IOP Conf. Series: Earth and Environmental Science **108** (2018) 052013 doi:10.1088/1755-1315/108/5/052013

A Wave Power Device with Pendulum Based on Ocean Monitoring Buoy

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Abstract. The ocean monitoring buoy usually exploits solar energy for power supply. In order to improve power supply capacity, this paper proposes a wave power device according to the structure and moving character of buoy. The wave power device composes of pendulum mechanism that converts wave energy into mechanical energy and energy storage mechanism where the mechanical energy is transferred quantitatively to generator. The hydrodynamic equation for the motion of buoy system with generator devise is established based on the potential flow theory, and then the characteristics of pendulum motion and energy conversion properties are analysed. The results of this research show that the proposed wave power devise is able to efficiently and periodically convert wave energy into power, and increasing the stiffness of energy storage spring is benefit for enhancing the power supply capacity of the buoy. This study provides a theory reference for the development of technology on wave power generator for ocean monitoring buoy.

1. Introduction

The ocean monitoring buoy is a kind of platform for monitoring ocean dynamical environment and ecological parameters, and also a key infrastructure of exploring ocean resource. With the range of exploring ocean extending to open and deep ocean, more and more instruments are carried by buoy, and so adequate energy supply is very important for normal working. At present, the energy supply of ocean buoys usually adopts solar cells, which restricts the amount and working performance of carried instrument on the buoy. If the ocean date buoy adopts oil for power generation, the charge for usage and maintenance will increase. As a large storage and widespread resource, the wave energy offers a convenient way for ocean monitoring buoy to realize power self-support.

The early researches about wave energy utilization dates from 1970s [1], then kinds of wave power generation device have sprung up. According to wave energy capture method, the wave power generator device can be mainly classified into three kinds [2, 3, and 4]: oscillating water column device (OWCD), over-topping device (OTD), and wave-activated floater device (WAFD). WAFD are more compact and efficient than OWCD and OTD [5], and is more suitable for near/off shore application. The researchers about wave energy conversion device mainly focus on offshore wave farm which offer electrical energy for the land at present, while there are a little works about wave energy conversion using for offshore equipment especially for ocean monitoring buoy. George et.al fabricates an eel effect device that uses piezoelectric polymers to convert the mechanical flow energy to electrical power [6], this device can produces 1 watts power to recharge batteries of unattended sensor. Seiki proposes an electro active polymer artificial muscle generators that provide on-board power for a navigation buoy [7], and the output power is also small. Serna present a proposal about offshore plants that applies wave energy converter to generate power to produce hydrogen [8]. Chen designs a kind of backward bent duct wave power device with a pentagon buoyancy cabin for beacon lights [9]. In the synthesis, the wave power devices for theses offshore equipment are different due to their diversity in work purpose and structure, and the researches about wave power device which is used for ocean monitoring buoy has not been reported.

Considering the structure and mooring feature of ocean monitoring buoy, this paper proposes a wave power generation device with pendulum capturing wave energy in order to enhance the ability of power self-supply of the buoy. Firstly, the structure and working principle of wave power generator device is explained. Then the dynamical equation for this device is established. At last, the characters of pendulum motion and electricity generating of the device are analyzed. This study proposes a theoretical basis for ocean monitoring buoy using wave energy to producing electrical energy for power self-support.

2. The Structure and Working Principle of Wave Power Device with Pendulum

2.1. Structure of Wave Power Device

The ocean monitoring buoy system including wave power generation device is shown in Fig.1. As shown, the part that on surface and under water is disc-like form, and above the water, the buoy is a slender cylinder-like form. The top of buoy is platform for installing instruments. The buoy is anchored to seabed and its mooring chain adopts catenary form, so the motion of any point on the buoy is synthetic movement of translation of barycenter and rotation around barycenter.

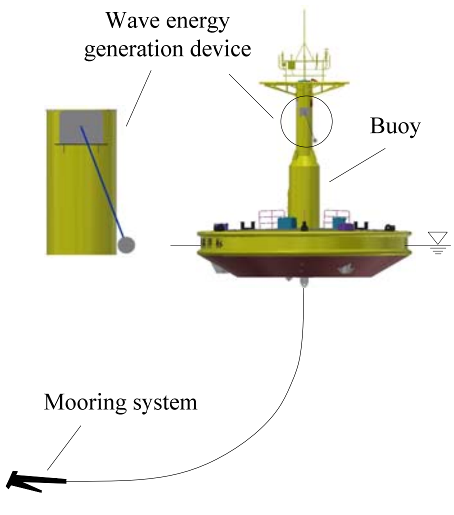

Figure 1. System diagram of ocean monitoring buoy with power device

There are two points worth noting when power generation device is designed, one is that the installing space should be enough in order to avoid crashing against buoy; the other one is that the generation device should keep away from sea level, which prevents corrosion and makes a high survivability of the device. Considering the characteristics of structure and movement about ocean buoy, this paper applies pendulum for wave energy capture. The installing position of power generation device is selected at the upper end of slender cylinder, where the space for pendulum motion is enough and reliability is improved markedly.

2.2. Page Numbers Working Principle of Wave Power Device

The structure composing of power generation device and energy conversion process are shown in Fig.2. This device mainly composes of pendulum, energy storing mechanism and power generator. Because of intermittent and randomness of wave motion, the output power of generation is instability and the energy conversion efficiency is low if the pendulum directly connects to power generator. For this reason, the energy storing mechanism proposed in this paper is placed between pendulum and generator.

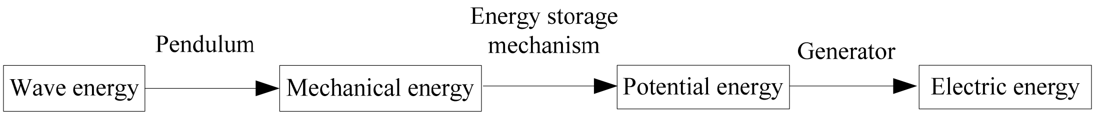

Figure 2. Diagram of structure composing and energy conversion process

The structure diagram of energy storing mechanism is shown in Fig.3, and the working principle of wave energy generator device for ocean monitoring buoy is described below. The wave energy is changed into mechanical energy through pendulum swing under the action of wave movement, and then the mechanical energy is input into energy storing mechanism by input shaft. Because of unidirectional transmission of one-way bearing A and B, the torque only transmits from large gear of first stage to large gear of second stage when input shaft rotates in forward direction, while the small gear of first stage idles; when input shaft rotates in reverse direction, the torque transmits from small gear of first stage, to medium gear, till small gear of second stage, while the large gear of first stage idles. As a result, when the swing motion of pendulum transmits to middle shaft, the teeth-uncompleted gear fixed to middle shaft only rotates in reverse direction. In the process of teeth-uncompleted gear rotating and engaging with rack, the energy storing spring is compressed and the mechanical energy is converted into potential energy of spring. As soon as the missing teeth parts of teeth-uncompleted gear rotate into meshing area with rack, the teeth-uncompleted gear is out of contact with rack, resulting in the potential energy stored in spring being releasing and driving output gear rotating. The rotation of output gear is transmitted to output shaft, and then the energy is imported quantitatively into generator, finishing a cycle of energy conversion.

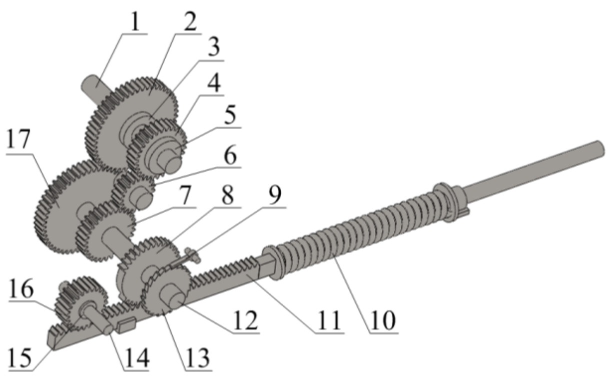

Figure 3. Diagram of energy storing mechanism model1 input shaft; 2 large gear of first stage; 3 one-way bearing A; 4 small gear of first stage; 5 one-way bearing B; 6 medium gear; 7 small gear of second stage; 8 teeth-uncompleted gear; 9 pawl; 10 energy storing spring; 11 rack; 12 middle shaft; 13 ratchet; 14 output shaft; 15 one-way bearing C; 16 output gear; 17 large gear of second stage.

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3. Modelling and simulation of the wave power device

3.1. Dynamical Modelling

As shown in Fig.4, the global coordinate system *OXY* is established on sea surface, and the direction of *x*-axis is parallel to that of incident wave, and the *y*-axis is perpendicular to sea surface. The local coordinate system with zero point coinciding with the centroid of buoy is parallel to coordinate *OXY*. This paper applies potential flow theory to establish the hydrodynamic equations about wave power generator device. Here, it assumes that the incident wave is two-dimension and wave direction is perpendicular to the axis of input shaft.

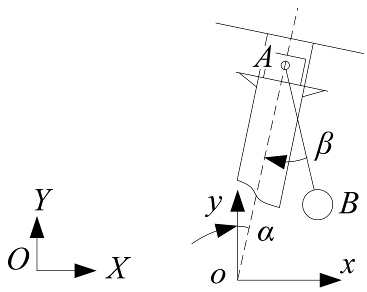

Figure 4. Diagram of pendulum motion analyses

In Fig.4, the angle between vertical axis of buoy and y-axis is denoted by α; the angle between vertical axis of buoy and the spindle axis of pendulum, namely point A, is denoted by β; the length of swing link of pendulum is represented by l; the distance between point o and point A is represented by L; the horizontal and vertical position of buoy in global coordinate system is denoted by x and y respectively; the independent variables can be represented by r=(x,y,α,β)T. Then the dynamical equations for buoy with wave power generator is expressed as

$$(\boldsymbol{M} + \Delta \boldsymbol{m})\ddot{\boldsymbol{r}} = \boldsymbol{F}_w - \boldsymbol{F}_i - \boldsymbol{F}_g - \boldsymbol{F}_c - \boldsymbol{F}_{es} \tag{1}$$

Where, $\Delta \boldsymbol{m}$ denotes additional mass matrix; F_w is wave action force; Fi is anchor action force; and the expression for these three items can be referred to literature [10]. M is the system mass matrix, and its expression is

$$\boldsymbol{M} = \begin{pmatrix} m_b + m_p & 0 & m_p[L\cos\alpha - l\cos(\alpha+\beta)] & -m_p l\cos(\alpha+\beta) \\ 0 & m_b + m_p & -m_p[L\sin\alpha - l\sin(\alpha+\beta)] & m_p l\sin(\alpha+\beta) \\ m_p[L\cos\alpha - l\cos(\alpha+\beta)] & -m_p[L\sin\alpha - l\sin(\alpha+\beta)] & I_b + I_p + m_p(L^2+l^2) - 2m_p Ll\cos\beta & I_p + m_p l^2 - m_p Ll\cos\beta \\ -m_p l\cos(\alpha+\beta) & m_p l\sin(\alpha+\beta) & I_p + m_p l^2 - m_p Ll\cos\beta & I_p + m_p l^2 \end{pmatrix} \tag{2}$$

In equation (2), m_b denotes buoy mass; I_b is buoy moment of inertia about horizontal axis; m_p denotes pendulum mass; I_p is moment of inertia for pendulum rotating around spindle.

F_g denotes gravity, and the expression is

$$\boldsymbol{F}_g = \begin{pmatrix} 0 \\ 0 \\ m_p g[L\sin\alpha - l\sin(\alpha+\beta)] \\ m_p gl\sin(\alpha+\beta) \end{pmatrix} \tag{3}$$

$\boldsymbol{F}_c$ is Carioles force, and writes as:

$$\boldsymbol{F}_c = \begin{pmatrix} -m_p[l(\dot{\alpha}+\dot{\beta})^2\sin(\alpha+\beta) - L\dot{\alpha}^2\sin\alpha] \\ -m_p[l(\dot{\alpha}+\dot{\beta})^2\cos(\alpha+\beta) - L\dot{\alpha}^2\cos\alpha] \\ -m_pLl[(\dot{\alpha}+\dot{\beta})^2 - \dot{\alpha}^2]\sin\beta \\ m_pLl\dot{\alpha}^2\sin\beta \end{pmatrix} \tag{4}$$

$\boldsymbol{F}_{es}$ denotes the load of energy storing mechanism, and the expression is

$$\boldsymbol{F}_{es} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ kr_s^2\beta \end{pmatrix} \tag{5}$$

In equation (5), k is stiffness of energy storing mechanism; and rs is radius of reference circle of teeth-uncompleted gear.

Because of the mass and moment of inertia of wave power generation device is much smaller than that of buoy, the mass and moment of inertia of this device has little effect on buoy motion. Then simplifying equation (1), the relative motion between pendulum and buoy can be written as

$$\begin{gathered}(I_p + m_pl^2)\ddot{\beta} + C\dot{\beta} + m_pgl\sin(\alpha+\beta) + m_pLl\dot{\alpha}^2\sin\beta + kr_s^2\beta = \\ m_pl\cos(\alpha+\beta)\ddot{x} - m_pl\sin(\alpha+\beta)\ddot{y} - (I_p + m_pl^2 - m_pLl\cos\beta)\ddot{\alpha}\end{gathered} \tag{6}$$

When energy storing spring is compressed in maximum value, the energy is released and drive generator to generate electricity, and the electrodynamics equation for generator is [10]:

$$T_m \square c_e\dot{\varphi} \tag{7}$$

Where, T_m is drive torque of the input shaft of generator, c_e is damping coefficient related to generator structure, and φ is rotation angle of generator. The value of T_m is equivalent to potential energy of energy storing spring, and its expression is

$$T_m = k(\Delta x - r\varphi)r \tag{8}$$

Where, Δx is the maximum of spring compression; r is radius of reference circle of output gear.

The mechanical power that is inputted into generator is

$$P_m = T_m\dot{\varphi} \tag{9}$$

3.2. Simulation and Analyses

In this section, the simulation results of the buoy with wave power generator device are presented. The diameter of the buoy is 10 m, and the height of pendulum shaft relative to ocean surface is 8 m. The motion response of the buoy in regular wave is referenced literature [11], and in the condition of wave excitation with amplitude of 0.5 m and period of 5 s, the expressions for describing buoy movement are:

$$x = 0.76\cos(0.46t) \tag{10}$$

$$y = 0.5\sin(0.46t) \tag{11}$$

$$\alpha = 7\cos(0.46t) \tag{12}$$

The values of each parameter for simulation are listed in Table 1.

Table 1. Three Scheme comparing.

Parameter	l	L	Δx	r	c_e	m_p	I_p	k
Value	1.5	6	0.1	0.03	0.42	30	46	1000/2000
Unit	m	m	m	m	Ns/rad	kg	kg•m^2	N/m

According to equations (6), (10), (11) and (12), the motion characteristics of include angle between pendulum and buoy, β, are shown in Fig.5 and Fig.6. It can be seen from Fig.5, when spring stiffness, k, is set to 1000 N/m, the variation trend of rotation angle of pendulum, β, is similar to sinusoid. When k is 2000 N/m, the variation period of pendulum angel changes little, while β slightly increases. According to Fig.6, the angular velocity of pendulum increases with k enlarging, and the fluctuation of angular velocity aggravates over time. This variation about angular velocity may be relate to the revolute pair that connects pendulum and buoy, and the revolute pair is under actuated and presents highly nonlinear characteristics.

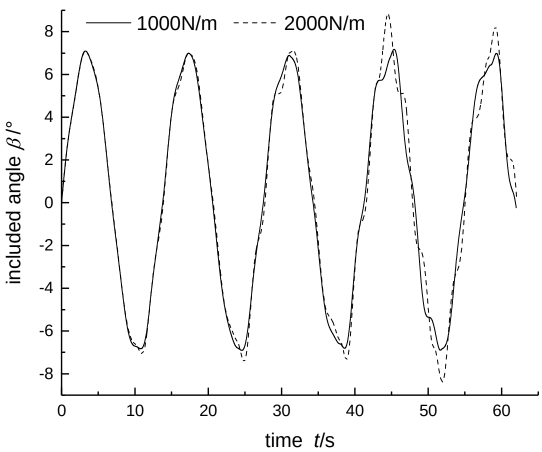

Figure 5. Variations of include angle between pendulum and buoy with time

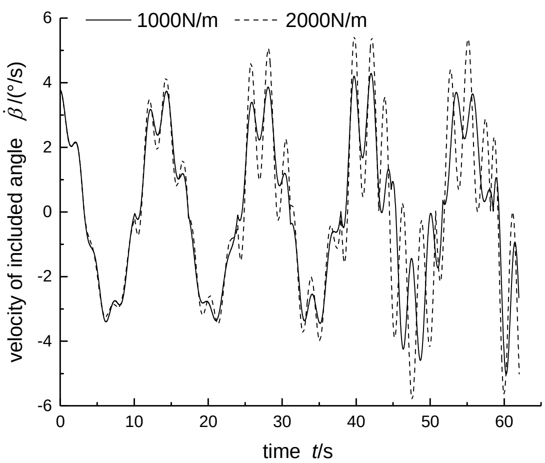

Figure 6. Variations of include angle velocity between pendulum and buoy with time

The variation of spring force with time is shown in Fig.7, and it can be seen that the force almost linearly increases. Once the spring is stretched to the maximum elongation length, the spring force rapidly decreases from maximum to zero because the teeth-uncompleted gear loses contact with rack. It also shows that the energy storing progress is about 1 min, and the release progress is only 2 s. This mechanism has the ability of slow storing wave energy and fast releasing the energy, which particularly applies for accumulating and converting the slow varying wave energy. Moreover, the released energy, i.e., the energy that is input into generator is a constant value for each cycle, which is convenient for designing electrical system.

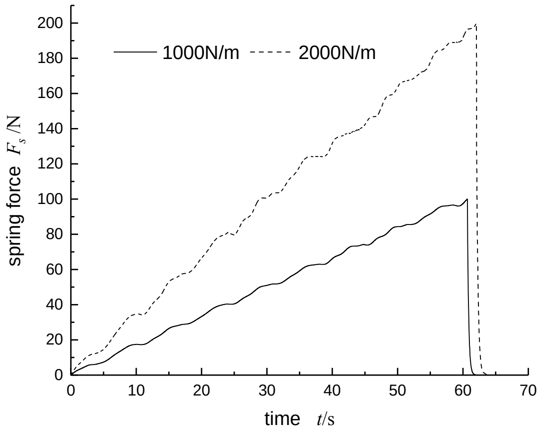

Figure 7. Force variations of energy storing spring with time

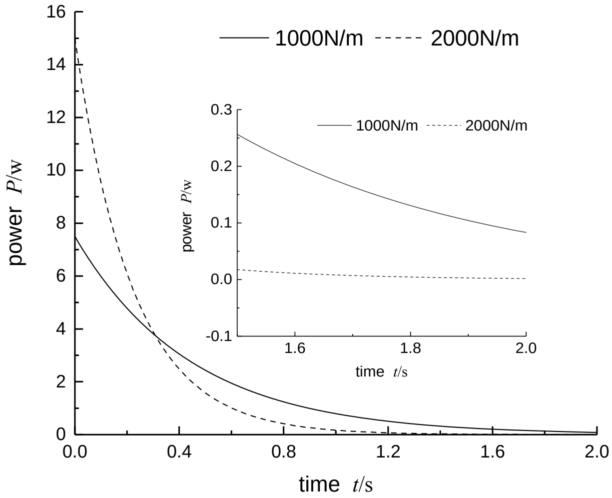

Figure 8. Variations of generator input power with time

After the spring energy being input into generator, the wave energy is converted into electric energy at last. Based on equations (7)-(9), the input power of generator can be obtained, and the cure is shown in Fig.8. It can be seen that the input power decreased from the maximum to the minimum in 2 second, which indicates the elastic potential energy is efficiently and rapidly converted into electrical energy. Increasing spring stiffness, the input power enlarges and is beneficial for electrical energy storage. The peak power of ocean monitoring buoy applied in China Sea usually is 18 W, and the maximum input power of generator is 15 W when spring stiffness is 2000 N/m, which reveals that the proposed wave energy generator efficiently supplements power for the buoy in the case of night-time and adverse weather.

4. Conclusion

Because of the buoy adopts catenary mooring system, the energy involved in waggle movement of buoy is captured by use of pendulum. The pendulum is positioned above the ocean surface and has high reliability. The energy storing mechanism unidirectionally compresses spring to convert kinetic energy of pendulum into potential energy, and simplifies the electrical control system. The kinetic equation about the wave energy conversion device is established. The results show that the device is able to slowly store wave energy and rapidly release the energy for converting into electrical energy. The electrical energy can be enlarged by increasing the stiffness of energy storing spring. This work lays theoretical foundation for subsequent application of prosed wave energy conversion device.

Acknowledgments

This work was financially supported by the Youth Foundation of Shandong Academy of Sciences (2015QN026), the National Natural Science Foundation of China (61405106) and the National Key Research and Development Program of China (2017YFC1403302) fund.

References

[1] Salter S H 1974 Wave power Nature 249: 720-724.
[2] Drew B, Plummer A R and Sahinkaya M N 2009 A review of wave energy converter technology Proc. IMechE Part A: J. Power and Energy 223(8): 887-902.
[3] Falcão A F D O 2010 Wave energy utilization: A review of the technologies Renew Sustain Energy Rev 14(3): 899-918.
[4] Ruud K and Frank N 2014 IRENA Technology Briefs on Wave Energy (Masdar City: IRENA

Headquarters)
[5] French M J 2006 On the difficulty of inventing an economical sea wave energy converter: a personal view Proc. IMechE Part M: J. Eng. Marit. Environ. 220(220):149-155.
[6] Taylor G W, Burns J R, Kammann S A, Powers W B and Welsh T R 2002 The Energy Harvesting Eel: a small subsurface ocean/river power generator IEEE J. Oceanic Eng. 26(4): 539-547.
[7] Chiba S, Waki M, Kornbluh R and Pelrine R 2009 Innovative wave power generation system using electroactive polymer artificial muscles Proc. Int. Conf. on Oceans (Bremen) (New York: USA IEEE) p 1-3.
[8] Serna A and Tadeo F 2014 Offshore hydrogen production from wave energy Int. J. Hydrog. Energy 39(3): 1549-1557.
[9] Chen T X, Wu B J and Li M 2017 Flume experiment study on capture width ratio of a new backward bent duct buoy with a pentagon buoyancy cabin Ocean Eng.141:12-17.
[10] Beatty S J, Buckham B J and Wild P 2007 Modeling, design and testing of a two-body heaving wave energy converter Int. Conf. on Offshore and Polar (Lisbon) (California: USA ISOPE) p 380-387.
[11] Leonard J W, Idris K and Yim S C S 2000 Large angular motions of tethered surface buoys Ocean Eng. 27(12): 1345-1371.