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The maximum wave energy conversion by two interconnected floaters: Effects of structural flexibility

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ABSTRACT

The effect of structural flexibility on the maximum wave energy conversion by two interconnected floaters is investigated. For the wave energy converter (WEC), the relative pitch motion of two floaters is converted into electricity by a power take off (PTO) system, which is simplified as a linear damper. The hydrodynamic coefficients of the WEC are calculated based on linear potential flow theory. The coupled effects of structural deformation and hydrodynamic interaction are considered using an approximate approach based on discrete-modules and Euler-Bernoulli beam bending. Then equations of motion of the hinged two-floater WEC with structural deformation considered are established in frequency domain. Based on the motion equations, a mathematical model is proposed for evaluating the maximum wave energy conversion of a hinged two-floater WEC in waves. This mathematical model can be used to calculate the maximum power capture and the corresponding optimum PTO damping for both rigid and flexible two-floater WEC with or without motion constraints. Results show that the structural flexibility has a negative effect on the power capture performance for relatively large wave length but a positive influence for relatively small wave length. The motion constraints lead to a reduction of the captured power for both rigid and flexible WEC.

1. Introduction

Wave energy is a kind of renewable resources with large density of power and is still under development. Until now, various types of devices have been proposed to capture wave energy from oceans, such as oscillating water column, overtopping device, point absorber and hinged multi-module floating-body wave energy converter (WEC), etc. [1–5]. The motion of these devices induced by ocean waves can be converted into electricity by the power-take-off (PTO) systems, which may consist of a rotating electrical generator driven by a mechanical machine including air or hydraulic turbine or hydraulic motor. The commercialization of a WEC concept highly depends on the maximum power generated by the device [6]. As a result, what is the maximum power that a WEC can generate and how to realize such an optimal condition has been a research hotspot in recent years.

Much early work on the power efficiency of WECs did not specify the PTO system. For a freely floating WEC, the incident wave energy is scattered due to the presence of the bodies and in the meanwhile, some energy is radiated due to the oscillation of the floaters excited by incident waves [7]. Therefore, the time-averaged power absorbed by the WEC can be calculated by the difference between excitation power and radiated power [8]. The above-mentioned maximum power is obtained based on the assumption that the amplitude of the motion of a WEC can be always reached with no limitations in order to achieve the optimal condition. However, in practical application, physical limitations of the motion of a WEC always exist due to the constraints such as pump stokes or mooring lines [9]. Later, some researchers further investigated the maximum power obtained by a WEC (the PTO system was still not specified) under motion constraints by using a Lagrange multiplier and a motion limitation matrix [10,11]. A problem of not specifying the PTO system is that most of the elements of the matrix of

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PTO system will be non-vanishing in order to obtain the optimum power. This will lead to the realization of the optimal PTO system being impossible in practical application, especially for multiple floaters with multiple degrees-of-freedom.

Subsequently, the maximum power captured by a WEC was calculated by specifying a PTO system. In most cases, the PTO system is simplified as a linear damper. For a WEC consisting of a single floater with a single degree-of-freedom in waves, the maximum power absorption by a specified PTO was analysed [12,13]. A slightly more complex representation of a PTO system considered the nonlinear motion characteristics of a hydraulic PTO system [14–16]. For such a PTO system, the theoretical expression of the maximum absorbed power is difficult to derive and the power is usually calculated numerically by using time domain analysis.

The present study focuses on a type of WEC consisting of two or more interconnected floaters hinged together by joints. This type of WEC usually utilizes the relative motion between two floaters to drive the PTO system to convert ocean wave energy into electricity. Based on the assumption of ideal fluids (i.e. inviscid, incompressible and irrotational) and rigid body, Zheng et al. [17] derived a mathematical model for evaluating the maximum wave energy conversion of two hinged floaters with motion constraints using the linear three-dimensional wave diffraction-radiation theory. The PTO system was simplified as a linear damper. Based on the mathematical model, effects of wave frequency, PTO system, floater rotatory inertia radius, and motion constraints on the power capture performance of the WEC were discussed in detail. To the authors' knowledge, most WECs (including oscillating water column, point absorber and hinged floaters) are taken as rigid bodies when the hydrodynamic interactions between waves and WECs are analysed. This assumption may be reasonable and acceptable for some types of WEC such as point absorbers, for which the structural flexibility may be neglected. However, for the hinged-floater WEC considered in the present study, the dimension in the longitudinal direction (parallel to the incident wave direction) is much larger than those in the other directions. For the floater considered by Zheng et al. [17], the dimension in the vertical direction is smaller than (half of) that in the horizontal direction for the elliptical cross section. In such conditions, the floater may be regarded as a beam and the structural flexibility (or deformation) may be important. If the structural flexibility has a positive effect on the power capture performance of the WEC, we can choose proper materials and shape of floaters to ensure the flexibility of the structure. Otherwise, the structure should be designed to be as rigid as possible to reduce the negative effect. Such a consideration motivates us to investigate how the flexibility of floaters will affect the power capture performance of hinged-floater WEC.

Some researches, although limited, were carried out on wave energy conversion by a flexible structure. Farley [18] investigated the power absorption of a floating beam sufficiently flexible to follow the waves. Michailides and Angelides [19,20] introduced a flexible floating structure which was capable for both energy production and shore protection. Based on numerical analysis, the combined effects of wave energy extraction, behaviour and a desired level of protection were illustrated. Babarit et al. [21] developed a linear numerical model for analysing the dynamic response of a flexible electroactive wave energy converter. The numerical results were compared with experimental data in regular waves, which showed rather good agreement.

When the structural flexibility (or deformation) of a floating system in waves is considered, the traditional hydrodynamics theory based on rigid body assumption is no longer valid. The hydroelasticity theory in which the coupling between fluid motion and structural deformation is taken into account is adopted to calculate the dynamic response of a flexible floating structure in waves. The classic three-dimensional hydroelasticity theory calculates the response in three main steps: evaluation of dry modes of flexible structures; evaluation of hydrodynamic coefficients for each mode; and solving the coupling modal equation to obtain the hydroelastic response of flexible structures in waves [22]. Unlike the traditional modal superposition approach, Lu et al. [23] proposed a new method to calculate the dynamic response of continuous flexible structures based on multi-rigid-body dynamics and Euler-Bernoulli beam bending theory. The effects of structural deformation can be simply considered by adding a structural stiffness matrix to the motion equation of a rigid body in waves. This approach was extended by Sun et al. [24] to investigate the hydroelastic behaviour of hinged multi-module structure in waves. In the present work, the hydroelasticity theory proposed by Lu et al. [23] is adopted to analyse effects of structural flexibility on the power capture efficiency of a hinged flexible two-module WEC. The mathematical formula derived by Zheng et al. [17] can be extended to consider the structural flexibility by just adding a structural stiffness matrix to the original rigid-body motion equations. Then the maximum power absorbed by the WEC with different structural flexibility will be explored.

2. Description of a hinged two-module WEC

The WEC model adopted is the same as that in Zheng et al. [17] and is briefly described here. As shown in Fig. 1, the WEC consists of two identical floaters (including the fore raft in the upstream of incident waves and the aft raft in the downstream), which are hinged together by a joint. Each floater is a horizontal cylinder with elliptical cross section. The length of each floater is denoted as L. The length of the major and minor axis of the cross section are a and b, respectively. The gap between two floaters is l_s. c_{PTO}, I_{PTO} and k_{PTO} are the PTO damping, inertia and stiffness coefficient, respectively. The water density is ρ. The water depth is d. The global coordinate system oxyz is denoted as follows: the xoy plane is located at the still water surface with the origin o being the geometric center of the fore raft and x pointing in the longitudinal direction. For each floater, there is a local coordinate system (parallel to the global coordinate system), i.e. $o_1 \times {}_1y_1z_1$ and $o_2 \times {}_2y_2z_2$. o_1 and o_2 are the geometric centre of fore and aft raft, respectively. The angle between regular incident wave direction and the longitudinal direction of the floater (x axis) is denoted as β. Each floater has six modes of oscillation, i.e. surge, sway and heave (linear displacement along x, y and z axis, respectively); and roll, pitch and yaw (rotatory displacement around x, y and z axis, respectively). In the present analysis, only the wave direction $\beta = 0$ is considered. Due to the symmetry of the floater, only three modes of oscillation, i.e. surge, heave and pitch are considered. The inertial radius corresponding to pitch motion for each floater is denoted as r.

3. Derivation of theoretical maximum wave energy conversion

In this section, we use the hydroelasticity theory proposed by Lu et al. [23] to derive the maximum wave energy conversion by a hinged two-module structure (see Fig. 1) with structural flexibility taken into account. Following Lu's approach, each floater of the WEC is divided into several submodules and imaginary beam is added between the centres of gravity of two adjacent submodules. As shown in Fig. 2, each floater is divided into n submodules. The length of each submodule is thus $l_0 = L/n$. This idea is somewhat similar to the mass-spring model used in mooring system analysis [25]. The difference is that the latter ignores the bending effects and thus springs are added between masses to model the tension in mooring system. However, in the present study, both the tension and bending are important and should be considered, leading