed for modelling wave energy converters consisting of floats connected by slender structural elements. The hydrodynamic and structural dynamic analyses are separated in a two-stage process, though the model is fully coupled. The method of dynamic substructuring is used to achieve this separation. The linear diffraction/radiation problem is solved with a finite element idealisation for axisymmetric floats, and drag forces are incorporated by equivalent linearization. Results for a planar representation of the M4 device, and comparisons of theory and experiments undertaken for two scale models tested in regular and random waves, confirm the validity of the theoretical approach. A series of parametric studies is performed to clarify the important physical variables, including natural periods, the ratio of a characteristic length of the device to the wave length, and power take-off.

1. Introduction

In recent years the topic of wave energy has received much attention in the technical literature, and there have been several valuable reviews of the resource (for example Bryden, 2006; EPRI, 2011; Arinaga and Cheung, 2012), and technological developments (e.g. Falnes, 2007; Cruz, 2008; Greaves et al, 2009; Falcão, 2010). A wide range of devices has been proposed for harnessing wave energy (as reviewed for example in López et al. (2013) and Babarit et al. (2012)), and appropriate numerical methods for modelling and methods of benchmarking have also been subjected to extensive examination and review (e.g. Babarit et al., 2012; Wolgamot and FitzGerald, 2015). Out of these various reviews have emerged suggestions for classifying wave energy converters according to their geometric form and their principles of operation. Widely used is the distinction between overtopping devices; terminators; attenuators; and point absorbers (e.g. Wolgamot and FitzGerald, 2015). But these authors and others have also pointed out that some of the more promising devices do not readily fit into such a scheme of classification. The system under investigation in the present paper is such a device. It has a long articulated spine and points into the waves, so has some of the attributes of an attenuator (such as described by Yemm et al. (2012) and Farley et al. (2012)). The spine, however, is supported by individual floats, which have characteristics of point absorbers (see for example Evans and Porter (2012)). The aim of the present paper is use a coupled method to provide some of the theoretical background to explain how the device operates, leading to its good power output as measured against standard metrics such as capture width (Evans, 1981).

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There are 3 collinear axisymmetric floats in the M4 wave energy converter, each separated from its neighbour by about half a wave length at the optimal operating condition. The bow and mid float are rigidly connected, and the significantly larger stern float is attached to the mid float by an articulated joint at which power is generated by the relative angular motions of those two floats. The relevant motion of each float involves a combination of heave, pitch and surge. The progression down wave from small to medium to large floats serves to keep the heading of the device roughly aligned with the incident waves. The half wave length spacing is intended to optimise the anti-phase forcing on adjacent floats, hence maximising the angular motions at the joint. The near-trapping phenomenon however (e.g. Evans and Porter, 1997; Wolgamot et al., 2014), through which for an array of equally sized and spaced floats very large hydrodynamic responses can arise at certain critical wave frequencies, does not play a significant part in the behaviour of the device. Some of the details of its design principles have been explained by Stansby et al. (2015a), which together with Stansby et al. (2014, 2015b) also give results from experiments at two scales in regular and irregular waves. Fig. 1 shows the elevation of one of the experimental models of the initial concept, and Fig. 2 illustrates the relative motions of the floats when excited by a wave.

Stansby et al. (2015a) have also outlined a theoretical model, in which the (linear) hydrodynamic parameters are evaluated using the diffraction analysis software WAMIT, and dynamic response of the device in the vertical plane is obtained by a time-stepping procedure. This was used to assist in optimising the device performance in regular long-crested waves. For the results given here, we use a different method to develop the model, which is slightly simpler in the hydrodynamic representation: an axisymmetric diffraction analysis (as summarised in Eatock Taylor et al. (2009)) is used for each float, but there is assumed to be no hydrodynamic interaction between them. The modelling of the system dynamics, however, is more detailed, in that the connecting members can be assumed to be flexible. This is achieved by using the two-stage approach described by Sun et al. (2011, 2012). The first stage is the hydrodynamic analysis of the floats, considered as independent rigid bodies. Analysis of the structural dynamics of the mechanical interaction between the floats is then undertaken in the second stage: in this, the method of substructuring (also known as the master–slave approach) is used to condense out all structural degrees of freedom except those describing the motions of the rigid floats.

Details of the method of analysis are given in Section 2. The model is essentially linear, intended for investigating performance of the device under operational conditions. It is clear however that if the floats are flat-bottomed, as shown in Fig. 1, drag forces need to be included in the model. This is achieved by an iterative process using an approximation by equivalent linearization. As the emphasis here is on the geometric parameters governing the device, the power take-off is modelled simply as a linear damper. The resulting model is intended to be simple and efficient to use in exploring the design space for power capture from the device, and to highlight the significance of some key parameters. It is not suggested that this would be sufficient for detailed design, particularly where extreme wave conditions must be investigated. It is expected that at that stage (as discussed for example by Wolgamot and Fitzgerald (2015)) a fully nonlinear analysis may be appropriate, including full hydrodynamic interactions and modelling the details of what may be a nonlinear control system. It may also be considered desirable then to undertake limited CFD studies to develop a much more detailed assessment of how viscous effects influence the response of the device.

Application of the numerical model to different devices in the M4 family is illustrated in Section 3, where some comparisons are made with experimental measurements at two different scales. This section also includes some parametric

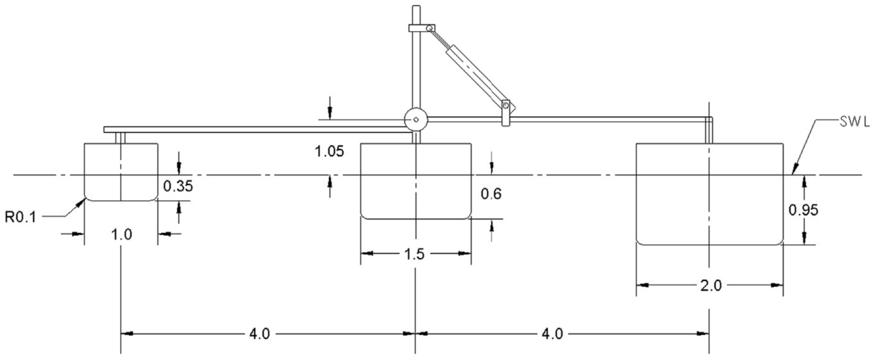

Fig. 1. Elevation of experimental model of initial concept with flat ends.

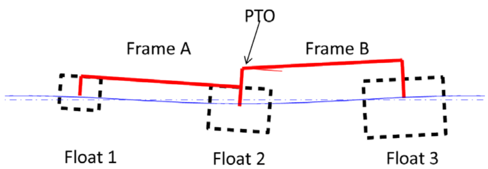

Fig. 2. Sketch showing motions of floats during the passage of a wave.