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A Model and Experiment Study of an Improved Pendulor Wave Energy Converter

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Abstract

This paper proposes one improved design of pendulor wave energy converter (PWEC), which integrates a pendulor, two side-walls and a slope to concentrate wave power. The slope guides the incident wave upward, and the wave drives the pendulor to rotate upward. Different from previous pendulors, one end of present pendulor is hinged near the free water surface, and the other end swings upward and downward. The mechanical flapping energy is converted to hydraulic energy by the connected hydraulic pump, and then it is converted to electrical energy. The proposed design is verified by theoretical and model-experimental study. The energy conversion efficiency is estimated by a simple weight-lifting method. Experimental results show that the first level conversion efficiency is averaged at 35% under the condition of wave height 0.18m, wave period 1.11s and pendulor length 0.6m. In short, this system has various advantages including simple, compact, modularized, light-weight and low-cost structure, which can be generally installed on ocean shore, near-shore piles and offshore platform, especially for China sea conditions.

Keywords: Wave energy converter; Pendulor; Estimated model; Water tank test; Integrated Design;

1. Introduction

As one of the significant renewable energy, ocean wave energy holds a large part of the potential renewable energies. For China, the wave energy is rich, and the investigated potential is around 12.84 million kW at 20 miles offshore [1]. The wave energy of China is not well-distributed. The energy density of the sea in the South is larger than that in the North; that in the offshore areas is larger than that in the

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near-shore areas; that around the far islands is larger than that around the near-shore islands; that in autumn and winter is larger than that in spring and summer. Particularly, the wave energy of Southern Sea is much more promising. The annual power level of the areas from Luzon Strait to the coasts of the Indo-China Peninsula varies between 10 and 16 kW/m, with the highest values occurring in the area of Luzon Strait. Thus, developing effective and economic devices to utilize the potential tremendous wave energy in China is quite promising.

Compared to other sustainable energy utilization, there are various design types of wave energy conversion or converter (WEC), which can be generally divided into a few types including oscillating water column, overtopping apparatus, point absorber and surging equipment, etc. [2-4]. To be competitive, the conceptual WEC design has to be effective, efficient, environment-friendly and economical. One type of these designs is surging pendulum device, which contain a pendulum flap to swing back and forth to harvest the wave energy near-shore or at the sea bottom.

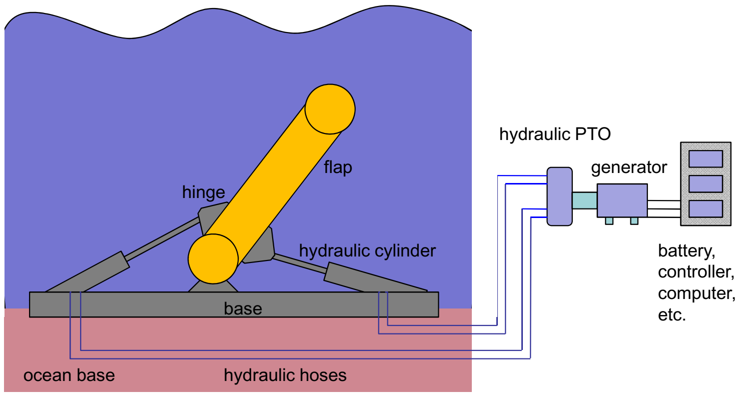

Fig. 1. A concept design of an 'Inverted Pendulum' wave energy converter (WEC) in the bottom wave areas of China

In China, especially since 2010, the efforts in research and development (R&D) in WEC have gained the support of national plans and funding, which is optimistic on the development in the wave energy fields. The R&D works on the surging type of WEC start a few more only from recent years. As demonstrated in Figure 1, Zhang et al. [5,6] report studies on a dual action hydraulic power take-off (PTO) system for a WEC device with inverse pendulum. To find out the complex interaction between PTO characteristics and WEC hydraulic performance, these papers describe time domain simulation and corresponding preliminary experiment verification, by which the design feasibility, reliability and advantages are discovered. Recently, Wan and co-workers proposed an innovative pendulum WEC with track, caisson and wave collectors used onshore and near-shore, since China has long coastlines and numerous islands that need nearby renewable energies [7,8]. This designed device can collect more waves and energies.

Since the general wave energy density in China is smaller than that in Europe [9,10], especially in north China sea areas, lowering the utilization cost and expanding application ocean areas are necessary for China to utilize wave energy. Consequently, this paper proposes one improved kind of pendulor wave energy converter (PWEC) to lower the above mentioned cost, combining the principle of pendulum, overtopping and wave moment concentration. The floating pendulor swings above the water surface around the fixed horizontal axis. Under the pendulor, there is a slope, along which incident waves climb up and drive the floating pendulor to rotate upward. There are walls on both sides of the pendulor. The walls prevent ocean water flowing outside the two sides and may improve the wave energy conversion efficiency. This system possesses competitive advantages of simple, compact, modularized and light-weight structure, which can save the component manufacture materials. Light-weight material is applied to fabricate the pendulor. Compared with other existing modern systems, the present design has rather lower weight for convenient transportation, installation and maintenance [11]. Finally, this system can be generally installed on ocean shore, near shore piles and off shore platform.

2. System Setup and Design Principle

The proposed pendulor wave energy conversion system consists of two parts: wave energy harvester (EH) and energy converter (EC). The former one, EH as named, aims to collect the wave energy and convert to hydraulic energy (HE). An EH consists of a pendulor, a slope, a supporting frame and two side walls. With a cross-section shape of triangle, the pendulor is hinged with supporting frame near the free water surface and connected with the hydraulic pump rod. When the sea wave drives the pendulor to flap up, then the pendulor drives the hydraulic pump rod to convert mechanical energy to hydraulic energy. After it reaches the maximum height, the pendulor automatically flaps down to its original position by its gravity. Correspondingly, the hydraulic pump rod is restored to its original position and suck hydraulic oil into hydraulic cylinder. Therefore, the weight design of the pendulor should have this restoration function. However, our previous design and measurement in Zhejiang University have revealed that the pendulor has little impact to sea water and generates no reflection wave due to its light weight [12].

By the integration of a pendulor, a slope and two side walls, the waves are concentrated to enhance the perpendicular wave force, which drive the pendulor to rotate upward more effectively. These design concepts are based on basic mechanical and fluid dynamic theories of overtopping WEC designs, wind fluid concentration around buildings, flow dynamic pressure change at varied channel width and ship motions caused by waves, according to published literature [2,13,14]. Along the slope, incident waves climb upward and drive the floating pendulor to rotate upward. Two side walls of the pendulor prevent ocean water from overflowing outside, and transform the wave moment onto the pendulor, then finally enhance the wave energy conversion efficiency. These enhanced powers can be imaged as the near-shore waves lap against the shore stones and splash on them. Under the action of water kinetic energy and pressure beneath the pendulor, rotational kinetic energy and potential energy of pendulor are enhanced. The wave energy is transferred much efficiently to mechanical energy of the pendulor. When the pendulor rotates upward, all the above energies are converted to pendulor potential energy and hydraulic energy at the maximum height with a conversion coefficient.

Converting hydraulic energy to electric energy is the work of the second part, energy convertor (EC). It consists of rod hydraulic pump, hydraulic accumulator, hydraulic motor and generator. Hydraulic pump rod is forced to press the hydraulic oil out from the cylinder. During this process, mechanical energy is converted to hydraulic energy. This high-pressure hydraulic oil flow into the hydraulic accumulator to store and stabilize the high-pressure energy, which then power the hydraulic motor to rotate continuously and steadily. The variable displacement hydraulic motor adopts this smooth hydraulic liquid supply to rotate the electrical generator and provide electrical power to needed systems [15].

3. Water Tank Experiment

The physical model experiment was conducted in the hydraulic water tank of the ocean experimental center, Zi-jing-gang Campus, Zhejiang University. This tank adopted a wave generation system with pushing paddle to generate wave trains. In detail, this system is powered by alternating current servomotor, which is followed by ballscrew subsidiary driving to power the wave paddle. This paddle can produce regular and irregular waves, and two dimensional regular wave is selected in this experiment.

The PWEC was installed in the wave water tank as shown in Figure 2. The walls of the water tank act as the walls of the PWEC, where water tank width is *D* with unit *m.* The distance between the paddle and tested PWEC is 30 *m*, long enough for wave to be fully developed. The pendulor moving condition was recorded by the camera, and was post-processed to obtain the height displacement *S* of the pendulor flapping end. During the experiment, the guide rope was loose when the pendulor flaps upward under the wave action; and it became tight when the pendulor reached the maximum height; then it was smoothly controlled to slowly lay down the pendulor to avoid reflection waves to affect the incident wave.

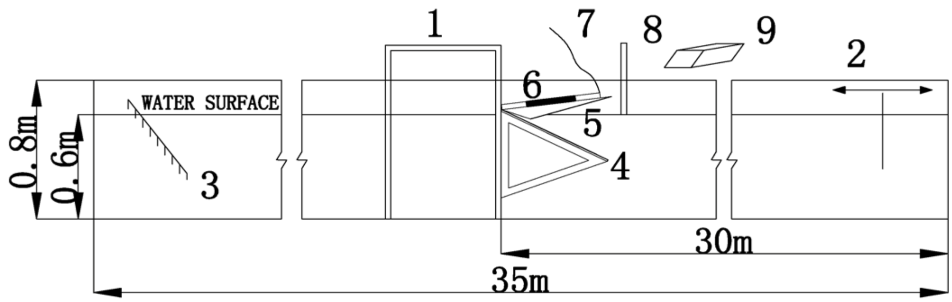

Fig. 2. Physical model installation diagram of the pendulor wave conversion system (PWEC) in water tank (1 Supporting frame, 2 Wave generator, 3 Dissipative beach, 4 Slope, 5 Pendulor, 6 Extra weight, 7 Guide rope, 8 Scaled ruler, 9 Camera)

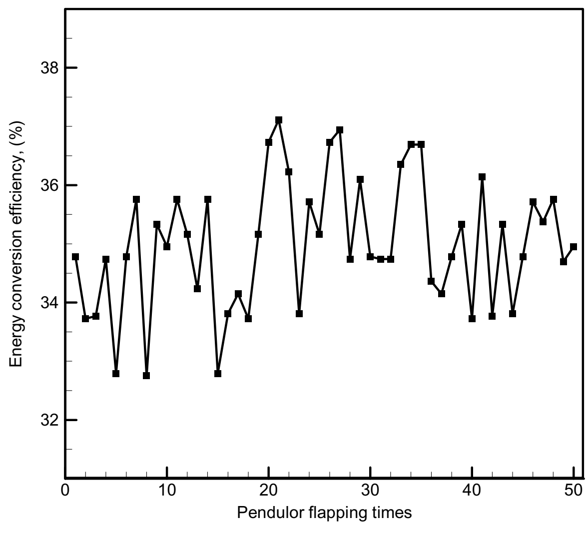

Fig. 3. Estimated first-order conversion efficiency from wave energy to mechanical energy against flapping periods under stable incident wave condition

The experimental results demonstrate that the conversion efficiency from wave energy to mechanical energy is the highest under the condition that wave height is *H* 0.18 *m*, wave frequency *f* is 0.9 *Hz* and extra weight number n is 36. The measured maximum, minimum and average displacements S are respectively 18.7, 16.5 and 17.6 *cm*. Correspondingly, the computed 1st-order maximum, minimum and average conversion efficiencies from wave energy to mechanical energy are respectively 37.1%, 32.8% and 35.0% as demonstrated in Figure 3. During the experiment condition, the generated mechanical power is around 20.5 to 23.2 kWh. The data deviations are within 6.3% for both the pendulor end displacement and conversion efficiency. These results show the certain reasonability of the new device.

4. Technical Analysis and Discussions

Present paper presents a recently patented WEC and its ongoing test and analysis to be developed as a valuable and viable system. Firstly, on a conceptual level, the tests have the capability to verify the concept for wave energy conversion. Secondly, the experimental results show that the wave energy conversion efficiency has around 6.3% variations. The main reason is that the downward movement of the floating pendulum is not the same for each flapping time. Further improvement will be conducted to minimize this kind of variations. During experimental trials, wave radiation is confirmed as the floating pendulor swinging by hand on still water would generate a few waves sometimes. The reflected wave would affect the incident wave and the conversion of wave energy. Therefore, it is significant to reduce the reflection wave from the pendulor to improve the energy conversion efficiency for our further works.

The concept design presents an advantage with respect to other WECs. It has a slope design where the angle can be varied during normal operation to optimize the efficiency—the smaller the waves, the larger the wedge angle-according to the sea state. Under extreme (e.g. storm) conditions, the slope can be horizontally placed and locked, thereby incident waves can transmit across the WEC, which constituting a significant asset for survivability.

5. Conclusion and Further Work

This work presents a principle study and system design of pendulor wave energy converter (PWEC), which adopts an improved integration of pendulor, slope, side-walls and hydraulic rod pump to generate electric power from ocean wave. The designed hydraulic pump can convert mechanical energy to hydraulic energy. To verify the feasibility of this design strategy, theoretical and model-experimental studies are conducted and the system succeeds to generate electric power normally. From the deducted first-order efficiency and corresponding test results, around 35% estimated efficiency from wave energy to mechanical energy is found in this project under tested conditions.

In the future work, system optimization and experimental trials will be conducted to improve the whole apparatus structure, working stability and energy conversion efficiency, and two wave reflectors or collectors will be connected to the physical model [12]. These fundamental study and system design are believed to be promising for academic, engineering, economic and policy communities to harvest and utilize the ocean wave energy.

6. Copyright

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Biography

Dr. Zhanhong WAN is an associate professor from Zhejiang University, China. He focuses on the studies of fluid dynamics, ship & ocean engineering, new energy and etc.