Applied Ocean Research 80 (2018) 24–36

Contents lists available at ScienceDirect

Applied Ocean Research

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

On a submerged wave energy converter with snap-through power take-off

Lixian Wang[a,b,c,*], Hui Tang[c], Yanhua Wu[d]

[a] *Key Laboratory of High Performance Ship Technology (Wuhan University of Technology), Ministry of Education, China*
[b] *Departments of Naval Architecture, Ocean and Structural Engineering, School of Transportation, Wuhan University of Technology, China*
[c] *Department of Mechanical Engineering, The Hong Kong Polytechnic University, Kowloon, HKSAR, China*
[d] *School of Mechanical & Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore*

ARTICLE INFO

Keywords:
Nonlinear wave energy converter
Submerged cylinder
Snap-through PTO
Efficiency
Two-body system

ABSTRACT

This paper investigates the performance of a bistable snap-through power take-off (PTO) operating inside a submerged wave energy converter (WEC). The equation of motion of the surging WEC is derived in the time domain using the Euler–Lagrange equations. The dynamic response of the WEC in regular waves is studied first. It is found that the wave amplitude has a significant impact on the energy conversion efficiency with the proposed energy extraction mechanism. With larger waves impacting on the WEC, the conversion efficiency of the present nonlinear PTO increases significantly. Three response regimes, i.e. local oscillation, aperiodic snap-through, and periodic snap-through, of the nonlinear PTO system are observed with various wave amplitudes. This nonlinear feature is quite different from the linear PTO mechanism that is independent of the wave amplitude. Further, the dynamic response of the nonlinear WEC subjected to irregular wave sea conditions is investigated. Parametric studies have been carried out to determine the optimum operating conditions of the bistable device in order to maximize the wave energy extraction. The utilization of the snap-through PTO can enhance the efficiency of the WEC over its linear counterpart in irregular waves.

1. Introduction

Renewable energy is energy that comes from resources that are replenished continuously such as the sun, wind, ocean current and wave. These sources of energy have been explored globally as conventional sources of energy such as fossil fuel are limited and will be depleted in the foreseeable future. Furthermore, conventional sources of energy create pollution and carbon dioxide emission, posing a severe threat to the environment. Hence, it is vital to find a reliable and clean substitution for sustainable development. Compared with other renewable energy such as wind and solar energy, wave energy is superior in terms of energy density and stability [1,2].

To extract wave energy, various technologies have been proposed since the 1970s, which have been well reviewed in Refs. [1–3], just naming a few. Based on the working principle, wave energy converters can be categorized as oscillating water column, overtopping devices, and oscillating body systems. Most of the oscillating water column wave energy converters (WECs) are located nearshore while the oscillating body systems are often deployed in deep water (> 40 m), where wave energy is more intensive. Among the oscillating-body based WECs, the oscillating body can be either floating (e.g. [4–7]) or submerged (e.g. [8–14]). Compared with floating WECs, submerged WECs are superior in terms of survivability during sea storms when they are located offshore in deep water [15]. Submerged WECs such as the Bristol Cylinder device invented by Evans et al. [9] have been studied extensively [8,10,14]. Advantages of the Bristol Cylinder WEC include shedding excessive power levels, reducing excessive wave loads, and avoiding “end stop” problems. Recently, Evans & Porter [11] and Crowley et al. [12,13] further enhanced the efficiency of the submerged WEC technologies.

Generally, an efficient wave energy extraction device is designed by being resonant at the incident wave frequency. However, there are two major difficulties for this kind of resonant WECs: one is that the response efficiency curve is narrow banded of wave periods if it is resonant at a certain frequency; the other is that resonant WECs are required to be of large size for a typical Northern Atlantic wave period (10 s). Therefore, the irregularity in the ocean waves will pose a serious problem for such WECs. To overcome these challenges, many studies were carried out by using control strategies such as the linear/nonlinear passive control [16], latching control [17–19], declutching control [20], and reactive control [21], etc. Various control techniques dedicated to increasing power production of WECs have been summarized in Ref. [22]. However, most control strategies (e.g. latching and declutching control) require that the wave information is known as a

---

[*] Corresponding author at: Key Laboratory of High Performance Ship Technology, Wuhan University of Technology, Ministry of Education, China.
E-mail address: lixianwang@whut.edu.cn (L. Wang).

https://doi.org/10.1016/j.apor.2018.08.005
Received 25 April 2018; Received in revised form 1 August 2018; Accepted 9 August 2018

prerequisite in order to predict the wave forces acting on the WECs. The performance of these control techniques may be significantly diminished if the prediction deviation of wave information of real sea state is considered [23]. Besides, additional sensors, activators and processing elements are needed to implement these control strategies, thus leading to high installation costs and maintenance difficulties. Apart from control strategies, multi-resonant devices [11,12] or nonlinear snap-through power take-offs (PTOs) [5,24] were also used to enhance WEC efficiency. Evans & Porter [11] introduced a multi-resonant WEC consisting of a submerged buoyant circular cylinder tethered to the sea bed by inextensible mooring lines. An internal mass-spring-damper PTO is located within the cylinder. In this way, a two-body wave energy converter is created. This allows the use of the internal mass to further improve the performance of the WEC [25]. The idea behind this concept is to tune devices to be resonant at a broader range of incident wave periods in realistic sea state. Inspired by this, Crowley et al. [12] introduced a novel internal PTO device comprising multiple pendulums within the submerged cylinder. Apart from multi-resonant PTOs, Zhang and his co-workers [4,5] initiated the use of the nonlinear snap-through PTO to increase the power extraction of a heaving WECs. The snap-through mechanism is made up by two oblique linear springs and a linear damper connected to a mass. Details of this bistable mechanism are reported in [26]. It was found that the nonlinear PTO system outperforms its linear PTO counterpart in waves of relatively low frequencies. Similar conclusions were made in Ref. [24] by using other types of bistable PTOs. In these bistable PTO based WECs, the floating buoy itself is used as the mass experiencing snap-through.

Inspired by the above nonlinear PTO studies, in this paper, we proposed a submerged cylinder WEC containing an internal mass-spring-damper snap-through PTO, as shown in Fig. 1. To investigate the performance of this two-body system WEC, the equations of motion are derived in the time domain using the Euler–Lagrange equations. Instead of the frequency-domain method, a time-domain numerical method using fourth-order predictor–corrector Adams–Bashforth–Moulton method [27] is adopted to solve the system of ordinary differential equations. The performance of this WEC subjected to either regular or irregular waves is studied.

2. WEC with snap-through PTO

As shown in Fig. 1, the proposed WEC consists of a submerged circular cylinder, a mooring line and an internal PTO mechanism. The same as the submerged WECs in the work of Evans & Porter [11] and Crowley et al. [12], this device is assumed to span a narrow wave tank. So the problem can be treated as two dimensional and the submerged cylinder is of unit length in the third direction. The cylinder is selected such that its buoyancy is larger than its weight. As such, the mooring line connecting the cylinder center and a fixed pivot is taut and the cylinder is restrained to pitch around this pivot. Located inside the cylinder is a PTO that comprises of a mass-spring-damper system. Different from the simple mass-spring-damper system, the present PTO consists of two oblique linear springs connecting to an internal mass. This arrangement yields a nonlinear restoring force acting on the mass. Due to this nonlinear force, two stable equilibrium positions exist for the internal mass [26]. It will thus oscillate around one of the two stable equilibrium positions if the motion is small, and oscillate between the two stable equilibrium positions if the motion is large, indicating a snap-through motion.

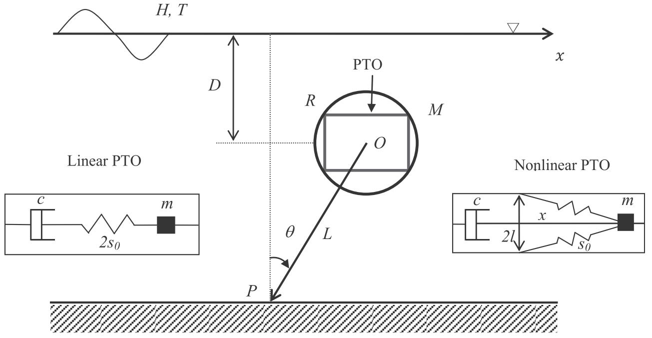

Fig. 1. Submerged cylinder WEC with the nonlinear PTO.

3. Mathematical formulations

In order to investigate the performance of the proposed WEC, the dynamic response of this WEC subjected to incident waves is analyzed. The present WEC is a two degree-of-freedom dynamic system: the pitch motion of the submerged cylinder and the horizontal surge motion of the internal mass relative to the cylinder. Assume that the pitch angle of the cylinder is small, the vertical force acting along the mooring line balances the difference between the buoyancy and the gravity of this WEC. In this study, this difference is assumed in the same order with the buoyancy acting on the cylinder (see Section 4.1). With the small-motion assumption, the wave forces are not comparable with the buoyancy. Thus, the mooring line keeps taut and its length does not vary during the motion of the cylinder. The heave of the cylinder is of second-order and thus can be neglected in the present analysis. To deal with these coupled motions, the equations of motion are readily derived from the Euler–Lagrange equations. θ and x are selected as two generalized coordinates, representing pitch of the submerged cylinder and relative surge of the internal mass, respectively. When the aforementioned snap-through based PTO is incorporated into the submerged cylinder, as depicted in Fig. 1, the potential energy $V_e(x)$ stored in the new system is

$$V_e(x) = s_0(\sqrt{x^2 + l^2} - l_0)^2 \tag{1}$$

and the kinetic energy $T_e(\theta, x)$ carried by this system is

$$T_e(\theta, x) = \frac{1}{2}m(\dot{x} + L\dot{\theta})^2 + \frac{1}{2}\mathrm{M}\mathrm{L}^2\dot{\theta}^2 \tag{2}$$

where s_0 is the stiffness constant of the springs, l_0 their original length, l the half distance between the two ends of springs that are fixed on the cylinder, m the internal mass, L length of the mooring line, M the mass of the submerged cylinder per unit length. $\dot{x}$ and $\dot{\theta}$ denote the horizontal velocity of the internal mass and the angular velocity of the submerged cylinder, respectively. In the above two equations, Eq. (1) represents the elastic potential energy stored in the two oblique springs of the internal PTO. Note that since the heave of the cylinder is ignored in this study, the gravitational potential energy is omitted. The second equation, i.e. Eq. (2), denotes the kinetic energy stored in both the internal mass (m) and the submerged cylinder (M). Similar to [11], in the present study the cylinder is forced into horizontal surge motion in the framework of small-amplitude linearized theory, thus the rotational kinetic energy is not taken into account in Eq. (2). By applying the Euler–Lagrange equations, the equations of motion for this system are

$$(m + M)L^2\ddot{\theta} + \mathrm{mL}\ddot{x} + (M_w - M - m)\mathrm{gL}\theta = F_{\mathrm{wave}}L \tag{3}$$

and

$$\mathrm{mL}\ddot{\theta} + m\ddot{x} + c\dot{x} + 2s_0\left(1 - \frac{l_0}{\sqrt{x^2 + l^2}}\right)x = 0 \tag{4}$$

where $\ddot{x}$ and $\ddot{\theta}$ denote the horizontal acceleration of the internal mass and the angular acceleration of the submerged cylinder, respectively. The damping of the damper in the internal PTO is represented by c. The last term on the left hand side of Eq. (3) describes the restoring force exerted by the mooring line, which is the horizontal component of the tension force in the mooring line. The mooring tension force is estimated from the force balance involving the buoyancy $M_w g\,(\equiv \rho\pi R^2 g)$ and gravities of the submerged cylinder and the internal mass. F_{wave} on the