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Experimental Study on the Characteristics of the New Designed Wave Energy Converting System

Chen Qi-Juan[1], Guo Hai-Feng[1], Shang Xin-Xin *[2] and Xu Zhi-Xiang[1]

[1] School of Power and Mechanical Engineering and [2]School of Civil Engineering,Wuhan University, Sichuan Chengdu, P.R.China 430072
**Corresponding author*
shangxinxin@whu.edu.cn

Abstract

The wave energy converting system (WEC) can convert the unstable wave energy into stable electric power. In this paper, the new WEC which is mainly composed of three hydraulic circuits viz, the commutation, decompression and speed regulation circuit. It is controlled by various electronic valves. A series of experimentations were done to investigate its static and dynamic characteristics under the condition of variable load and variable flow rate, and its influence on the grid was analyzed as well. The experimental result shows that when the flow rate of the system which is controlled by the electro-hydraulic proportional flow control valve varies, the accumulator conserves part of the hydraulic energy and consequently the output power decreases. The revolving speed and working pressure show the different change trend in the response to the variation of the flow rate. However, when the load varies, the revolving speed of the hydraulic motor varies marginally. In the case of identical load change, the amplitude of variation is not the same at different revolving speed. Because of adopting the proportional flow control valve, the new WEC can be regarded as a non-differential control system which may cause the oscillation of the active power. To avoid this, this paper suggests using the variable-speed constant-frequency device or electrical governor.

Keywords: *wave energy, WEC, hydraulic device, non-differential regulation*

1. Introduction

There is a large amount of energy in the ocean wave. It is calculated that the global wave energy power is more than 70 billion KW and 2 to 3 billion KW can be exploited. In 1955, the first wave power generation device was invented. After that, thousands of experimental devices are proposed all over the world. Wave energy is a kind of ocean kinetic energy. Presently, there are three ways to convert the wave energy into electronic power [1]. The first way is to use the reciprocating flow of air (water) to drive an air (hydraulic) turbine and then generate electricity. The second way is to use the air (water) flow which is caused by the back and forth swinging or rotation motion of the wave energy device to drive an air (hydraulic) turbine. The third way is to convert the low-pressure large waves into the small-volume high-pressure water and then conduct the water to a saving pool which is used to form a head to push the air (hydraulic) turbine.

Hydraulic components are widely used in wave energy conversion devices [2-4]. There are following several advantages in adopting a hydraulic device: 1. there is small inertia when the hydraulic cylinder is taken as the rigid inertia components; 2. the hydraulic damping is easy to control by the hydraulic valves [5-7]; 3. the hydraulic device can reduce the energy loss; 4. the hydraulic device can do well in storing the energy and keep the output power stable.

Ocean Power Delivery demonstrated the Pelamis floating offshore device at the

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European Marine Energy Center (EMEC) on Orkney (UK) in 2004[8], the total efficiency is about 60% to 70%. In 2009 Oyster wave energy device have been successfully installed and put into operation in the European Marine Energy Center [9], the highest output power can reach 800KW. The Finnish AW-Energy corporation developed the WaveRoller near-shore wave generator which uses wave kinetic energy under the sea, the average capture power of WaveRoller 1 reached 13KW[10]. Many other forms of wave power devices are also efficient and well known such as the Wave-driven Resonant, the Arcuate-action, the Surging Power Absorber (WRASPA)[11], the BioWAVE, the Langlee[12] and so on.

2. The Mathematical Model of Wave Energy Conversion

2.1. Wave Energy Extraction [13]

Assuming that the floating body, most of which is under the sea water, executes simple harmonic motion and the wave pressure distribution stays constant which is not influenced by the existence of the floating body. According to the Froud-Krylov function assumption, the vertical wave force F_v is given by

$$F_V = C_V \iint_S P_z dS \tag{1}$$

where C_v is the vertical diffraction coefficient. The instantaneous velocity can be written as $V = \dot{\xi} = R_e\{Ze^{-i\omega t}\}$ (2)

where Z is the average complex amplitude, ω is the wave frequency. The acceleration is the derivative of V, it can be written as

$$a = \ddot{\xi} = R_e\{-\omega^2 Ze^{-i\omega t}\} \tag{3}$$

F_s is the restoring force which is determined by the submerged depth, it can be written as $F_S = -\iint \rho g A_{wp} Z$ (4)

where A_{wp} is the float sectional area on the free-water level. The damping force in the vertical direction is given by

$$F_C = -i\omega Z P_C \tag{5}$$

where P_C is the damping coefficient. According to the Newton's second law, the equilibrium equations of the resultant force on the float is written as

$$F(t) = ma = F_V + F_S + F_C \tag{6}$$

where M includes the mass of the float (m) and the water attached mass (m_a). F_v can be written as

$$F_V = -[-(m+m_a)\omega^2 + \rho g A_{wp} - i\omega P_C]Z \tag{7}$$

and then

$$Z = \frac{F_V}{K - i\omega P_C} \tag{8}$$

where K is given by

$$K = -(m+m_a)\omega^2 + \rho g A_{wp} \tag{9}$$

The obtained power from the wave energy can be written as

$$N = \frac{1}{2}\omega^2 F_V \bar{F}_V \frac{P_C}{K^2 + \omega^2 P_C} \tag{10}$$

2.2. Wave Energy Conversion

In absence of the intermediate energy loss, the power of the double-rod piston hydraulic cylinder equals to the output power of the wave absorber which is given by

$$P_h Q_p = F_C V = \omega^2 F_V \bar{F}_V \frac{P_C}{K + \omega^2 P_C{}^2} \tag{11}$$

where P_h is the internal pressure of the hydraulic cylinder, Q_p is the flow rate of the hydraulic cylinder. The flow rate and pressure fluctuation of the WEC are caused by the reciprocating motion of the hydraulic cylinder. The maximum oil storage volume (V_w) of the accumulator can be calculated as:

$$V_w = V_0 P_0^{\frac{1}{n}} \left[\left(\frac{1}{P_2}\right)^{\frac{1}{n}} - \left(\frac{1}{P_1}\right)^{\frac{1}{n}} \right] \tag{12}$$

where P_0 and V_0 are the inflation pressure and the initial volume of the accumulator bladder, P_1 is the chamber pressure when the accumulator bladder is compressed, P_2 is the chamber pressure when the oil is released by the accumulator bladder. When the accumulator is used to supply a large amount of oil, the assumption of adiabatic process can be adopted with the ratio of heat capacity n=1.4. In consideration of the leakage of the hydraulic motor, the flow rate is defined as follow:

$$Q_m = \frac{d(V_w + V_c)}{dt} = \frac{q_m n_m}{60} - C_m P_m \tag{13}$$

where Q, q, n, C and P are the flow rate, displacement, revolving speed, leakage coefficient and inlet pressure, and the subscript m represents the hydraulic motor. V_c is the volume of the oil inside the pipe and the single-rod piston hydraulic cylinders. Neglecting the energy loss of the hydraulic motor, the output power P_o and the input power P_i can be substituted by the theoretical power P_t which is given by

$$P_t = P_m Q_m = T_t \omega \tag{14}$$

According to the equations above and considering the wave absorber's resonance with the wave [14], the different working condition are shown in Table 1, A, λ and T are the amplitude, length, and period of the wave. The calculated parameters are listed in Table 2. D_h, L_s and $P_{h,max}$ are the diameter, stroke and maximum pressure of the single-rod piston cylinder; D_p is the diameter of the hose; ρ is the density of oil; D_a, S_a and $P_{a,max}$ are the diameter, stiffness and maximum pressure of the accumulator; Q_c is the calculated flow rate; P_i is the initial generation pressure; D_r is the damping ratio. Among them, D_h=0.02, L_s=0.0785, D_p=0.005, ρ=1000, D_a=0.057, S_a=1021. In this paper, the experimental parameters are mainly based on case 1.

Table 1. The Wave Parameters of Different Cases

Wave parameters	Case1	Case2	Case3	Case4	Case5	Case6
A(m)	0.25	0.5	0.75	1.15	1	1.4
λ (m)	22	32	43	48	45	63
T(s)	4.5	5.5	6	6.1	6.2	7.2

Table 2. The Parameters of Different Calculated Working Condition

Parameters	The calculated working conditions					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Q_c(L/S)	0.07852	0.06512	0.06031	0.1191	0.1169	0.1018
P_i(MPa)	7.171	8.516	9.954	7.199	6.147	5.969
D_r(%)	11.4	20.12	27.88	41.63	36.75	47.91
$P_{a,max}$(MPa)	14.36	18.24	21.33	15.43	13.17	12.79
$P_{h,max}$(MPa)	9.388	11.15	13.03	9.425	8.048	7.815

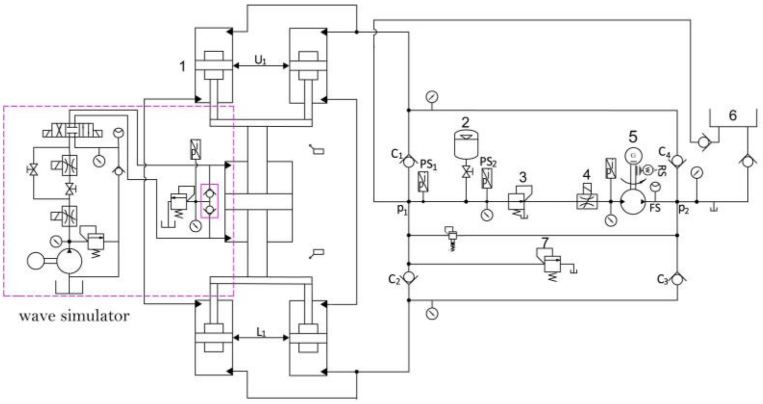
3. The Experimental Installation and the Principle of Operation

3.1. Experimental Device

As Figure 1 shows, the new WEC is composed of three parts *viz*. the fluid drive mechanism, automatic controller and power generation assembly. The fluid drive mechanism includes a bladder accumulator, a refueling tank, a hydraulic motor, a proportional flow control valve, a proportional overflow valve, a pressure reducing valve, a generator and several hydraulic cylinders (single-rod piston cylinder， double-rod piston cylinder). The virtual assembly and the physical device are shown in Figure 2.a and Figure 2.b.

3.2. Experimental Strategy

When the double-rod piston hydraulic cylinder is driven by the wave simulator to produce reciprocating movement, the oil can be discharged from two single-rod piston hydraulic cylinders (U_1) and inhaled to the other two piston hydraulic cylinders (L_1) from the refueling tank (6). The check valves ($C_{1\text{-}4}$) ensure the hydraulic oil flow along the specified direction (from p_1 to p_2) regardless of the reciprocating movement of the hydraulic cylinders during the commutation process. The bladder accumulator (2) is used to balance the flow rate, stabilize the pressure and recover the energy in the system. Moreover, the pressure reducing valve (3) can keep the inlet pressure of the proportional flow control valve (4) stable, and the proportional flow control valve can avoid the fierce fluctuation of n_m when the load varies. The refueling tank (6) can replenish the oil. Additionally, the safety valve (7) can guarantee the system pressure below the setting pressure value. PS_1 is the measurement point of working pressure, FS is the measurement point of the flow rate, RS is the measurement point of the revolving speed. The output power is measured through the voltage and current sensor.



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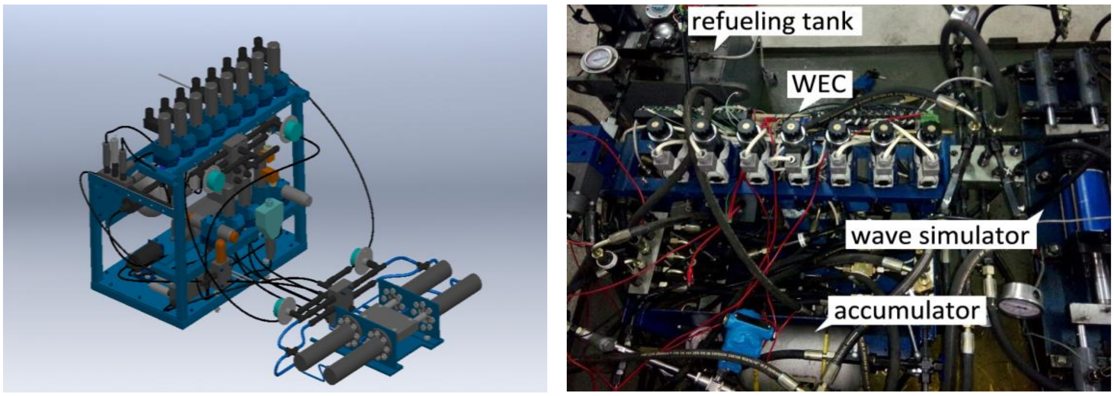

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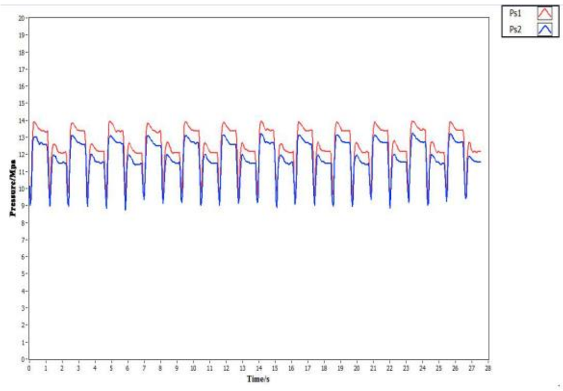
4. Results and Discussion

A series of experiments, which can be sorted as the load-change and the flow-change, were conducted to validate the stability of the new WEC and confirm the feasibility of the principle. The hydraulic oil pump can provide an approximate practical working environment. The reversal time of the double-rod piston hydraulic cylinder is controlled by the three-position four-way solenoid valve, the maximum working pressure is determined by the proportional overflow valve and the system flow rate is regulated by the proportional flow control valve.

As Figure 3a shows, without the accumulator, the pressure fluctuation of measurement points is violent. Compared with Figure 3b, it can be found that, the average pressure fluctuation (APF) in Figure 3a is about 36% but only 2.6% in Figure 3b. The accumulator can do well in stabilizing the pressure fluctuation. In addition, the inflation pressure (P_n) of the accumulator should be neither too high nor too low, this article suggested that $P_w/P_n = 2.8$.



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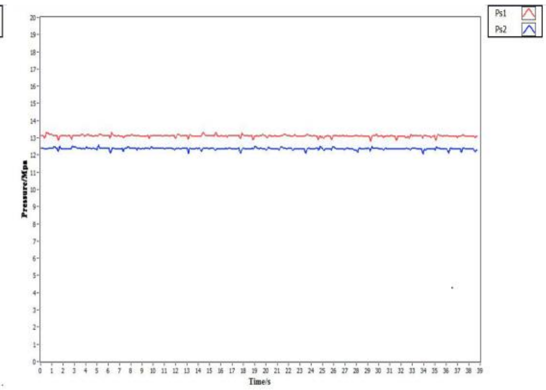

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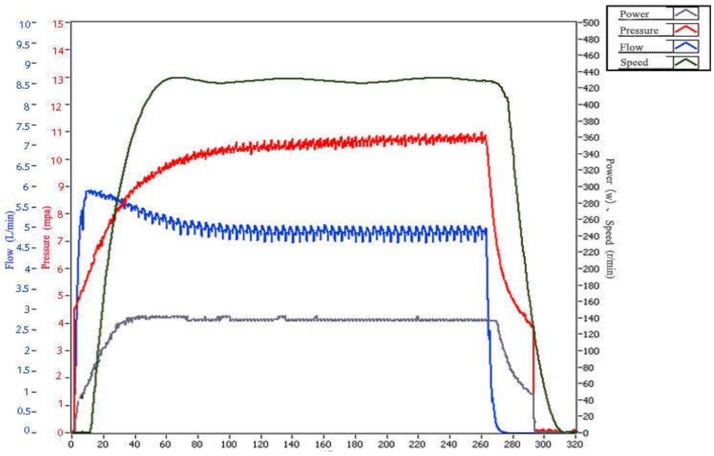
From Figure 4, after the new designed WEC started, the working pressure (P_w) increases rapidly from 0 to 4.5MPa in 3s, and then at T=70s P_w becomes stable. There is a slight flow overshoot of the flow rate (Q_m) which is caused by the compression of the accumulator bladder.



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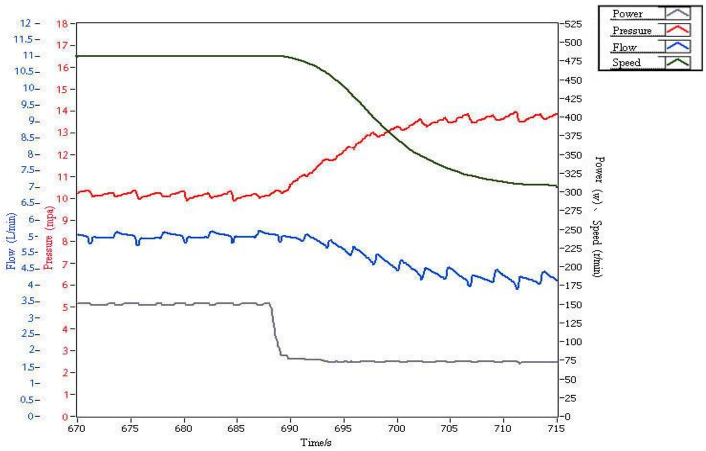
When the new WEC runs in a stable state, the maximum fluctuation of P_w is less than 4%, the maximum fluctuation of Q_m is 6.8%, and the maximum fluctuation of the output power (E_{out}) is 3.7%. According to the E_{out} curve, it can be seen that the WEC has a good static stability. Even though Q_m drops dramatically at T=263s, P_w and E_{out} decline steadily due to the accumulator. However when P_w drops below 4.5MPa, the accumulator stops working and E_{out} falls to 0 instantly. Because of the mechanical inertia, the revolving speed (n_m) takes a longer time to fall to 0.

4.1. The Variable Flow Test

The variable flow test was conducted to study the dynamic stability of the system. As can be seen from Figure 5, when the load is constant and Q_m varies, the accumulator can conserve part of hydraulic energy and consequently E_{out} decreases. n_m and P_w show the different change trend in the response to the variation of Q_m. Because of the influence of the hydraulic transition process which is brought by the change of working condition, the stabilization periods of n_m and P_w are much longer than that of E_{out}.

It should be noted that the Q_m cannot exceed the maximum flow rate at the outlet pressure of the pressure reducing valve. The pressure drop between the inlet and outlet of the proportional flow control valve should be more than 1.2MPa, otherwise the phenomenon of flow instability may occur.



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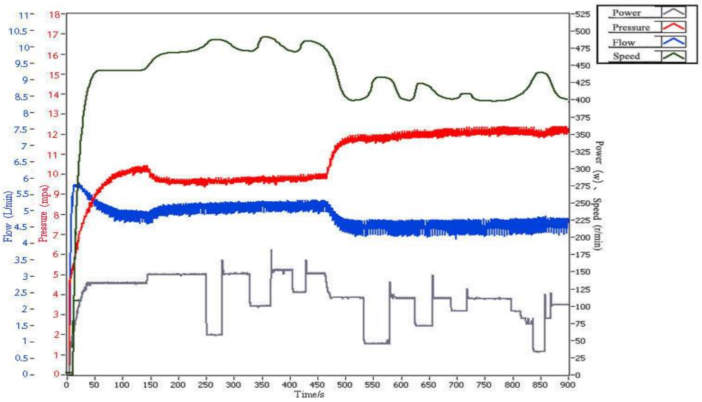
4.2. The Variable Load Test

This experiment was conducted to validate the self-adjusting ability and stability under the condition of variable load. From Figure 6, it can be seen that there is a small fluctuation of n_m which varies with E_{out}, P_w and Q_m stay relatively stable due to the proportional flow control valve. In the case of identical load change (50W), the amplitude of variation is not the same at different revolving speed. When n_m=475r/min and 400r/min, the amplitude of variation is about 5% and 9.6% respectively. The faster the hydraulic motor runs, the smaller the amplitude of variation is. Therefore the gearbox can be used to increase the revolving speed and reduce the amplitude of variation which is caused by the load change.



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Though the designed WEC adopted the proportional flow control valve and the accumulator as the pressure and flow rate stabilizer, inevitably the revolving speed still has a small fluctuation when load varies, the PID strategy can help reduce the fluctuation. As the proportional flow control valve was adopted, the WEC can be regarded as a zero-error output adjustment system (in the case of variable load).

When the two light bulbs of 60W were turned off, the brightness of the rest of each light bulb has no change (see Figure 7) and vice versa. It can be considered that in the case of combined operation, the electric load cannot be assigned automatically among the generation devices and the grid frequency cannot be regulated regardless of the small fluctuation of the revolving speed which is caused by the variation of the load. Hence it can cause the oscillating of the active power.

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In the WEC assembly process, the efficiency and energy loss caused by the manufacture and assembly sectors cannot be ignored. In addition, the gearbox can be used to increase the revolving speed of the hydraulic motor and consequently improve the efficiency of the generator when the generator is working at low revolving speed.

5. Conclusion and Further Works

6. Conclusion

The characteristics of the new designed WEC are investigated in this paper. The experimental results confirm that the WEC can convert the unstable wave energy into stable electrical energy. The bladder accumulator can do well at balancing the flow rate, stabilizing the pressure and recovering the energy. The inflation pressure of the accumulator should be neither too high nor too low. This article suggested that the ratio of the working pressure and inflation pressure is 2.8. When the load is constant and the flow rate varies, the accumulator can conserve part of hydraulic energy and the output power decreases. When the flow rate is constant and the load varies, there is a small fluctuation of the revolving speed. Neglecting the fluctuation of the revolving speed, the new WEC is a non-differential regulation power generation device which can cause the oscillation of the active power. The possible solution is to adopt the variable-speed constant-frequency device or design an electrical governing system of the wave power device. Compared with the designed parameters, the error of the corresponding parameters, which is mainly caused in the manufacture and assembly process, is from 18% to 38%. The efficiency and energy loss can be improved in the further design.

Further works

As mentioned above, this work is as a first step to introduce the experiment of the new designed WEC. A power generation system is a system which can be incorporated into the grid and adjusted automatically according to the change of the load. The next step is to design and develop an electrical governing system of the wave power device. The appropriate control algorithm will be addressed in order to make the WEC adjustable.

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References

[1] Y.-B. Yan, Editor, "Principle and Device of the Ocean Wave Energy Conversion Generation", Shanghai Scientific and Technical Publishers, Shanghai, **(2013)**.

[2] A. Ramadan, M. H. Mohamed, S. M. Abdien, S. Y. Marzouk, A. El Feky and A. R. El Baz, "Analytical investigation and experimental validation of an inverted cup float used for wave energy conversion", Energy, **(2014)**, pp. 1-8.

[3] M. A. Mueller, H. Polinder and N. Baker, "Current and novel electrical generator technology for wave energy converters", Electric Machines & Drives Conference, 2007. IEMDC'07. IEEE International, IEEE, vol. 2, **(2007)**, pp. 1401-1406.

[4] Ahmed M, Murillo-Cruz S C, Hably A, Bacha S. A comparative study on a pumping wave energy conversion system [C]. Industrial Electronics (ISIE), 2012 IEEE International Symposium on. IEEE, 2012: 1419-1424.

[5] M. Yi and F. Zhu, "An energy-saving hydraulic system with a self-regulated and servo-valve-controlled variable displacement pump", Journal of Huazhong University of Science and Technology, **(1997)**, vol. 25, no. 3, pp. 57-59.

[6] T. Heath, T. J. T. Whittaker and C. B. Boake, "The Design, Construction and Operation of the LIMPET Wave Energy Converter (Islay, Scotland)", 4th European Wave Energy Conference, **(2000)**, pp. 4-6.

[7] C. Wang, "Hydraulic servo control system", Beijing：China Machine Press, **(1989)**.

[8] B. Drew, A. R. Plummer and M. N. Sahinkaya, "A review of wave energy converter technology", Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 223, no. 8, **(2009)**, pp. 887-902.

[9] A. Henry, K. Doherty, L. Cameron, T. Whittaker and R. Doherty, "Advances in the design of the Oyster wave energy converter", Marine and Offshore Renewable Energy Conf., London, UK, **(2010)**.

[10] F. Zabihian and A. S. Fung, "Review of marine renewable energies: case study of Iran", Renewable and Sustainable Energy Reviews, vol. 15, no. 5, **(2011)**, pp. 2461-2474.

[11] R. V. Chaplin, G .A. Aggidis and M. T. Rahmati, "WRASPA:(Wave-driven, Resonant, Arcuate action, Surging Power-Absorber)", Wave and Tidal Symposium, Renewable Energy Association, Cardiff, Wales, **(2008)**.

[12] A. Pecher, J. P. Kofoed, J. Espedal and S. Hagberg, "Results of an experimental study of the langlee wave energy converter", Proc. 20th International Offshore and Polar Engineering Conference, **(2010)**, pp. 877-885.

[13] K. Nielsen and P F. Smed, "Point absorber optimization and survival testing", Proceedings of the Third European Wave Energy Conference, no. 18, **(1998**), pp. 207-214.

[14] Y.-Q. Cai, "Resonant wave power device", PRC. Patent CN 102287315 B 29-43, **(2013)**.

Authors

Chen Qi-Juan, he received the Ph.D. degree in Water Resources Engineering from Wuhan University, Wuhan, China, in 1996. Now he works at College of Power and Mechanical Engineering of Wuhan University. His current research interests include modeling, control and fault diagnosis in the field of fluid machinery.

Guo Hai-Feng, he received the B.Eng. degree in electrical engineering from Southwest Jiaotong University, Chengdu, Sichuan, China, in 1998, the M.S. degree in electrical engineering from South China University of Technology, Guangzhou, Guangdong, China, in 2004. He is currently pursuing the Ph.D. program at Wuhan

University. His research interests include the renewable energy generation technology.

Shang Xin-Xin, he received the Ph.D in Power and Mechanical Engineering from Wuhan University, Wuhan, China, in 2012. He is now working in GUODIAN Science and Technology Research Institute, Chengdu Electric Power Technology Branch, Sichuan, China. His research interests include the control and monitoring of hydropower station.