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Numerical study on the dynamics of a two-raft wave energy conversion device

Si-Ming Zheng [a], Yong-Hao Zhang [b], Yong-Liang Zhang [a,*], Wan-An Sheng [c]

[a] State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow G1 1XJ, United Kingdom
[c] Marine Renewable Energy Ireland, University College Cork, Ireland

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ABSTRACT

This paper presents a dynamic analysis of a two-raft wave energy conversion device based on the three-dimensional wave radiation-diffraction method. The device consists of two hinged cylindrical rafts of elliptical cross section and a power take-off system at the joint. The effect of raft length, linear damping and spring coefficient in the power take off (PTO) system, axis ratio (ratio of minor axis to major axis of raft elliptical cross section) and raft radius of gyration on wave energy capture factor has been investigated in frequency domain, while the effects of a nonlinear Coulomb power take-off, raft radius of gyration and latching control have been studied in time domain. The difference in the performance of a raft-typed device obtained using a linear damping and a Coulomb damping is also illustrated.

1. Introduction

Among ocean energies, wave power has the largest energy flux density, and is the most widely distributed marine renewable energy around the world (Sun et al., 2007; Zhang et al., 2014). How to exploit and utilize energy effectively from ocean waves has received extensive attention in many countries over the past decade. So far, there are numerous concepts for wave energy conversion, and more than 1000 wave energy conversion techniques have been patented in Europe, North America and East Asia (Drew et al., 2009; Chen and Zhang, 2013). Among the wide variety of devices proposed thus far, raft-type wave energy converters (WECs) are proven to have a high wave energy conversion efficiency for a given volume of machine without having to rely on fixed frames of reference so that they can be very complaint to the extreme waves for a good survivability (Yemm et al., 2012). These raft-type WECs mainly use the relative rotation around the hinge(s) to drive electricity generation system, such that the ocean wave energy can be converted into electricity.

As early as 1974, Cockerell designed a raft-type structure (Wooley and Platts, 1975) called Cockerell raft, consisting of a series of rafts hinged together by joints. Equipped with a hydraulic pump as power take-off (PTO) at each joint, the relative angular motion of two rafts activates a hydraulic pump which could drive a hydraulic motor to generate electricity. Haren (1978) studied the wave energy absorption of a Cockerell raft by using a two dimensional fluid-structure coupling model based on an assumption that the raft width is larger than the wave length. In the research, the hydraulic PTO was supposed

* Corresponding author. Tel.: +86 10 62797802.
E-mail addresses: zhengsm11@mails.tsinghua.edu.cn (S.-M. Zheng), yonghao.zhang@strath.ac.uk (Y.-H. Zhang), yongliangzhang@tsinghua.edu.cn (Y.-L. Zhang), w.sheng@ucc.ie (W.-A. Sheng).

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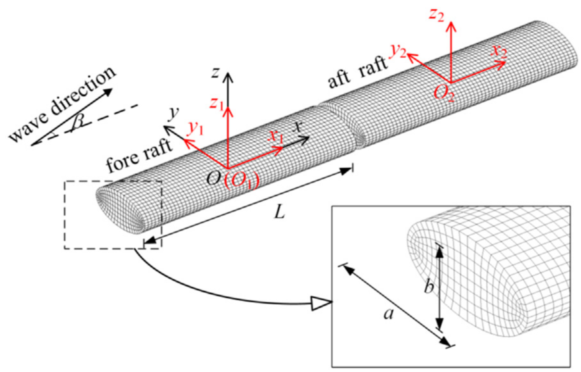

Fig. 1. Schematic of the wave energy conversion device floating on the sea under investigation.

to be a linear system. It has been shown that the wave energy absorption efficiency of a single floating body articulated with a vertical wall reached 100% through the optimization of articulated damping coefficient. It is also shown that wave period played a major role in wave energy absorption efficiency of multi-raft devices. The absorption efficiency of the two-raft device may be better than that of a three-raft device because the more rafts lead to smaller relative angular displacement which reduces energy conversion rate (Haren, 1978; Zheng and Zhang, 2014).

Another similar device is the McCabe Wave Pump (Wan Nik et al., 2011), consisting of three rectangular steel floating pontoons hinged together, in which the fore pontoon and aft pontoon can be seen as two arms hinged on the central small floating pontoon symmetrically. The rotary motion of the pontoons around the joint could be converted into hydraulic energy by hydraulic pumps, which could be used to generate electricity or desalinize seawater, depending on the utilization of the device. Assuming the Power Take-Off (PTO) system as a linear damper, Kraemer (2001) simulated a generic hinged-barge system in regular waves and pointed out that the power output of the system could increase by optimizing the length of the system to be compatible with the wavelength for the maximum pitching excitation. Later, a more complicated PTO system, including a nonlinear damping, was also investigated (Nolan et al., 2003).

The Pelamis, a good example of the raft-type WEC (with 4–5 floating circular segments) by the Pelamis Wave Power in the UK, has undergone a significant development from concept to commercial deployment (Yemm et al., 2012). There are normally two degrees of freedom at each joint, hence the incoming waves cause the segments not only to pitch, but also to yaw relative to each other. The relative rotational motion around the joint is used to pump oil into high pressure storage accumulators, which then could drive generators to produce electricity (Henderson, 2006). Retzler et al. (2003) conducted a numerical and experimental study on the Pelamis wave energy conversion capacity and the ability of resistance to extreme wave conditions, the results showed that the maximum wave energy capture width is as large as 150% of their ‘displacement width’ (i.e., the cube root of displaced volume).

In a similar way, floating breakwaters can be also used as a device for wave energy production. In the floating breakwaters, a grid of floating rectangular modules are connected by connectors and a linear hydraulic PTO system is utilized to generate power from waves (Loukogeorgaki et al., 2012; Michailides and Angelides, 2012, 2015). Effect of the connectors’ stiffness on the response and the produced power was investigated in frequency domain using hydroelastic analysis, showing that increasing the connectors’ stiffness results in the occurrence of the peaks of response and total averaged power in a higher wave frequency (Michailides and Angelides, 2012). To improve the produced power or the protection effectiveness, a multi objective optimization process of the floating breakwater was also developed (Michailides and Angelides, 2015).

So far, most of the studies are limited to the dynamics of raft-typed wave energy convertors of either circular or rectangular cross-section, and to the best of authors’ knowledge, no work has been reported about the influence of cross section of the raft and raft radius of gyration on the wave energy conversion as well as the differences between the assumed linear damping and the actual Coulomb damping. The aim of this paper is to present a dynamic analysis of raft-typed wave energy conversion device of elliptical cross-section (see Fig. 1), focusing on the dynamic behaviour and the wave energy capture factor of the device over a wide range of raft length, wave period, axis ratio of cross-section, raft radius of gyration as well as the difference between linear and nonlinear PTO systems. The performance of the device with latching control is also investigated.

2. Formulation of the problem

A wave energy conversion device consisting of two hinged rafts and a PTO system at the joint is considered, as shown in Fig. 1. The two elliptical rafts linked by a hinged joint float on the sea with water depth d. Each raft with a length L has a uniform elliptical section with a major axis a and a minor axis b. The centre of each raft mass coincides well with the raft geometry centre. The density of each raft is ρ_0 for a uniform distribution of the mass. The spacing between the rafts in still water is l_s. The mass of each raft and the rotary inertia about the centre of mass are m and I, respectively. The radius of gyration of each raft is $r = (I/\mathrm{m})^{0.5}$. Wave with an amplitude A and a period T passes in a direction with angle β relative to the longitudinal axis of the rafts so to drive the two rafts (viz. the fore and aft rafts) to rotate relatively. The wave-induced relative rotation of the rafts around the hinge is