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Influence of hydraulic power take-off unit parameters on power capture ability of a two-raft-type wave energy converter

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ABSTRACT

In this paper, a two-raft-type wave energy converter (WEC) consisting of two rafts and a hydraulic power take-off (PTO) unit is considered. The hydraulic PTO unit composed of two hydraulic cylinders, two gas accumulators and a hydraulic motor coupled with a generator is available to capture wave power by using the relative pitch motion between the two rafts. To investigate the influence of hydraulic PTO unit parameters on the power capture ability of the two-raft-type WEC, a combined model based on the linear wave theory and basic-hydraulic equations is presented. The model is validated by comparison of the present results with the data obtained by a hardware-in-the-loop (HIL) test rig, and there is a good agreement. Based on the validated model, the influence of piston area, rod-to-piston area ratio and mounting position of the hydraulic cylinder, displacement of the hydraulic motor, initial volume and pre-charge pressure of the high-pressure (HP) gas accumulator and effective damping of the generator on the power capture ability of the two-raft-type WEC is given and discussed. The variations of the optimal hydraulic PTO unit parameters and their corresponding peak capture width ratios with the wave states are also illustrated.

1. Introduction

Wave power with large energy flux density is regarded as one of the most promising renewable energy source. How to extract and utilize this type of energy from the ocean waves has received considerable attention from the researchers and engineering designers in many countries over the past two decades. So far, numerous concepts of wave energy conversion have been proposed and many of wave energy conversion techniques have been patented (Drew et al., 2009). Among the various concepts of wave energy converters (WECs), the raft-type WECs consisting of a series of semi-submerged rafts hinged end to end by the joints with hydraulic power take-off (PTO) systems are proven to have high stability and energy conversion efficiency. Since their PTO units react against their own body rather than against a separate external reaction frame, which enable them to quickly adapt to the extreme sea states for a good survivability (McCormick, 2007; Yemm et al., 2012).

The raft-type WECs are offshore, floating, slack-moored devices. Normally, they are aligned with the predominant wave propagation direction such that they can use the wave curvatures to improve the energy extraction (Haren and Mei, 1982; Yemm et al., 2012). As the wave passes along the length of the rafts, each raft outputs surge, heave, and pitch motions. The relative pitch motion between different rafts around the joint would force the hydraulic cylinders to pump the high-pressure (HP) oil through the HP gas accumulator to the hydraulic motor. Then, the difference pressure between the HP gas accumulator and low-pressure (LP) gas accumulator drives the hydraulic motor shaft to rotate, and this rotation forces the generator to produce electricity (Henderson, 2006; Liu et al., 2017).

The concept of the raft-type device seems to be first conceived by Cockerell, who designed a raft-type articulated barge system (called Cockerell raft) in 1974 (Wooley and Platts, 1975). Later in 1978, Haren (1978) used a two-dimensional fluid-structure coupling model to make a comprehensive theoretical study of a Hagen-Cockerell raft by assuming the hydraulic PTO unit as a linear damper, and proved that the efficiency of a floating raft hinged at a vertical wall can reach 100% when the damping coefficient of the PTO unit is optimized. Following the research of Haren (1978), Kraemer (2001) and Nolan et al. (2003) studied another similar raft-type wave energy conversion device, which is known as McCabe Wave Pump (MWP). The MWP is composed of three rectangular steel floating pontoons articulated together, in which the heave motion of the central pontoon is damped by a submerged horizontal plate (Wan Nik et al., 2011). Two sets of hydraulic cylinders are equipped in the device such that the relative pitch motion between the barges around the joint could be used to drive the hydraulic cylinder to convert the wave energy

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into useful energy or desalinize seawater. A study of the MWP showed that the pitch motion and energy absorption can be optimized by adjusting the ratio between the length of barges and the wavelength (Kraemer, 2001). In comparison with MWP, the Pelamis WEC is another more cost-effective raft-type device containing four or five cylindrical segments articulated end to end by the joints. It can utilize not only the relative pitch motion around the joints but also the relative yaw motion to pump HP oil into HP gas accumulators and then drive the generators to produce electricity (Henderson, 2006; Yemm et al., 2012). The wave energy conversion capability and the ability of resistance to aggressive wave conditions of the Pelamis WEC had been explored by Retzler et al. (2003), whose results showed that the maximum power capture width of the device could reach a value as large as 1.5 times of its displacement width.

In the recent studies, the power capture ability of a raft-type-like wave energy conversion device M4 consisting of three cylindrical floats was experimentally investigated by Stansby et al. (2014, 2015a, 2015b). In their research, the power capture abilities of the devices M4 with rounded base floats were compared with that with flat base floats, and their finding showed that the floats with rounded base can extract more 60% energy due to reducing energy losses. Zheng et al. (2015) investigated the effects of cross section of the raft and raft radius of gyration on the wave energy conversion capacity of a raft-type WEC with an elliptic cylinder shape. And with the assumption of linear PTO unit, two theoretical models for maximizing wave energy conversion of the device was proposed in the research of Zheng et al. (2016a, 2016b). Considering the combined action of non-linear waves and viscous flows, Chen et al. (2016) studied the influence of wave height, wave period, PTO damping coefficient and flow velocity on the wave energy dissipator ratio and wave transmission coefficient of a twin-raft wave energy dissipator. Following the work of Zheng et al. (2015) and Chen et al. (2016), Yu et al. (2016) combined the advantage of raft-type WECs and pendulum-type WECs, and proposed a novel WEC (called Wave Loong) composed of two rafts hinged end to end by the joint and one pendulum hung at the hinged joint. The effect of pendulum radius of gyration, pendulum length, pendulum mass, raft length, PTO damping, and wavelength on the capture ability of the novel WEC was investigated. More recently, with the consideration of dynamics of hydraulic circuit and hydraulic components, Liu et al. (2017) investigated the performance of a two-raft-type WEC connected with a hydraulic PTO unit. They highlighted the difference in the behavior of a raft-type WEC with a hydraulic PTO unit and with a linear PTO unit, and the relationships among the optimal power capture ability, the normalized optimal magnitude of the hydraulic PTO force and the wave states were numerically revealed in their research.

So far, most of the previous studies are limited to characterizing the hydraulic PTO unit as a linear PTO unit, and to the best of the authors' knowledge, no work has been reported about the influence of hydraulic PTO unit parameters on the wave energy capture ability of the raft-type WECs. Actually, the wave energy capture ability of the raft-type WECs relies on several parameters of the hydraulic PTO unit: the piston area, rod-to-piston area ratio and mounting position of hydraulic cylinder, the displacement of hydraulic motor, the initial volume and pre-charge pressure of HP gas accumulator and the effective damping of generator. This paper is an extension and a continuation of the work of Liu et al. (2017). The aim of this paper is to present a numerical study of a two-raft-type WEC, focusing on the influence of hydraulic PTO unit parameters on the power capture ability of the raft-type WEC.

The rest of this paper is organized as follows. In Section 2, a two-raft-type WEC is first introduced then a mathematical model for the dynamics of such a WEC is presented based on the linear wave theory and hydraulic-basic equations. Model validation and numerical investigations into the effect of hydraulic PTO unit parameters on the power capture ability of the two-raft-type WEC are shown in Section 3. Finally, conclusions are made in Section 4.

2. Formulation of the problem

We consider a raft-type WEC consisting of two rafts and a hydraulic PTO unit (called two-raft-type WEC), as shown in Fig. 1. The two rafts with cylindrical shape have the same length L and diameter D, and are hinged by a joint with a gap d_0 between them. Actually, the two-raft-type WEC can be considered as a two-barge Pelamis device, in which only the relative pitch motion between the two barges is utilized to capture energy. The mass center of each raft coincides well with its geometry center. The motion characteristic of the WEC is described in a Cartesian coordinate (x, y, and z) system with its origin O coincident with the center of the joint, where the x- and y-axes are taken along the length and the diameter direction of the rafts in still water, respectively, while the z-axis is in the vertical direction, as shown in Fig. 1(a).

2.1. Equation of motion

Assuming the incident wave with amplitude a_{w} and angular frequency ω propagating along the positive x-axis, the motion of the WEC takes place in xoz plane. In the linear wave theory, the wave force can be written as: $f_{\mathrm{w},j}(t) = f_{\mathrm{e},j}(t) + f_{\mathrm{r},j}(t) + f_{\mathrm{hys},j}(t)$ ($j = 1, 3, 5$ indicates the surge, heave and pitch modes of the fore raft, respectively; $j = 1', 3', 5'$ indicates the surge, heave and pitch modes of the aft raft, respectively) (Falnes, 2002). For the WEC in the wave considered, the rafts are regarded as rigid bodies since their deformation is very small. Based on the Lagrange's equations, Liu et al. (2017) adopted a generalized displacement vector $\mathbf{x}_{\mathrm{gen}}(t) = [x_0\ z_0\ \theta_1\ \theta_2]^{\mathrm{T}}$ (here, superscript "T" means the transpose of a vector) to describe the motion characteristic of the WEC, and gave the time domain motion equation as:

$$\left(\mathbf{M}+\mathbf{A}_{\mathrm{gen,add}}(\infty)\right)\ddot{\mathbf{x}}_{\mathrm{gen}}(t)+\int_0^t\mathbf{h}(t-\tau)\dot{\mathbf{x}}_{\mathrm{gen}}(\tau)\mathrm{d}\tau+\mathbf{K}_{\mathrm{gen}}\mathbf{x}_{\mathrm{gen}}(t)=\mathbf{f}_{\mathrm{gen,e}}(t)+\mathbf{f}_{\mathrm{pto}}(t) \quad (1)$$

where $\mathbf{A}_{\mathrm{gen,add}}(\infty)$ is the limiting value of the generalized added mass matrix $\mathbf{A}_{\mathrm{gen,add}}(\omega)$ for $\omega = \infty$. The expressions of terms used in Eq. (1) are given in the Appendix.

The wave excitation force acting on mode j of the rafts, $f_{\mathrm{e},j}(t)$, can be given by (Falnes, 2002):

$$f_{\mathrm{e},j}(t) = a_{\mathrm{w}}\cdot\left|\Gamma_j(\omega)\right|\cdot\cos\left(-\omega t+\angle\Gamma_j(\omega)\right) \quad (2)$$

where $\Gamma_j(\omega)$ is the frequency-dependent complex excitation force coefficient (force per unit incident wave amplitude) at mode j, whose modulus and argument are $|\Gamma_j(\omega)|$ and $\angle\Gamma_j(\omega)$.

As shown in Eq. (1), there is a convolution term, which makes it inconvenient to perform the simulation of such type of time domain model. Taghipour et al. (2008), and Perez and Fossen (2008, 2011) adopted a linear-time-invariant parametric model in state space form to substitute the convolution term by frequency domain identification. With the assumption of linearity, the convolution integral in Eq. (1) can be approximated by a state space model:

$$\boldsymbol{\mu}(t) = \int_0^t\mathbf{h}(t-\tau)\dot{\mathbf{x}}_{\mathrm{gen}}(\tau)\mathrm{d}\tau \Rightarrow \begin{cases}\dot{\mathbf{x}}_{\mathrm{s}} = \mathbf{A}_{\mathrm{s}}\mathbf{x}_{\mathrm{s}}+\mathbf{B}_{\mathrm{s}}\dot{\mathbf{x}}_{\mathrm{gen}}(t)\\ \boldsymbol{\mu}(t) = \mathbf{C}_{\mathrm{s}}\mathbf{x}_{\mathrm{s}}\end{cases} \quad (3)$$

where $\mathbf{A}_{\mathrm{s}}$, $\mathbf{B}_{\mathrm{s}}$ and $\mathbf{C}_{\mathrm{s}}$ are coefficient matrices of the state space model; $\mathbf{x}_{\mathrm{s}}$ is the state vector of the state space model.

2.2. Equations for the hydraulic PTO unit

The hydraulic PTO unit widely used in the raft-type WEC is shown in Fig. 2. The chamber without piston-rod of the top hydraulic cylinder is connected to the chamber with piston-rod of the bottom hydraulic cylinder, to be chamber 14, since they perform the same function when the