Research on Wave Energy Generation Device Based on Artificial Heart Pump

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***Abstract-* This paper discussed a new method of wave energy conversion (WEC), with a pump-based system simulating the function of heart pump. First, developments of wave energy conversion technology will be introduced. Then the mechanisms of animate heart, artificial heart and pump structure in the WEC device will be analyzed respectively. Thirdly, the relationship between wave forces and geometric figure is studied, the energy calculation is discussed, and the power and efficiency of the device is investigated. Fourthly, a design based on artificial heart pump technique is put forward and its feasibility is reviewed. At last, a feasible way of mass application of the WEC device is discussed.**

Keywords-wave energy conversion; Froude-Krylov hypothesis; artificial heart pump; mass application

I. INTRODUCTION

Accompany with the developments of economy and society, the demand of energy increases steadily. However, the global reserve of fossil fuels is finite, and the oil crisis in the 70s made people realize the existence of the energy problem.[1] In addition, the data shows that the contemporary stock of fossil fuels will be depleted in less than 100 years.[2]

In order to solve the bottleneck problem of energy supply in the social advancing process, developing stable renewable sources is gradually gaining significance in the world energy fields. Among numerous renewable energy generation methods, PV generation and wind power generation have developed most successfully. Nevertheless, more than 70% of the earth is covered by ocean, which contains huge amount of energy and appeals much attentions of researchers, many laboratories and companies have begun developing ways to maintain the energy in oceans. And one of the successful methods is wave energy conversion technique. Generally speaking, the contemporary existing wave energy converters can be subdivided into 4 categories: oscillating water column (OWC)–air-turbine base systems, direct drive converters, hydraulic pump-based devices, and overtopping devices. [3,4]

The device discussed in the paper is a pump-based device. In view of the single travel problem of generation process and the instability in the existing devices, a new pump structure based on bionics is designed.

II. MECHANISM OF HEART PUMP

A. Animal Heart

Take the left ventricle of human heart as an example, pumping blood process of an animate heart is the interaction of myocardial electric activities, mechanical contracture and heart valve activities. A cardiac cycle can be divided into 3 stages: atrial systole, ventricular systole and ventricular diastole.[5] And it is usually considered that a cardiac cycle begins when the atrium starts to contract.[6]

At the beginning of atrial systole period, both atrium and ventricle are in diastole, venous blood keeps flowing in ventricle when atrium contracts, pumping blood into ventricle, making ventricle contain more blood. The progress lasts 0.1s, and atrium then goes in diastole. As soon as ventricular systole period begins, ventricle contracts, making the inner pressure increase sharply and the heart valve shut, and this progress called isovolumetric contraction phase. When isovolemic ventricular pressure exceeds the aortic pressure, semilunar valve opens and the blood is shot into aorta. In this phase (ejection phase), ventricle continues contracting, aortic pressure increases and ventricular pressure decreases. And in the last period, when ventricular pressure is smaller than aortic pressure, blood pushes semilunar valve close, atrial pressure forces heart valve open, and blood flows into ventricle.[7]

From cardiac cycle, it is clear that an animate heart pump has 2 motivating forces, that is, the contraction forces of atrium and ventricle. And it has 2 valves, the semilunar valve and the heart valve.

B. *Artificial Heart Pump*

The development of artificial heart pump has been through 2 generations.[8] At the beginning, the blood pump designed by the early researchers simulated the function of human heart, so the blood pumps in this stage were mainly positive-displacement pumps. This kind of blood pump mainly consists of a blood bag, valves controlling blood flowing direction and dynamic. But this kind of blood pump faded in the history due to its large contact area contributing to serious hemolysis, fragility of its structure and vulnerability to infection. The 2nd generation of blood pump is advection pump. There are 2 kinds of such pump, centrifugal pump and axial-flow pump. Centrifugal pump adjusts vanes on the axis, and these vanes will direct blood into aorta and produce an aortic pressure under the centrifugal effect of high-speed rotating. On the other hand, the vanes of axial-flow pump are also fixed on the axis, but blood is ejected in a slant direction, after the diversion of guide vane, blood mainly flows along the axis. [9]

In a similar way with animate heart pump, artificial heart has one motivating force, bionic pumps use motors to offer a contraction force, and advection pumps take the rotating movements of vanes as a motivation. The former one still has valve structures while the latter one does not.

C. *Pump in the WEC Device*

According to the mechanism of animate heart pump and artificial heart pump, the research team comes up a new pump structure suitable in WEC process.

Compared to the motivating force of animate heart pump and artificial heart pump, the tractive force of WEC device is offer by buoy, which moves up and down with the waves. The pump consists of two parts, a wave energy extraction device and a flow accelerator. As shown in Figure 1, a pump and a buoy form the extraction device. And the upper structure is the flow accelerator. The buoy can move up and down with waves, extracting the motion energy from the waves. When the piston moves upward, the oil in the pump flows into the accelerator through the one-way valve, pushing the magnet steel wave rotate. Then the rotor magnet steel will start moving as a result of magnet coupling. Because of the connecting rod between rotor magnet steel the ejection guide vane will start rotating. As the cylinder diameter diminishes, the velocity of oil flow increases, so does the inner pressure of the accelerator. When the oil flows to the ejection guide vane, the oil will rotate with the vane, the velocity of oil flow will continues increasing as a result of centrifugal effect. Finally, the oil will be ejected out the accelerator through the ejection hole.

When the buoy move downward, the connecting one-way valve will close and the refilling one-way valve will open due to the negative pressure. At the same time, the driving magnet steel vane, the rotor vane and the guide vane will keep rotating, acting the role of flywheel, reserving the motion energy of oil.

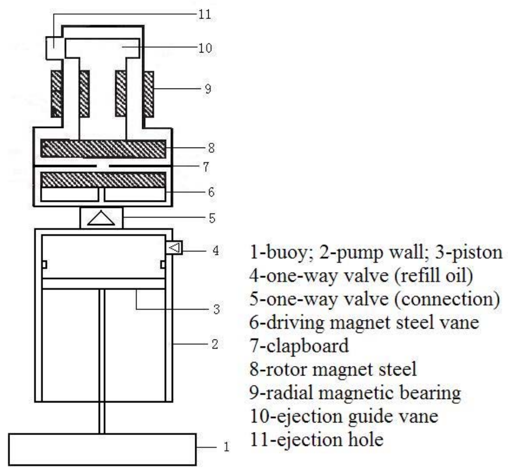

Figure 1. Pump Structure of WEC Device

III. THEORETICAL ANALYSIS

A. *Buoy Shape*

In the process of the extracting, absorbing and transforming ocean energy, a suitable shape of buoy is the key to gaining the maximum absorption rate of wave energy. Considering the complexity of numerical methods, Froude-Krylov hypothesis [10] is used to get the analytical solution of wave force in this paper.

In Froude-Krylov hypothesis, the original wave pressure in the incident wave field is supposed without changing by the existence of submerged object. The unperturbed incident wave pressure force on the floating object is calculated first, then multiplied diffraction coefficient C, which reflects additional quality effect, to modify the former result. (Diffraction coefficient C should be determined through model test.)

According to the Froude-Krylov hypothesis, the expression of wave force acting on floating objects is given as follows:

$$F = CF_k \tag{1}$$

Where F_k is given by $F_k = \rho\overline{V}_0\left(\frac{dv}{dt}\right)_a$, and $\left(\frac{dv}{dt}\right)_a$ is the average full acceleration of unperturbed water with a drainage volume $\overline{V}_0$ when floating object is not existed. For the reason that the accelerations of unperturbed particles in the incident wave with drainage volume $\overline{V}_0$ are different from each other, the wave forces can be obtained through integrating unperturbed incident wave pressure of any point on the submerged structure across the whole surface of the submerged structure. Hence, the horizontal and the vertical component forces on the whole submerged object can be expressed respectively as follows:[11]

$$F_H = C_H \iint_S p_x \, dS \tag{2}$$

$$F_V = C_V \iint_S p_Z \, dS \tag{3}$$

Using Froude—Krylov hypothesis, make surface integral on expression (2) and (3), then choose a proper diffraction coefficient C, and the wave force acting on floating object will be clear.

The wave force on a floating object includes 2 parts: the pressure acting on the bottom of the buoy, whose direction is vertically upward, and the horizontal force applied on the side, whose direction is the same with the wave. Under the action of the combination of the two parts, the buoy will gain a trend to revolve. But the work made by the horizontal force is negligible relative to that of the vertical one, so only the vertical wave force acting on submerged object will be calculated.

To get the most efficient buoy shape, wave forces on several common ideal floating structures (rectangular parallelepiped, vertical cylinder, horizontal cylinder and spheroid) are calculated.

The expressions of the wave forces acting on the floating structures are given as follows:[12]

1) Rectangular parallelepiped:

$$F_V = C_V\frac{\rho g H l_2}{k}\frac{\cosh k(h-d(t))}{\cosh kh}\sin\left(\frac{1}{2}kl_1\right)\cos wt$$

2) Vertical cylinder:

$$F_V = C_V\frac{\rho g\pi H J_1(kR)}{k}\frac{\cosh k(h-d(t))}{\cosh kh}\cos wt \tag{4}$$

3) Horizontal cylinder:

$$F_V = C_V\frac{2\rho g H R A}{chkh}\sin\left(\frac{kL}{2}\right)\cos wt$$

4) Spheroid:

$$F_V = C_V\rho g\pi H(B + C\tanh kh)\cos wt$$

The wave forces acting on buoys of 4 different shapes with same water condition and same drainage volume are drawn in the graph below.

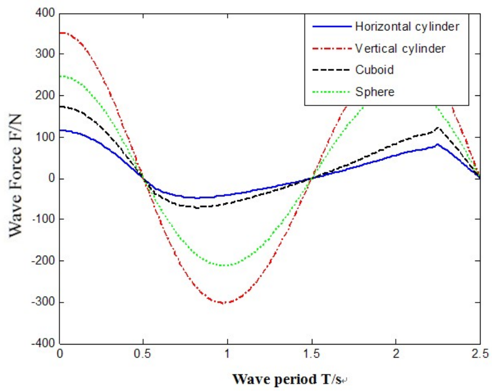

Figure 2. Wave forces on different shapes of buoys

It is clear that a vertical cylinder obtains the largest buoyancy when water condition and drainage volume are the same.

B. Wave Energy Calculation

The wave energy consists of two parts, one is the potential energy caused by the displacement of water surface, and the other is the motion energy of the moving particles in the fluid.

1) Potential Energy

For the reason that potential energy is caused by the wave fluctuation which makes the particles overcome gravity field and leave the equilibrium position, it is as contrasted with the inactive state of fluid. The average potential energy within a wave period of an advancing wave with height H can be expressed as follows: [13]

$$\overline{E_P} = \int_x^{x+\lambda} dE_p = \frac{\rho g}{2\lambda}\int_x^{x+\lambda}(h^2 + 2h\eta + \eta^2)dx \tag{5}$$

Put expression (4) into expression (5) and integrate,

$$(\overline{E_p})_T = \frac{1}{2}\rho g h^2 + \frac{1}{16}\rho g H^2 \lambda$$

While the potential energy within a wave period without fluctuation is given by: $(\overline{E_p})_0 = \frac{1}{2}\rho g h^2$, so the wave potential energy is $(\overline{E_p})_p = (\overline{E_p})_T - (\overline{E_p})_0 = \frac{1}{16}\rho g H^2 \lambda$.

2) Motion Energy

Motion energy generates from the moving water particles, and the fluctuation motion energy within a unit area can be expressed as: $\overline{E_k} = \frac{1}{16}\rho g H^2 \lambda$.

Hence, the complete energy of wave can be calculated by the expression below: [9]

$$E_w = (\overline{E_p})_p + \overline{E_k} = \frac{1}{8}\rho g H^2 \lambda \tag{6}$$

C. Power and Efficiency

The energy absorption rate refers to the ratio of power of the fluctuating system and the energy of the wave.

The complete energy of fluctuating system is given by: [14]

$$E_z = E_{kz} + E_{pz} = \frac{1}{2}[(m + m_z)w^2 + \rho g A_{wp}]{Z_0}^2 \tag{7}$$

So the absorption rate is:

$$\eta = \frac{E_z}{E_w} \tag{8}$$

And the average power in a single wave period can be obtained by:[15]

$$\overline{P_z} = \frac{1}{T}\int_0^T p_z\, dt = \frac{1}{2}F_0 w Z_0 \tag{9}$$

IV. SCHEME

A. Wave Generation Device

In order to simulate the real water environment, the research team selects a track-shape pool as an alternative. According to the micro-amplitude wave theory, the potential function of an advancing wave is given as follows: [16-17]

$$\phi = \frac{gH}{2\omega}\frac{\cos k(d+z)}{\cos kd}\sin(kx - \omega t)$$

Where *x*, z are the horizontal and the vertical coordinate of any particle on the wave. So the vertical speed η and the horizontal speed ξ of particle (*x, z*) can be expressed respectively as follows:

$$\xi = \int_0^t \frac{\partial \phi}{\partial x}|_{x=x_0, z=z_0} dt = -\frac{H}{2}\frac{\cosh k(d+z_0)}{\cosh kd}\sin(kx_0 - \omega t)$$

$$\eta = \int_0^t \frac{\partial \phi}{\partial z}|_{x=x_0, z=z_0} dt = \frac{H}{2}\frac{\sinh k(d+z_0)}{\sinh kd}\cos(kx_0 - \omega t)$$

So the position (*x, z*) of water particle at any time can be expressed as $x=x_0+\xi$, $z=z_0+\eta$. And the moving orbit of water particle can be expressed as :

$$\frac{(x-x_0)^2}{A^2} + \frac{(z-z_0)^2}{B^2} = 1$$

And it is an ellipse. When water depth approaches infinity, d→∞, A→$\frac{H}{2}e^{kx_0}$, B→$\frac{H}{2}e^{kz_0}$, the moving orbit of particle can be expressed as :

$$(x - x_0)^2 + (z - z_0)^2 = \left(\frac{H}{2}e^{kz_0}\right)^2$$

Which is a circle with radius $\frac{H}{2}e^{kz_0}$, the moving radius on water level equals the wave aptitude, and it decreases rapidly when the water depth increases. When z0→L/2, the moving radius is 1/23 of wave aptitude, which is negligible. Hence, the water depth can be regarded as infinity when it is larger than L/2. [18]

According to the analysis above, the research team designed a track-shape pool as below, with the parameter shown in the table.

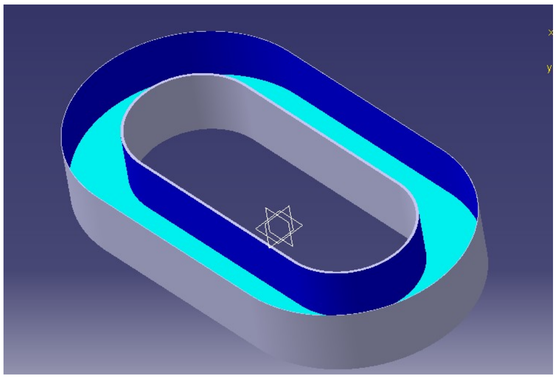

Figure 3. Track-Shape Pool

Parameter	Value
Depth	1.5m
Width	0.8m
Length of Straight Path	3m

Inner radius of curve	0.5m
Outer radius of curve	1.3m

Table 1. Parameters of the Pool

B. *Wave Energy Convertor Design*

The device consists of 4 parts, buoy, pump, pipe system and hydraulic motor. The pump is fixed on a bracket, while buoy is connected with the pump by a piston, and it can move up and down with waves. From the pipe system connected to the pump, oil is transported to the hydraulic motor.

The energy conversion process can be divided into 4 steps. First, the buoy will move up and down with the wave, through which process the motion energy of wave will transmit to the buoy. Then the buoy moving upward will squeeze the oil in the hydraulic pump, at the same time, the motion energy transform into the potential energy of the oil. The oil extruded by the pump will flow into the hydraulic motor, in which process the potential energy of oil transform into the motion energy of the motor. And finally the hydraulic motor drives the generator, which means the motion energy transform into the electricity.

The whole process can be described as follows:

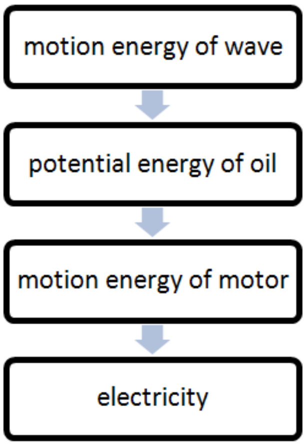

Figure 4. Energy Conversion Process of WEC Device

V. DISCUSSION

From the scheme and the designed pump above, the device still has the single way generation problem, but its stability is improved as the oil only flows in a fixed direction. And the energy utilization rate also increases, for the accelerator will store the motion energy of the oil when the buoy moves downward.

In the accelerator, a magnetic levitation structure is used. On one hand, this structure can reduce mechanical frictional resistance effectively, helping conducting energy more efficiently, on the other hand, the continuity of the device is guaranteed as the magnetic levitation structure is utilized as a flywheel, which overcomes the dead center in the converting process.

A single device of this wave energy convertor can only achieve single travel generation, that is, only when buoy moves upward, the oil is ejected out and the hydraulic motor is motivated. But multiple of such devices can achieve continuous generation.

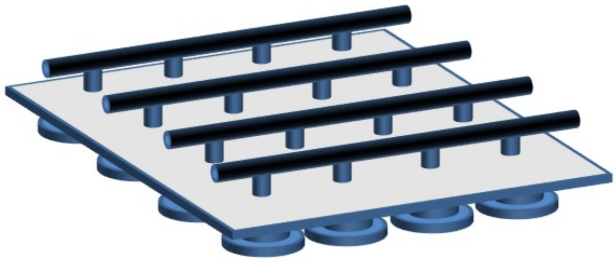

Figure 5. Mass Application of WEC Device

Due to the randomness of waves, if the array of WEC device is large enough, that is, the quantity of such device is adequate, in every time unit of a wave period, there will be at least one buoy moving upward to motivate the hydraulic motor. As a result of mass application of such device, there are different individual device working in each time unit, the hydraulic motor can be regarded as working continuously.

Besides, as a result of randomness of waves and mass application of this device, there will be buoys moving upward and ones moving downward simultaneously in each time unit, that is, the amount of ejected oil equals to that of refilled oil. And due to the negative pressure appeared when buoy moving downward, oil is imbibed into the pump, adding the motivation of hydraulic motor. So the whole system is at a status of dynamic balance, and all the devices form a dynamic circulation.

VI. CONCLUSION

In this paper, the basic theories of animate heart pump and artificial heart pump are introduced, and their similarities and differences are analyzed. And from the mechanism of artificial heart pump, a new pump structure suitable to WEC progress is designed. And correlative parameters of WEC device are calculated. In the investigation of such device, researchers find that the single travel generation problem can be solved by mass application of such devices, and the feasibility of mass application is discussed.

The research in next stage will focus on the simulation and construction of prototype of the WEC device, the optimization of instructive effect and the development of suitable monitor software.

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