China Ocean Eng., Vol. 27, No. 3, pp. 359 – 368

DOI 10.1007/s13344-013-0031-y, ISSN 0890-5487

Experimental Study on A Pendulum Wave Energy Converter*

QIU Shou-qiang (邱守强)[1], YE Jia-wei (叶家玮),

WANG Dong-jiao (王冬姣) and LIANG Fu-lin (梁富琳)

School of Civil Engineering and Transportation, South China University of Technology,

Guangzhou 510640, China

(Received 27 November 2011; received revised form 10 October 2012; accepted 15 December 2012)

ABSTRACT

Many of the existing wave energy converters (WEC) are of oscillating water column (OWC) and point absorber (PA) types. Fewer references have been published in public on the pendulum type WEC. A series of experimental tests on a bottom-hinged pendulum WEC model are carried out and some results are revealed in the present study. The purpose of this paper is to present a detailed description of the tests. It is found that wave energy conversion efficiency varies with the applied damping and wave conditions. In addition, special attention is given to the effect of the water ballast on the efficiency of the wave energy converter. It is demonstrated that the ballast plays an important role in energy extraction. Better understanding on how the performance of the device is influenced by damping, wave height, wave period and ballast is shown.

Key words: *wave energy converter*; *pendulum*; *damping*; *efficiency*; *ballast*

1. Introduction

The research and development of wave energy conversion (WEC) technology have been ongoing for more than two hundred years; many proposals have been put forth by researchers around the world, mainly in Japan, the UK, the USA and Norway as well as other countries. Several efficient configurations for energy converters have been designed and tested at the model scale, and some have been operated in the sea. Masuda studied the wave energy in the 1940s and developed what was called the oscillating water column devices. Salter (1974) published a paper, which was considered as a landmark and brought wave energy to the attention of the international scientific community. A single-body heaving buoy consisting of a spherical floater that could be phase-controlled by latching was tested in Norway (Budal *et al.*, 1982). A wave-power system which combines the concept of a breakwater and a harbor resonance chamber was developed (Tseng *et al.*, 2000). All together, there are more than 1000 patents related to WECs, many of which have been well studied, but there are only about nine concepts used for these technologies (McCormick, 1981). It is expected that the number will increase markedly in the future. In the past twenty years, ocean wave energy conversion has received increasing interest, stimulated mostly by increasing energy demands, climate change,

* This research was financially supported by the Special Fund for Marine Renewable Energy of the Ministry of Finance of China (Grant No. GD2010ZC02).

1 Corresponding author. E-mail: qiushouqiang@163.com

environmental pollution and so on (Zuo *et al*., 2001). To date, WEC technology has developed rapidly, and the efficiency of converting wave energy to electricity or other types of energy has progressed. In particular, the applications of technologies, such as multi-resonant oscillating water columns (Lye *et al*., 2009), symmetrical wing turbines (Wells, 1976), phase control (Falnes and Budal, 1978), backward bent duct buoy (Masuda and McCormick, 1987) and so on, have been reported. All of these technologies have advanced WECs. However, the technology still needs further development.

Literature review on the existing WECs in the UK, Japan, Norway and other countries, has found that the concept of the pendulum WEC is a unique design whose motion of a pendulum flap matches the low-frequency motion of waves fairly well. This system is characterized by a flap and a shaft, which is fixed below or above. The flap swings forward and backward due to the incident waves against a shaft.

Some researches on this device were carried out experimentally and theoretically, and its high-energy conversion efficiency was shown. The use of a pendulum WEC is not a new concept and many patents have been filed regarding this method of extracting energy from sea waves. The most successful device of this type was built and tested in Japan, which was a movable body type WEC and invented by Kondo and Watabe (1983) with Muroran Institute of Technology. It was reported that the maximum primary conversion efficiency of this fixed type pendulum WEC is 82% (Kondo *et al*., 1984). A full-size shoreline prototype pendulum WEC in Hokkaido was constructed with a rated power of 5 kW. The flap of the prototype was 2 m long, and the maximal swing angle amplitude was ±30º with a wave height of 1.5 m and a wave period 1.5 s. The overall efficiency was about 40% (Zuo *et al*., 2001). It is reported that a large pendulum WEC was deployed with a power rating of 300~600 kW with a 5 m flap on a breakwater in Japan (Zuo *et al*., 2001).

A novel design and originate hinged pitching plate WEC model was designed using an eddy current brake as a PTO simulator by Henriques *et al*. (2011). Experimental results have confirmed that the capture ratio for this model was around 30%. Toyota *et al*. (2011) presented a floating type pendulum WEC in regular waves. The power take off system used a belt and pulley. Power outputs and motions of the floating body were measured. His model mainly consists of a pendulum plate, a caisson and energy conversion unit. One promising advantage of this type of floating device lies in that it can sink into the bottom for safety when a storm comes. The total efficiency was about 26% shown in the results. Compressed air generation using a pendulum WEC was tested by Ogai *et al*. (2010) to determine the effects of wave and system load condition on energy conversion efficiency and wave reflection. A concept of combining the wave energy converter with a costal defensive structure was also proposed in his article. It was shown that the maximum efficiency about 34% was attained at T=3.0 s. A near shore flap that is hinge-connected to the seabed, with a combination of private equity and grant aid a 315 kW Oyster module was designed and manufactured by Aquamarine Power Ltd and Queens University Belfast in 2005 (Whittaker *et al*., 2007). In this version of Oyster, high-pressure seawater was pumped ashore to drive a pelton wheel, which turned an electrical generator.

In China, pendulum WEC research has begun in the 1980s. By now, many technologies have been advanced, and a 30 kW power station of this type has been established in Daguan Islands, Shandong province, China (Zhang *et al*., 2009).

Research of the bottom-hinged WEC was carried out at the South China University of Technology (SCUT) and preliminary results showed good prospects (Qiu *et al.*, 2011a, b). Our model's working mechanism is different from those generally by means of hydraulic systems, but by connecting a generator directly to the model with a gearbox and chain. It is safer and more economical than the hydraulic ones and more important that it has a higher efficiency because of omitting one conversion part. Furthermore, it is environment friendly for no worry about the oil leakage. Caska and Finnigan (2008) conducted similar researches. Nevertheless, there still exist some differences between us on some areas. Firstly, Caska's physical model is a cylinder but ours is a flap. A cylinder can receive waves coming from all directions, however a flap behaviors closely on the coming wave direction. Moreover, a flap can generate a much larger force than the cylinder ones. Secondly, the working mechanism in Casks's model is by directly connecting steel wires to the model shaft, but this is achieved by a flywheel and chain instead in our model. It is worth noting that several performance assess methods were also promoted in his article for advantages and disadvantages comparison.

A 1/10-scale bottom-hinged flap model was constructed and tested in a wave tank under various conditions in this study to assess its energy-conversion efficiency and hydraulic performance. First, details of the experimental setup and the scaled model are given. Then, in the main part of the paper, different sections are presented on some significant discoveries, including the result that the energy-conversion efficiency varies with damping and wave conditions. Subsequently, the effects of ballast on the performance of the model and distinctions between the cases with or without ballast are given followed by the conclusion. The ballast is proved to be useful; it not only broadens the resonant period but also increases the energy-extraction rate. It is found that the maximum of about 68% of the incident wave energy was converted into mechanical energy with this device.

The purpose of our research is to make clear the performance of bottom-hinged flap WEC as a wave energy converter and to make some comparisons between our model and those mentioned above.

2. Experimental Design

2.1 Wave Tank

A bottom-hinged flap model devised to assess performance and feasibility is analyzed in the present study. Experiments were carried out in a wave flume at the South China University of Technology. As illustrated in Fig. 1, the wave tank was 32 m long, 1 m wide and 1.5 m high. The water was 1.2 m deep. Researches focus on regular waves with wave periods ranging from 0.8 s to 3.2 s. Two wave gauges were deployed in the tank to monitor the water surface elevation. The motion of the flap was transferred to the rotation of the shaft; then, using a gearbox, the slow rotation was sped up to operate the sensors deployed on the top of the bracket connected by a gearbox and a chain. Tension and displacement sensors were connected in the middle of the chain to log signals. An angular position sensor was installed on the top shaft to measure the switching angle of the flap. A magneto-rheological damper was used to apply the resistance on the model as the damping can be regulated easily by changing the current. The experimental schemes are shown in Figs. 1~5.

2.2 Model

The flap is composed of five cylindrical buoys with the same diameter of D=12 cm, as shown in Fig. 4 and Fig. 5. The model is deployed in the middle of the wave flume, and the distance between the model and the wave maker is 13.8 m. The support frame is stainless. The flap is of dimensions of width B=61 cm and length L=65 cm, and the moment of inertia is 1.83 kg·m^2 against the bottom shaft. In the tests, upon being excited by waves, the flap moves forward and backward to extract wave energy. Generally, wave energy extracted by the bottom-hinged WEC is calculated by multiplying the corresponding rotational torque and the angle speed of the flap. However, in our case, a different method is applied for simplification which is determined by the product of the tensile force and the velocity of the chain. Furthermore, water ballast can be added into the hollow cylindrical buoys in order to adjust the mass and inertial moment of the flap, and then, the buoyancy centre and the moment of inertia of the flap can be changed. By doing this, the natural frequency can be controlled to match the frequencies of the incoming waves so as to obtain the energy optimally.

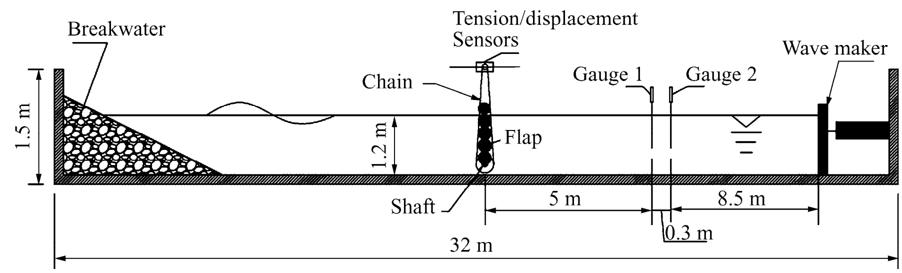

Fig. 1. Experimental setup (side view).

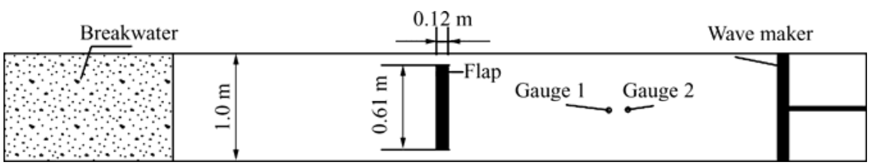

Fig. 2. Experimental setup (top view).

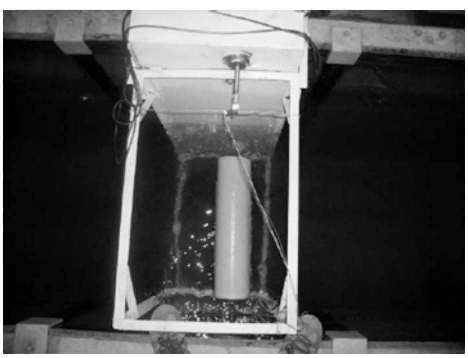

Fig. 3. Botttom-hinged flap model in the wave flume (top view).

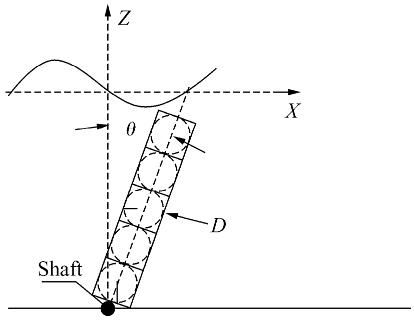

Fig. 4. Bottom-hinged flap model (side view).

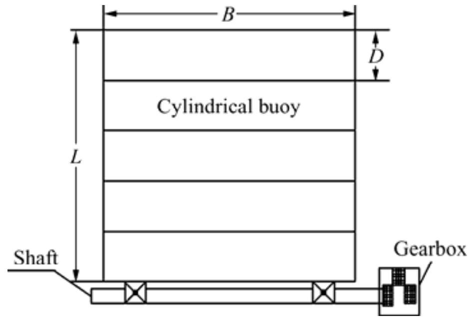

Fig. 5. Bottom-hinged flap model (front view).

3. Results and Discussion

3.1 Wave Energy Extraction

Based on the linear wave theory, the equation of motion for such a wave energy converter can be expressed as:

$$(I+I_{\mathrm{a}})\ddot{\theta}+(c_{\mathrm{r}}+c_{\mathrm{a}})\dot{\theta}+c_{\mathrm{d}}\dot{\theta}\left|\dot{\theta}\right|+K\theta=M_{\mathrm{w}}\,, \quad (1)$$

where I is the moment of inertia of the flap; I_{a} is the frequency-dependent moment of inertia of the additional mass; θ is the pitching angle of the flap; c_{r} is the radiation damping; c_{a} is the applied damping, which can be varied in the tests; c_{d} is the drag coefficient for the device, which is vital for estimating the device performance because it represents the most significant energy loss. In addition, K is the restoring coefficient of the flap due to buoyancy. Finally, M_{w} is the excitation moment induced by waves. Analog signals from the wave gauges are digitized at a sampling interval of 0.08 s. It is important to note that the wave elevations recorded from the gauges are separated to obtain the incoming wave energy. The analytical method (Wang *et al.*, 2003) is adopted in this study to separate the composite waves. Theoretical solutions of the incident and reflected waves are obtained based on the linear wave theory and measurements of water surface elevations using two wave gauges separated by a given distance. Experimental results for the incident, reflected and composite waves as functions of time and wave period are illustrated in Fig. 6 for the wave period T=0.8 s.

Incident wave power per wave front can be determined as follows:

$$p=\frac{1}{16}\rho gH^{2}\frac{\omega}{k}\left[1+\frac{2kh}{\sinh(2kh)}\right], \quad (2)$$

where ρ is the water density, g is the gravitational acceleration, H is the wave height, h is the water depth of the wave flume, ω is the wave frequency, and k is the wave number. Finally, we can obtain the incident wave power in the flap scale with Eq. (3).

$$p_{\mathrm{w}}=Bp\,, \quad (3)$$

where B is the width of the flap as illustrated in Fig. 5. The power absorbed by the flap is presented in Eq. (4).

$$p_{\mathrm{m}}=c_{\mathrm{a}}\dot{\theta}^{2}=M\dot{\theta}\,, \quad (4)$$

where c_a is the applied damping, M is the torque of the bottom shaft, and θ is the pitching angle of the flap. For our tests, p_m is obtained from F and $\dot{\theta}$, using the following equation:

$$M\dot{\theta} = Fr\dot{\theta} = Fv\,, \qquad (5)$$

where r is the radius of the flywheel that connects the shaft to the top damping sensors; F and v are the tension force and linear speed of the chain, respectively.

Several measures of power conversion performance can be considered. Caska and Finnigan (2008) gave a method considering the working volume of the device, which is not generally used in public. However, in our case, the generally applicable parameter defined as the ratio of power absorbed by the device to the incident wave energy is used to evaluate the performance of the model. We can express the ratio as follows:

$$\eta = p_m / p_w\,. \qquad (6)$$

One work cycle of the flap within a wave period is illustrated in Fig. 7 for periods T=1.2 s and T=1.4 s, respectively. The displacement label indicates the offset of the flap movement as opposed to its equilibrium position in still water, while the force label represents the tension force that the chain subjected. The damping coefficient corresponding to the work cycle is c_a=71.07 Nms/rad. The area enclosed in Fig. 7 is the energy obtained by the model. It is assumed that the displacement is negative when the flap responds to incoming waves. On the contrary, the displacement is positive when the flap reverses its motion. It is apparent that the force corresponding to the incoming wave is much larger than those of the reverse action.

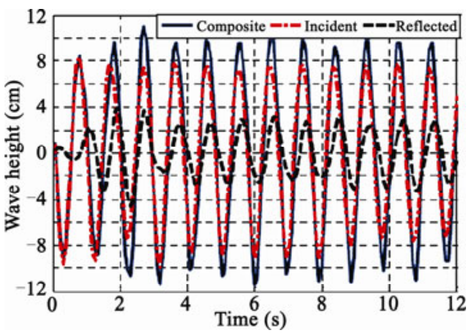

Fig. 6. Separated waves (T=0.8 s).

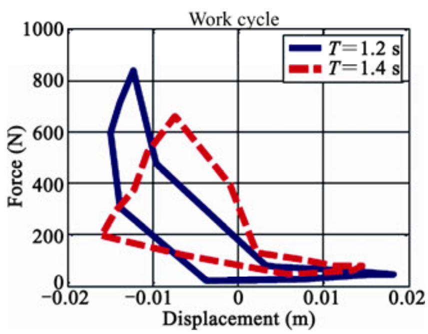

Fig. 7. Working cycle (c_a=71.07 Nms/rad).

3.2 Damping Effect

Five load-damping are chosen to derive the mechanical performance and characteristics of the power take-off system in the experiments which are c_{a1}=88.85 Nms/rad, c_{a2}=82.01 Nms/rad, c_{a3}=76.54 Nms/rad, c_{a4}=71.07 Nms/rad and c_{a5}=62.87 Nms/rad, respectively. The relations among the energy conversion efficiency, applied damping, wave period and wave height are analyzed as follows.

3.2.1 *Absorbed Power vs. Damping*

Experimental results for the absorbed power of the flap as a function of damping and wave period are illustrated in Fig. 8 for wave periods T=0.8 s, T=1.0 s and T=1.4 s, respectively. The wave height, which is a constant value of 14.53 cm, is the same for each wave period. The power captured by the model fluctuates with the damping and wave period. The absorbed power generally increases with the increasing wave period. For the wave period of T=1.4 s, the absorbed power initially increases with the damping and achieves the maximum near 70 Nms/rad. It then decreases with the increasing damping. The situation is reversed for a wave period of T=1.0 s, and in the case of T=0.8 s, the absorbed power is relatively stable.

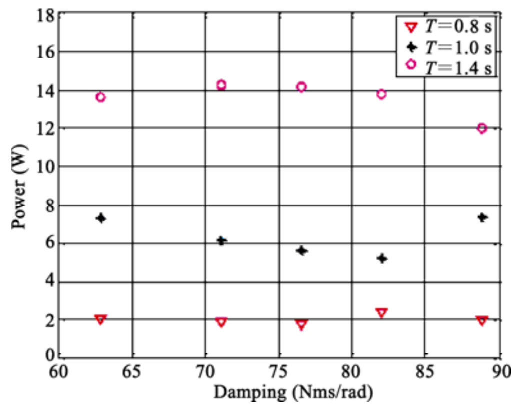

Fig. 8. Absorbed power vs. damping.

3.2.2 *Efficiency vs. Wave Height*

In this section, the energy conversion efficiency vs. wave height is investigated for a settled damping c_a=71.07 Nms/rad. Two wave conditions are investigated for T=1.2 s and T=1.4 s, as shown in Fig. 9. It is clear that for the case T=1.4 s, efficiency is slightly larger than that for T=1.2 s. Fig. 9 shows that the efficiency fluctuates with the increasing wave height. It is relatively higher for small waves and reaches the maximum of 70%, while it generally decreases with the increasing wave height. Energy dissipation in vortex shedding can contribute to this phenomenon because it is small in smaller waves. As wave velocity tends to increase for larger amplitude waves, this type of energy loss is evident in large waves. Thus, despite the fact that more energy is absorbed in larger waves, the ratio of absorbed energy into incident wave energy is relatively small. The trend has been previously illustrated in other WECs such as in Flocard and Finnigan (2012).

3.2.3 *Efficiency vs. Damping*

The best performance is observed in small wave periods. As viscous losses are small in smaller wave periods. Smaller wave conditions allow for the ideal liner conditions of the wave theory. While in higher wave periods, the device tends to be decoupled from the waves.

In this test, five different damping coefficients are chosen. Experimental results for energy conversion efficiency as a function of wave period and damping are illustrated in Fig. 10. It is found that η fluctuates with wave periods and damping dramatically. The fluctuation is more evident for small waves. The maximum η occurs at a wave period of around 1.0 s, which corresponds to real sea waves of 3.16 s. It is also found that η generally decreases with the increasing wave period and has the maximum value of 60% for a damping of c_a=62.87 Nms/rad. In particular, η is above 40% for T=0.8 s, 1.0 s, 1.2 s and 1.4 s, and above 30% for T=1.6~2.2 s. Moreover, η is higher than 15% for wave periods T=2.4 s and 3.2 s.

Furthermore, in this section, it is found that the optimal damping varies with the wave period. However, the optimal damping is not found, and its relationship with the wave period is not clear due to the limited damping tested here. Thus, further work should be carried out.

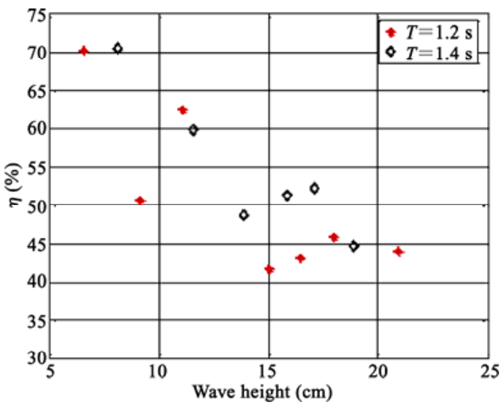

Fig. 9. Efficiency vs. wave height (c_a=71.07 Nms/rad).

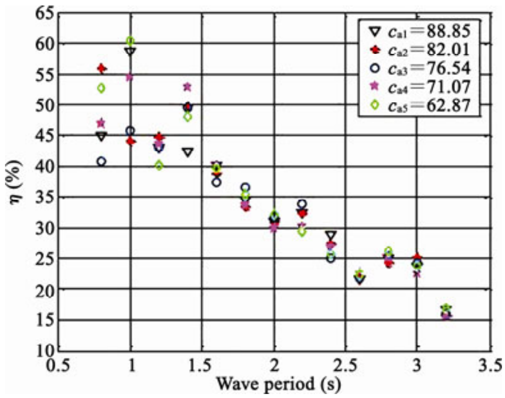

Fig. 10. Efficiency vs. damping.

4. Effect of Ballast

Flocard and Finnigan (2012) addressed an inertia adjustment influence on a wave energy device. Their results showed that this method could result in an increase of capture factor by almost 70%~100% for large regular waves, and an average 15%~25% increase in irregular waves. Modification of inertia is achieved by adding different mixtures of sand and lead shot into the hollow compartments of the model. While in our tests, this is done by allowing water to fill some portion of the cylinder (i.e. water ballast) instead. An increase of capture ratio around 10% is found although only one ballast case was tested in our tests. More ballast cases should be conducted for further study.

Water ballast is added to the bottom hollow cylinder to change the characteristics of the flap for the improvement of the system performance. The characteristics of the flap for the cases with and without water ballast are illustrated in Table 1. Fig. 10 clearly shows the influence of wave frequency on power extraction. It is necessary to change the nature frequency of the device so as to optimize the performance over the appropriate wave frequency band. In this study, this is achieved by altering the ballast of the flap. By pumping water ballast into the bottom hollow cylinder, thereby the position of the centre of gravity and the moment of inertia of the flap are changed to regulate the nature frequency of the uncontrolled device to match the dominant wave frequency of the waves.

Table 1 Characteristics of the flap with and without water ballast

Case	With ballast	Without ballast
Mass of the flap (kg)	22.29	9.5
Moment of inertia (kg·m^2)	2.91	1.83
Damping (Nms/rad)	71.07	

Added water ballast mass is M_w=12.79 kg and an additional inertial moment against the bottom shaft is I_{mw}=1.08 kg·m^2. Efficiency comparison for the cases with and without ballast is illustrated in

Fig. 11 for a fixed damping of c_p=71.07 Nms/rad. It is found that in the ballast case, η is slightly higher than that without ballast. Thus, the ballast plays an important role in the WEC efficiency of the model as well as damping does. The energy conversion efficiency proves to be higher for most of the wave periods and reaches a maximum of 68%. Hence, the maximum power can be achieved with effective control over the flap.

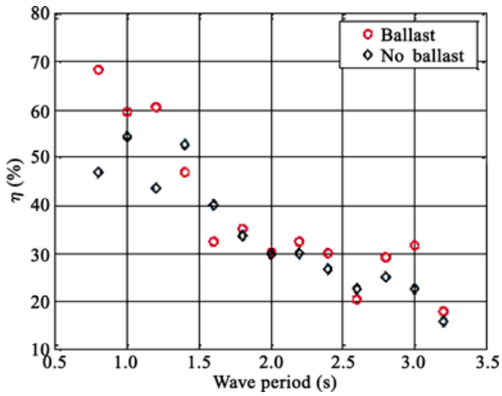

Fig. 11. Water ballast vs. no ballast (c_p=71.07 Nms/rad).

5. Conclusions

This paper presents the latest development in the design of a pendulum WEC. Based on the existing references, literature reviews on existing WECs are summarized. A distinctive type of WEC characterized by a pendulum flap is investigated. Promising power output characteristics are obtained, and the possibility of significant improvements in performance is anticipated. In order to investigate the mechanical performance of the power take-off system, a 1/10-scale physical model was constructed and tested in a wave flume for a range of regular waves. Experiments are conducted for various wave periods and wave heights as well as for different damping values. In consideration of the model dimension limits, the composite waves are separated into incident and reflected waves. The absorbed energy of the model is monitored in order to estimate the energy conversion efficiency of this system. Five different damping values are selected for various wave periods, and the experimental results show that, in the case of T=1.0 s, wave energy conversion efficiency achieves the maximum of 60% without ballast for a damping of 62.87 Nms/rad. Furthermore, a water ballast at the bottom cylinder of the flap proved to be useful. It is found that the ballast has a significant effect on the energy conversion absorption of the model and that the efficiency achieves the maximum of 68% in ballast cases. Hence, the efficiency of WEC can be enhanced by more precise control based on these technologies. Further work should be undertaken to concentrate on the controlled motion of a bottom-hinged WEC in irregular waves.

References

Budal, K., Falnes, J., Iversen, L. C., Lillebekken, P. M., Oltedal, G., Hals, T., Onshus, T. and Høy, A.S., 1982. The Norwegian wave-power buoy project, *Proceedings of the 2nd International Symposium on Wave Energy Utilization,* Trondheim, Norway, 323~344.

Caska, A. J. and Finnigan, T. D., 2008. Hydrodynamic characteristics of a cylindrical bottom-pivoted wave energy absorber, *Ocean Eng*., **35**(1): 6~16.

Falnes, J. and Budal, K., 1978. Wave-power conversion by power absorbers, *Norwegian Maritime Res.*, **6**(4): 2~11.

Flocard, F. and Finnigan, T. D., 2012. Increasing power capture of a wave energy device by inertia adjustment, *Appl. Ocean Res.*, **34**, 126~134.

Henriques, J. C. C., Lopes, M. F. P., Lopes, M. C., Gato, L. M. C. and Dente, A., 2011. Design and testing of a non-linear power take-off simulator for a bottom-hinged plate wave energy converter, *Ocean Eng*., **38**(11-12): 1331~1337.

Kondo, H., Watabe, T. and Yano, K., 1984. Wave power extraction at coastal structure by means of moving body in the chamber, *Proc. 19th Conf. on Coast. Eng.*, **3**, 2875~2891.

Lye, J. L., Brown, D. T. and Johnson, F., 2009. An investigation into the non-linear effects resulting from air cushions in the Orecon oscillating water column (OWC) device, *Proceedings of the 28th International Conference on Ocean Offshore Arctic Engineering*, Honolulu, Hawaii.

Masuda, Y. and McCormick, M. E., 1987. Experiences in pneumatic wave energy conversion in Japan, *Utilization of Ocean Waves-Wave to Energy Conversion*, ASCE, New York, 1~33.

Masuda, Y., 1971. Wave-activated generator, *Int. Colloq Exposition Oceans*. France: Bordeaux.

McCormick, M. E., 1981. *Ocean Wave Energy Conversion*, New York: Wiley.

Ogai, S., Umeda, S. and Ishida, H., 2010. An experimental study of compressed air generation using a pendulum wave energy converter, *Journal of Hydrodynamics, Ser. B,* **22**(5-Supp1): 290~295.

Qiu, S. Q., Ye, J. W., Wang, D. J. and Liang, F. L., 2011a. Capture width study on a pendulum wave energy converter, *Power and Energy Engineering Conference* (*APPEEC*), 2011 Asia-Pacific, 1~4.

Qiu, S. Q., Ye, J. W., Wang, D. J. and Liang, F. L., 2011b. Investigation on the efficiency of a pendulum energy converter in regular waves, *Proc. 21st Int. Offshore Polar Eng. Conf.* (*ISOPE*), Maui, Hawaii, USA, 650~654.

Salter, S. H., 1974. Wave power, *Nature*, **249**, 720~724.

Toyota, K., Nagata, S., Imai, Y., Ono, K. and Setoguchi, T., 2011. Energy conversion characteristics on floating type pendulum wave energy converter in regular waves, *Proc. 21st Int. Offshore Polar Eng. Conf.* (*ISOPE*), Maui, Hawaii, USA, 675~679.

Tseng, R. S., Wu, R. H. and Huang, C. C., 2000. Model study of a shoreline wave-power system, *Ocean Eng*., **27**(8): 801~821.

Wang, Y. X., Peng, J. P. Sun, H. Q. and Li, G. W., 2003. Separation of composite waves by an analytical method, *The Ocean Engineering*, **21**(1): 42~46. (in Chinese)

Wells, A. A., 1976. *Fluid Driven Rotary Transducer*, British Patent Spec No. 1595700.

Whittaker, T., Collier, D., Folley, M., Osrterried, M., Henry, A. and Crowley, M., 2007. The development of Oyster – A shallow water surging wave energy converter, *Proceedings of the 7th European Wave and Tidal Energy Conference*, Aporto, Portugal, pp.1-1.

Zhang, D. H., Li, W. and Lin, Y. G., 2009. Wave energy in China: Current status and perspectives, *Renewable Energy*, **34**(10): 2089~2092.

Zuo, R., Shi, M. H. and Wang, X. L., 2001. *Renewable Energy*, Beijing: China Machine Press. (in Chinese)