Journal of Marine Science and Technology

Volume 23 | Issue 6 Article 7

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Recommended Citation
Shi, Hong-Da; Cao, Fei-Fei; and Qu, Na (2015) "THE LATEST PROGRESS IN WAVE ENERGY CONVERSIONS IN CHINA AND THE ANALYSIS OF A HEAVING BUOY CONSIDERING PTO DAMPING," *Journal of Marine Science and Technology*: Vol. 23: Iss. 6, Article 7.
DOI: 10.6119/JMST-015-0610-6
Available at: https://jmstt.ntou.edu.tw/journal/vol23/iss6/7

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Acknowledgements

The authors would like to acknowledge the support of National High Technology Research and Development Program (“863” Program) of China (Grant No. 2012AA052601), and the National Science Fund Program (Grant No. 41376100).

Journal of Marine Science and Technology, Vol. 23, No. 6, pp. 888-892 (2015)
DOI: 10.6119/JMST-015-0610-6

THE LATEST PROGRESS IN WAVE ENERGY CONVERSIONS IN CHINA AND THE ANALYSIS OF A HEAVING BUOY CONSIDERING PTO DAMPING

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Key words: wave energy, current status, conversion efficiency, power take-off.

ABSTRACT

Wave energy conversions are being widely researched and developed in China; two key factors of significance with these devices are safety and efficiency. This paper provides information on the latest techniques of wave energy devices investigated in China, introduces their working principles, and describes performance briefly. To design a wave device, the conversion efficiency needs to be estimated. This paper describes a method for doing such analysis on a heaving buoy considering the power take-off, which is an important step for achieving wave-to-wire simulation.

I. INTRODUCTION

Wave energy, which is one of the most promising marine energies, has gained prominence for generating electricity (Falnes, 2002; Bjarte-Larsson and Falnes, 2006; Henderson, 2006; Cruz, 2008; Dalton et al., 2010; Choi et al., 2012; McCormick, 2013). It is estimated that the theoretical mean power of wave energy resource along the coastline of China is about 12.85 GW, with the majority of distribution in Taiwan, Zhejiang, Guangzhou, Fujian, and Shandong Provinces (Wang et al., 2008). The research on extracting energy from wave started in the late 1970s in China. As a result of the increase in financial and policy support from the central government, there has been considerable advancement in the field of wave energy conversions (WEC) and other relevant technologies. In the year 2010, a special funding for marine renewable energies was first established. The number of patents on WEC has grown dramatically over the past four years and over 300 patents were newly published in the last year (Wang et al., 2011; Zhang et al., 2012; Zhang et al., 2014).

This paper is organized into two sections, based on the key factors involved in the design of WEC devices. The first section illustrates some of the demonstration devices available in China, along with their working principles and performance. The second section describes a method for analyzing extracting efficiency, using the power take-off (PTO) system.

II. TECHNOLOGICAL PROGRESS

Wave energy is mainly used to generate electricity in China. According to the working principle, wave energy converters are classified into three categories: oscillating water column (OWC), overtopping converters, and oscillating body systems (which is also called heaving buoy system recently) (Falcão, 2008). The progress made in the field of WEC technology in China, for each of these three types of wave energy converters, is discussed in the subsequent sections. We investigate some of these devices by giving a brief introduction of their working principles, and measuring their main dimensions, technical parameters, and power output.

1. Oscillating Water Column

Oscillating water column (OWC) devices are composed by air chamber and air-operated energy conversion system such as Wells turbine and impulse turbine. They usually stand on the sea bottom or are fixed to the rocky cliff. Air chamber is submerged under the water and inside which air is trapped above the water free surface. The incident waves produce the oscillating motion of free surface, which makes the air flow blow out and breathe in through an air turbine that drives an electrical generator.

From 1980 to 2001, Guangzhou Institute of Energy Conversion (GIEC) constructed three shoreline OWC type wave power plants with capacities of 3 kW, 20 kW, and 100 kW, respectively. As a demonstration project, the 100 kW prototype (Fig. 1) was connected to the power grid. But in general,

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Fig. 1. The 100 kW OWC device developed by GIEC.

Fig. 3. The 30 kW pendulum WEC developed by NOTC.

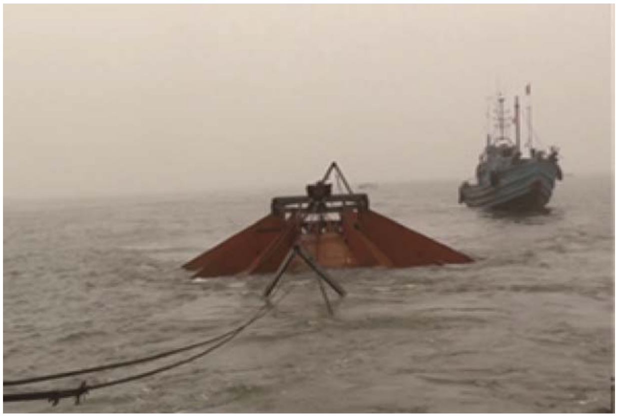

Fig. 2. The 10 kW dish-type overtopping WEC developed by OUC.

Fig. 4. The 100 kW nodding duck WEC developed by GIEC.

the conversion efficiency of these OWC devices were relatively low and the outputs were unstable. In 2010, Ocean University of China gave some feasibility studies on caisson breakwater used as OWC system.

2. Overtopping Converters

Overtopping converter is usually composed by hydraulic accumulator, hydraulic turbine, electric generator and other auxiliary devices. Hydraulic turbine converts the potential energy of wave into mechanical energy to drive the generator.

There has not been as much work in China on overtopping converters when compared with oscillating body systems. Ocean University of China took the research on a 10 kW floating dish-type overtopping WEC (Fig. 2) supported by National 863 Program from 2009 to 2011.

3. Oscillating Body Systems

Oscillating bodies constitute an important class of wave energy converters, especially for offshore deployment (Falcão, 2008). Oscillating body systems have many types, including single-body devices, two-body heaving systems, fully submerged heaving systems, pitching devices, bottom-hinged systems and multi-body systems (Falcão, 2010). Horizontal or vertical motion of the wave becomes the pendulum or heave motion of these devices, so that wave energy is converted into electricity with hydraulic systems or mechanical conversions.

In comparison with European countries, the wave energy resource of China has lower power density, shorter wave period, and smaller wave height. Therefore, since the year 2000 (China's 10^{th} five-year plan), several types of oscillating body systems have been developed and funded by the National Ocean Technology Center (NOTC), who set up a series of 8 kW, 30 kW (Fig. 3), and 100 kW pendulum type WECs in the years 1995, 2010, and 2013, respectively. Driven by waves, the pendulum flap swings back and forth to power a hydraulic pump and a generator. In the year 2010, Zhejiang University developed a similar 5 kW inverse pendulum WEC with a hydraulic PTO.

From 2009, GIEC began the research and development on the floating nodding duck, based on the well-known Salter's duck. Sea trials of the 10 kW and 100 kW nodding duck (Fig. 4) were conducted in 2011 and 2013, respectively. Furthermore, GIEC improved the design of the duck and developed a new device named "Sharp Eagle" (Fig. 5) in 2012, which has enhanced both wave capture efficiency and anti-typhoon ability. The capacity was 20 kW including a 10 kW hydraulic PTO system and a 10 kW linear electrical generator. The 150 kW Eagle (Fig. 6) developed by GIEC was finished in 2014.

Fig. 5. The 10 kW Eagle WEC developed by GIEC.

Fig. 7. The 10 kW combined oscillating buoys WEC developed by OUC.

Fig. 6. The 150 kW Eagle WEC developed by GIEC.

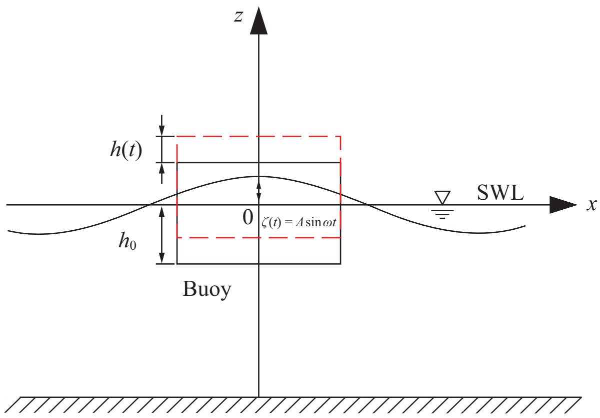

Fig. 8. Diagram of the wave and buoy.

Another technology that has been developing rapidly is the point absorber WEC. In 2006, the first 50 kW onshore oscillating buoy WEC was built by GIEC. The PTO system includes pressure-maintained storage, which converts unstable wave energy into stable hydraulic energy. This mechanical interface with pumps, gas accumulators, and hydraulic motors is used widely in point absorber devices, such as the single heaving buoy prototype (rated power 120 kW) developed by Shandong University in 2012, and the combined oscillating buoys WEC (rated power 10 kW) (Fig. 7) developed by Ocean University of China (OUC). A 100 kW offshore prototype of combined oscillating buoys WEC is supposed to be constructed in 2015. In addition to the hydraulic PTO, GIEC also developed a 20 kW single oscillating body device which directly drives a linear generator in 2012.

III. CONVERSION EFFICIENCY

According to the WECs discussed above with the exception of linear electrical generation, the process of extracting electrical energy from waves, in general, can be divided into three phases—transforming energy from incident waves into reciprocation of absorption systems, converting the wave induced motions into a one-directional motion of the mechanical interfaces (such as air turbines, low-head hydraulic turbines, and hydraulic motors), and generating electric power. These stages are defined as the primary, secondary, and tertiary conversion stages, respectively.

To design a wave device, the conversion efficiency of the three stages should be estimated in advance. In this paper, we focus on efficiency in the primary stage. It is obvious that the high pressure in the hydraulic system restricts the oscillation of buoys to some extent. Incident wave conditions, as well as the PTO damping effect should both be considered when designing an absorber.

We establish coordinates as shown in the Fig. 8.

Say that $\zeta(x,t) = A\sin(kx - \omega t)$ is the wave surface, then in the vertical axis of the buoy,

$$\zeta(t) = -A\sin\omega t \tag{1}$$

If the vertical distance of the buoy caused by the wave is $h(t)$, and the hydraulic resistance is $-C\dfrac{dh(t)}{dt}$, then we have

$$m\frac{d^2h(t)}{dt^2} = \rho gS[\zeta(t)-h(t)] + C_m\rho S[\zeta(t)-h(t) + h_0]\frac{d}{dt}(w|_{z=h(t)-h_0} - \frac{dh(t)}{dt}) - C\frac{dh(t)}{dt} \quad (2)$$

Here, the first variable on the right side of the equation is buoyancy caused by the movements of the wave and buoy. The second variable, which is the dynamic force, is proportional to the acceleration of water particles with the movement of the buoy. C_m is the inertia force parameter, which is defined in the Morison equation. The third variable, which is proportional to the velocity of the buoy, is linear hydraulic damping, PTO.

In potential flow and linear wave theories,

$$w = \frac{\partial\phi}{\partial z} \quad (3)$$

where

$$\phi = -\frac{Ag}{\omega}e^{kz}\cos\omega t \quad (4)$$

$$w|_{z=h(t)-h_0} = -A\omega e^{k[h(t)-h_0]}\cos\omega t \quad (5)$$

$$\frac{d}{dt}w\Big|_{z=h(t)-h_0} = -A\omega k e^{k[h(t)-h_0]}\frac{dh(t)}{dt}\cos\omega t + A\omega^2 e^{k[h(t)-h_0]}\sin\omega t \quad (6)$$

$$\because e^{k[h(t)-h_0]} \approx 1 \quad (7)$$

$$\therefore \frac{d}{dt}w\Big|_{z=h(t)-h_0} = -A\omega k\frac{dh(t)}{dt}\cos\omega t + A\omega^2\sin\omega t \quad (8)$$

$$\because -A\omega k\frac{dh(t)}{dt}\cos\omega t \approx 0 \quad (9)$$

$$\therefore \frac{d}{dt}w\Big|_{z=h(t)-h_0} \approx A\omega^2\sin\omega t \quad (10)$$

$$\because \zeta(t)-h(t)+h_0 \approx h_0 \quad (11)$$

$$\therefore m\frac{d^2h(t)}{dt^2} = \rho gS[\zeta(t)-h(t)] + C_m\rho Sh_0(A\omega^2\sin\omega t - \frac{d^2h(t)}{dt^2}) - C\frac{dh(t)}{dt} \quad (12)$$

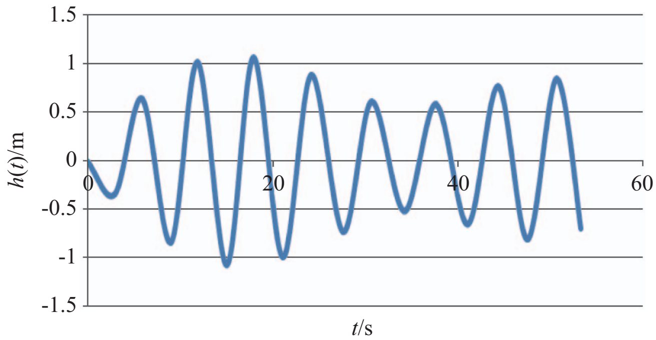

Fig. 9. The movement of the heaving buoy.

$$\therefore (m + C_m\rho Sh_0)\frac{d^2h(t)}{dt^2} + C\frac{dh(t)}{dt} + \rho gSh(t) = \rho SA(C_m h_0\omega^2 - g)\sin\omega t \quad (13)$$

The solution of the above equation is

$$h(t) = e^{-\frac{C}{2m'}t}(C_1\cos\omega' t + C_2\sin\omega' t + a\cos\omega t + b\sin\omega t) \quad (14)$$

where

$$m' = m + C_m\rho Sh_0 \quad (15)$$

$$\omega' = \frac{\sqrt{4\rho gSm' - C^2}}{2m'} \quad (16)$$

$$a = \frac{\rho SAC\omega(g - C_m h_0\omega^2)}{(\rho gS - m'\omega^2)^2 + C^2\omega^2} \quad (17)$$

$$b = \frac{\rho SA(g - C_m h_0\omega^2)(m'\omega^2 - \rho gS)}{(\rho gS - m'\omega^2)^2 + C^2\omega^2} \quad (18)$$

If $h(t)|_{t=0} = 0$, $\frac{dh(t)}{dt}\Big|_{t=0} = 0$, then

$$C_1 = -a = \frac{\rho SAC\omega(C_m h_0\omega^2 - g)}{(\rho gS - m'\omega^2)^2 + C^2\omega^2} \quad (19)$$

$$C_2 = \frac{C}{2m'\omega'}C_1 - \frac{\omega}{\omega'}b \quad (20)$$

The existence of C in the expression of a, b, C_1, and C_2 stands for the effect of hydraulic PTO.

Fig. 9 shows the movement of the heaving buoy under the wave height of 1 m, period of 6 sec, and with the diameter of

3 m and weight of 2 t. It is obvious that the amplitude of the vertical movement is reduced due to the PTO, but the period is still near the wave period.

Since the efficiency of the device is a function of C, we understand that when the buoy moves with a velocity, which is same as that of the water particles, the value of $C = 0$ and PTO = 0. On the other hand, when the buoy does not move, the value of $C = \infty$ and PTO = 0. Therefore, there must exist a certain value of C that lies between $C = 0$ and $C = \infty$, which maximizes the PTO efficiency. In the next step of our research, we focus on determining the optimized value of C for which the PTO efficiency is maximum.

IV. CONCLUSION

The utilization of wave energy in China is developing fast. The design parameters of PTO need to be further optimized.

As an essential part of WECs, we researched a PTO based working mechanism. The control equation is established and movement of the heaving buoy is obtained. Given the displacement of the buoy, it is obvious that there must exist an optimized PTO damping parameter C, which maximizes power.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of National High Technology Research and Development Program ("863" Program) of China (Grant No. 2012AA052601), and the National Science Fund Program (Grant No. 41376100).

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