Renewable Energy 101 (2017) 265–274

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

On the dynamics and design of a two-body wave energy converter

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ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form
26 August 2016
Accepted 27 August 2016

Keywords:
Wave energy converter
Two-body system
Dynamics
Suboptimal design
Optimal design

ABSTRACT

A two-body wave energy converter oscillating in heave is studied in this paper. The energy is extracted through the relative motion between the floating and submerged bodies. A linearized model in the frequency domain is adopted to study the dynamics of such a two-body system with consideration of both the linear viscous damping and the hydrodynamic damping. The closed form solution of the maximum absorption power and corresponding power takeoff parameters are obtained. The suboptimal and optimal designs for a two-body system are proposed based on the closed form solution. The physical insight of the optimal design is to have one of the damped natural frequencies of the two body system the same as, or as close as possible to, the excitation frequency. A case study is conducted to investigate the influence of the submerged body on the absorption power of a two-body system subjected to suboptimal and optimal design under regular and irregular wave excitations. It is found that the absorption power of the two-body system can be significantly higher than that of the single body system with the same floating buoy in both regular and irregular waves. In regular waves, it is found that the mass of the submerged body should be designed with an optimal value in order to achieve the maximum absorption power for a given floating buoy in the presence of viscous damping. The viscous damping on the submerged body should be as small as possible for a given mass in both regular and irregular waves.

1. Introduction

The utilization of wave energy has been actively explored for more than 200 years since the first patent was applied in Paris in 1799. Hundreds of wave energy converters have been developed in the past decades [1–11]. Among all the technologies that appeared in the past years, point absorber is one of the most popular designs and has been considered one of the most promising and cost effective devices. The first generation of point absorber is a single body system oscillating in heave. Two characteristic devices of the single body wave energy converter are Lysekil [12] and CETO-6 [13].

The early theoretical study of single body wave energy converters by Budal [14], Evans [15] and Mei [16] show that the maximum power of an axisymmetric point absorber oscillating in the heave under regular wave excitation is $P_{max} = \frac{\rho g^3 A^2}{4\omega^3}$, where ρ is water density; g is standard gravity acceleration;A is wave amplitude and ω is wave frequency. In order to achieve this maximum absorption power, the natural frequency of the oscillating body needs to match with incident wave frequency. In real application, however, this condition is usually hard to realize since the typical incident wave frequency is usually very low (0.1Hz-0.2 Hz). As a consequence, the dimension of the floating buoy needs to be impractically large in order to match its natural frequency with the incident wave frequency. Based on Falcao's calculation [17], the diameter of a submerged hemisphere needs to be 52.4 m in order to match an incident wave frequency of 0.1 Hz: too large to be practical. Therefore, people have developed different methods to approximate this frequency matching condition. In Ref. [18], an additional mass is attached under the floating buoy to decrease the natural frequency. Suboptimal control methods such as latching [19] and declutch control [20] were also developed based on this frequency match condition.

Another way to develop a resonant wave energy converter is to design an additional body under the floating buoy to create a two-body wave energy converter, where the energy is extracted through the relative motion of the two bodies. There are two advantages to add an additional submerged body under the floating buoy. Firstly, the second body can act as a reaction body, which makes mooring easier in deep water, compared with directly connecting the floating buoy to the seabed. Secondly, the dynamics of second body

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http://dx.doi.org/10.1016/j.renene.2016.08.059
0960-1481/

can be utilized to improve the performance of the overall system. Two typical designs of two-body wave energy converters are the Powerbuoy (Fig. 1 right), which was developed by Ocean Power Technology in the USA [21], and Wavebob (Fig. 1 left), which was developed in Ireland [22]. Both devices use the relative motion between the floating buoy and submerged body to extract energy from ocean waves. However, it is found in Fig. 1 that the design philosophy of the submerged body is quite different between these two devices. Wavebob used a second body with a streamline configuration and large mass while Powerbuoy used a resistive heave plate.

Early studies of two-body wave energy converters mainly focused on regular wave excitation. Falnes [23,24] investigated the concept of using relative motion between a floating buoy and a submerged body to harvest energy. He found that it is possible to achieve the optimum power for a two-body wave energy converter oscillating in heave in regular waves. Korde [25] explored the concept of two-body wave energy converter and compared the performance of a submerged reaction mass with a reaction mass out of water under regular wave excitation. He found that the submerged mass appears to perform better overall. Bijun Wu et al. [26] also studied the response and conversion efficiency of a two-body wave energy converter under regular wave excitation and they found that the performance of a two-body wave energy converter highly depends on the system parameters, like the physical properties of the buoy and incident wave frequency. These results obtained by the previous literature helped people to understand that it is possible to design a submerged body to achieve the theoretical maximum absorption power under regular wave excitation by neglecting the viscous damping. In real application, however, it is necessary to investigate the design of a two-body wave energy converter under irregular wave excitation as well.

Recently, an experiment was conducted by Beatty et al. [27] to compare the hydrodynamic performance of the submerged body for Wavebob and Powerbuoy. The authors found that a streamline submerged body has a smaller added mass compared with a resistive heave plate. The experimental results of added mass and excitation force on the submerged body agreed fairly well with the results obtained using boundary element method (BEM) for both prototypes. However, the damping on the second body is much larger in comparison with radiation damping obtained with BEM code. Therefore, it is necessary to consider the viscous effect while studying the two-body wave energy converter, especially for the submerged body. Based on Beatty's experimental study, in this paper, a linearized viscous damping is considered to account for the viscous effect. In the case study, the viscous effect on the floating buoy was neglected [27].

Based on the aforementioned literature review, the first objective of this paper is to study the dynamics of the two-body wave energy converter, including the viscous effect. In addition to radiation damping, a linearized damping due to viscous effect was considered to build the frequency domain model. The closed form solution of the absorption power for a two-body wave energy converter was obtained in terms of system parameters and wave information under regular wave excitation. The suboptimal and optimal power takeoff designs are defined based on the obtained closed form solutions. The results presented in this paper are further used to study the influence of submerged body on the absorption power of the two-body system.

The second objective of this paper is to study the design of the submerged body on the overall performance of a two-body wave energy converter under regular and irregular wave excitations. When the submerged body is deployed far enough from the floating buoy and free surface, the hydrodynamic interaction between these two bodies, as well as the radiation damping on the submerged body, can be neglected. Numerical simulations were conducted to study the influence of the submerged body on the power takeoff design and absorption power under regular wave excitation. The suboptimal and optimal designs are modified and investigated in irregular waves as well. The absorption power based on these two design principles are also compared with the maximum absorption power of a single body system with the same floating buoy. It is found that if the submerged body is designed properly, the absorption power of a two-body wave energy converter can be significantly higher than that of a single buoy system with the same floating buoy under regular and irregular wave excitation, even in the presence of a large viscous damping on the submerged body.

The remainder of this paper is organized as follows: In Section 2, the linearized model of a two-body wave energy converter under regular wave excitation is established and the closed form solution of absorption power and corresponding power takeoff parameters are obtained. In Section 3, suboptimal and optimum power takeoff design and the corresponding absorption power are studied in regular waves. In Section 4, the suboptimal and optimal design are implemented in irregular waves and compared with the single body system with the same floating buoy. The constrained simplex method is used to find the maximum absorption power of a two-body system under irregular wave excitation. Conclusions are given in Section 5.

2. Dynamics analysis and design of two-body wave energy converter in regular waves

Fig. 2 is the schematic of a two-body wave energy converter considered in this paper. A floating buoy is located on the water surface and is connected to a submerged body through a power takeoff (PTO) system. The submerged body is suspended in the water. The energy is extracted through the relative motion of the floating and submerged bodies. One should notice that the floating and submerged bodies considered in this paper are axisymmetric but they do not need to be cylindrical as shown in Fig. 2.

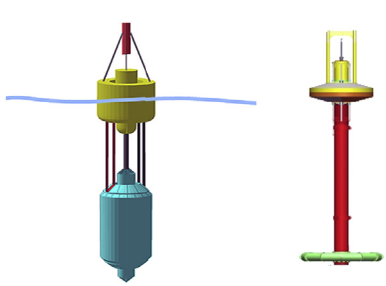

Fig. 1. Model of Wavebob (left) and Powerbuoy (right).

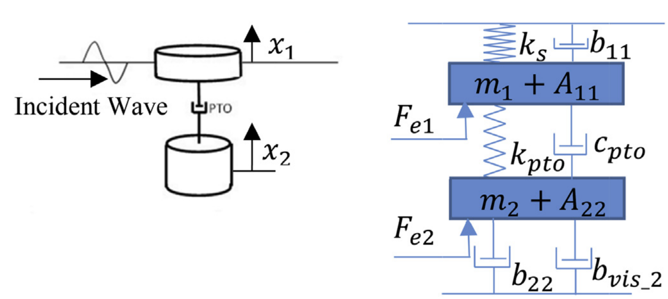

Fig. 2. Schematic of two-body wave energy converter.