Research on the Buoy-rolling Type Power Generation Device Driven by Wave Energy

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Abstract. Marine energy is inexhaustible form of energy. The utilization of wave energy depends on a certain number of energy conversion devices, but most of the aforementioned devices require a high level of the coastal environment and sea conditions, so it is difficult to popularize them on a large scale. In view of this research situation, this paper introduces a wave-driven buoy rolling power device, which has compact structure and convenient installation. The device is distinguished by superior structural strength and low energy transmission loss. Built on the analysis of the working principle of the device, the power calculation is performed and the strength of the key components is checked by the finite element method. Through simulation analysis, the feasibility of the device design is verified.

1. Introduction
With the development of economy and society, and people’s improving living standards, the demand for energy is likewise increasing. However, the traditional non-renewable resources such as oil and coal are shrinking. Energy problems increasingly become a bottleneck restricting the development of human society. For a possible outbreak of the energy crisis and energy battle, countries around the world are equally actively seeking new sources in the current energy situation. Currently the use of the extra energy has gradually become a worldwide topic. The world is paying increasing research and efforts, especially in the use of renewable energy [1-3]. Many countries according to their own environment and climate factors, such as wind energy, solar energy, and oceanic energy of research and utilization of renewable energy have made breakthrough progress [4-5]. Innovative energy development in China has a natural advantage because of China’s vast territory and distinct seasons. But at present, China is still in its infancy stage in the study of modern energy, with low energy utilization ratios, few types of applied equipment, and needed-reinforcing research and innovations.

Wave energy is a principal form of marine renewable energy. It is kept in the form of kinetic energy and potential energy in sea water, and can be transformed into mechanical energy or intermediate medium internal energy by energy conversion mechanism. Depending on different motion modes and the way of energy conversion, the current commonly-used types of wave energy power generation device mainly include the oscillating water column type, type of pushed oscillation, nodding duck type, contraction ramp type, float type and wave raft type [6-10]. The size of the wave energy depends on the size of the wave height and period, wide distribution, energy flow density is elevated, but wave energy is also one of the most unstable energy in the ocean. The energy conversion efficiency of wave energy
power generation device is generally not elevated, and to build coastal terrain has stringent requirements in the previous. Therefore, the outcome has certain limitations in the application. This paper introduces a rolling buoy power generation device driven by wave energy. It may change the suspension height device in the water by adjusting the volume of buoy, which can make the roller centre always located at the surface of the waves, and it collect wave energy by flushing action of waves on the blade. The reversing mechanism is designed inside the roller, and it can turn the before-and-after direction of flushing action into the same direction as the principal axis of rotation. This device has advantages including a wide range of application, high conversion efficiency, etc.

2. Wave energy movement and load characteristic analysis methods

To estimate buoy rolling type power generation device under the size of the wave energy preliminary and analyses the impact of each factor in the energy relationship, it is assumed that the wave height and wave period have had the determinate form and changed range, and Ariy wave theory is chosen to be analyzed.

In Airy wave theory, to simplify the calculation, the fluid is usually assumed as irrational incompressible ideal fluid. Considered by the hydrodynamics, for the irrational flow field, there must be a spatial distribution function (potential function). Its spatial position on the flow field is uniquely determined, thus, the gradient of the potential function can be applied to represent the situation of the flow field velocity distribution [1][12].

For x-z plane along the x forward movement of the two-dimensional wave, the potential function $\Phi$ is a function of spatial point $(x, z)$, which can be obtained by the Laplace equation:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \quad (1)$$

The linear wave theory shows that it meets the following boundary conditions:

1) Free surface conditions

On the surface wave, fluid particle cannot pass through the wave surface; its kinematic conditions can be obtained by substantial derivative:

$$\frac{\partial \eta}{\partial t} + \frac{\partial \Phi}{\partial x} \frac{\partial \eta}{\partial x} + \frac{\partial \Phi}{\partial z} \frac{\partial \eta}{\partial z} = 0 \quad (z = \eta(x, t)) \quad (2)$$

At the same time, on the free surface, water pressure should be equal to atmospheric pressure $p$ and atmospheric pressure $p_0$, available for its dynamic conditions:

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2} \left( \frac{\partial \Phi}{\partial x} \right)^2 + \frac{\partial \Phi}{\partial z} + g \eta = 0 \quad (3)$$

2) Bottom conditions

For the linear waves, the wave height is much smaller than the wavelength. The ratio is now set for a small parameter $\varepsilon$, to expand the velocity potential $\Phi$ and waveform $\eta$ into the parameter $\varepsilon$ of series solutions of each order by the perturbation expansion method, namely:

$$\left\{ \begin{array}{l}
\Phi = \sum_{n=1}^{\infty} \varepsilon^n \phi_n \\
\eta = \sum_{n=1}^{\infty} \varepsilon^n \eta_n
\end{array} \right. \quad (4)$$

The equation (4) is brought into equation (2), (3) respectively, and the first-order amount $\varepsilon$ has to be kept, the free surface condition of the linearization can be gained:

$$\left\{ \begin{array}{l}
\frac{\partial \eta}{\partial t} + \frac{\partial \Phi}{\partial z} = 0 \\
\frac{\partial \eta}{\partial x} + \frac{\partial \Phi}{\partial x} = 0 \\
\frac{\partial \Phi}{\partial t} + \frac{1}{2} \left( \frac{\partial \Phi}{\partial x} \right)^2 + \frac{\partial \Phi}{\partial z} + g \eta = 0
\end{array} \right. \quad (5)$$
In the equation (5), two simultaneous Pell equations and deleted $\eta$, can be obtained:

$$\frac{\partial^2 \Phi}{\partial t^2} + g \frac{\partial \Phi}{\partial z} = 0 \quad (z = h) \quad (6)$$

Introduce characteristic wave cycle conditions, set the speed of the wave propagation along the axis $x$ as $c$, with variable $a = x - ct$ representing the periodic of time and space collectively. The velocity potential $\Phi$ is transformed into the following form by using the separation variable method:

$$\Phi = T(x - ct)Z(z) \quad (7)$$

The equation (7) is brought into the Laplace equation, and the following can be obtained:

$$T^*(x - ct)Z(z) + T(x - ct)Z^*(z) = 0 \quad (8)$$

Make $\frac{Z^*(z)}{Z(z)} = k^2$, two differential equations can be obtained:

$$Z^*(z) - k^2Z(z) = 0, T^*(x - ct) + k^2T(x - ct) = 0 \quad (9)$$

Solutions of the equation (9), obtaining the general solution are:

$$Z(z) = A_1 \cosh(kz) + A_2 \sinh(kz) \quad , T(x - ct) = A_3 \cos[k(x - ct)] + A_4 \sin[k(x - ct)] \quad (10)$$

The equation (7), (10) are brought into equation (3), and can obtain: $A_3k = 0$, So $A_4 = 0$

The velocity potential:

$$\Phi = A_1 \cosh(kz) \{ A_3 \cos[k(x - ct)] + A_4 \sin[k(x - ct)] \} \quad (11)$$

The equation (14) are brought into waveform function $\eta = -\frac{1}{g} \frac{\partial \Phi}{\partial t}$ (5), and can obtain:

$$\eta = -\frac{A_1}{g} \cosh(kz) \{ A_3 k \cos[k(x - ct)] - A_4 k \sin[k(x - ct)] \} \quad (12)$$

When $x = 0, z = h$, if it taken $-ka = \frac{\pi}{2}$, $\eta = 0$, then this time the waveform is a cosine wave node, and the constant is $-\frac{A_1 \cosh(kh)}{g}$, it is substituted into the above equation: $A_3k = 0$, So $A_4 = 0$.

Then the velocity potential is transformed into:

$$\Phi = A_1 A_4 \cosh(kz) \sin[k(x - ct)] \quad (13)$$

The wave function is

$$\eta = \frac{A_1 A_4 k}{g} \cosh(kz) \cos[k(x - ct)] \quad (14)$$

When $t = 0$, take initial $x = 0, z = h$ and have $\eta = \frac{H}{2}$, substituted into (14), the following can be obtained:

$$A_1 A_4 = \frac{gH}{2k \cosh(kh)} \quad (15)$$

The expression is substituted into the equation (13) and (14), the followings can be obtained as speed and wave function:

$$\Phi = \frac{gH}{2k \cosh(kh)} \cosh(kz) \sin[k(x - ct)] \quad (16)$$
\[ \eta = \frac{H}{2} \frac{\cosh(kz)}{\cosh(kh)} \cos[k(x - ct)] \]  

(17)

From the equation (17), the waveform function at the surface of the water is:

\[ \eta = \frac{H}{2} \cos[k(x - ct)] = \frac{H}{2} \cos(kct - kx) \]  

(18)

With the former equation, it is gained that \( \omega = kc \). So, \( k = \frac{\omega}{c} = \frac{2\pi}{Tc} = \frac{2\pi}{L} \).

Wave horizontal motion velocity and acceleration can be calculated by the velocity potential function respectively:

\[ u_x = \frac{\partial \Phi}{\partial x} = \frac{\pi H}{T} \frac{\cosh kz}{\sinh kh} \cos(kx - \omega t) \]  

(19)

\[ a_x = \frac{\partial u_x}{\partial t} = \frac{2\pi^2 H}{T^2} \frac{\cosh kz}{\sinh kh} \sin(kx - \omega t) \]  

(20)

It is clear from the above two equations, the wave speed and acceleration of water points in a horizontal direction are related to the wave height, period and water depth as well as the phase angle and other factors. For the convenience of analysis, take the phase angle \( \theta = kx - \omega t \). The influence of the level of various factors on the wave speed are as shown in ‘figure.1’ and ‘figure.2’.

![Figure 1. Phase angle and water depth of the impact of wave horizontal velocity](image1)

![Figure 2. Phase angle and water depth of the impact of wave horizontal acceleration](image2)

As can be seen from the Figure1 and 2, the maximum height position in the water, namely static wave, the horizontal velocity and acceleration of the wave of the most dramatic changes are happened near the surface of the water. As showed in the above, the level of the wave velocity and acceleration is along with the increasing wave height, decreasing with the increase of the cycle. When the average wave height is within the range of 0.5-1.5 m, the wave period of the influence of wave motion is very obvious. When the cycle is greater than a certain value, the wave of horizontal acceleration is gradually close to zero. Then the wave motion in the horizontal direction can be approximated as uniform motion.

3. Power generation device design and discussion of results

3.1 Power generation devices are working principle and structure design

The floating drum rolling power generation device is mainly composed of three parts: absorbing mechanism, electromechanical conversion mechanism and electric energy. It includes a microwave absorbing mechanism in the form of a drum. The blade is driven directly by waves to rotate. The device structure is shown in ‘figure 3’.
As shown in ‘figure 3’ to make the roller centre located at the surface of water, the device changes the suspension height in the water by adjusting the volume of buoy. When the wave crest arrives, the wave drives the roller rotation by pushing the upper blade and the reversing mechanism is designed inside the roller. The device can absorb the front and rear rollers to generate wave energy, improve the effective wave energy density and the energy conversion efficiency.

3.2 Strength checks installations of key components
Roller blades to withstand the maximum impact load at different wave factor conditions are shown in Table.1.

| Height | T=6 s | T=8 s | T=10 s | T=12 s |
|--------|-------|-------|--------|--------|
| H=0.3 m | 140.7 | 79.1 | 50.6 | 35.2 |
| H=0.5 m | 385.8 | 217 | 138.9 | 96.4 |
| H=0.9 m | 1239.2 | 697 | 446.1 | 309.8 |
| H=1.2 m | 2197.0 | 1235.8 | 790.9 | 549.3 |
| H=1.5 m | 3427.3 | 1927.8 | 1233.8 | 856.8 |

From Table 1, it can be seen, the roller blade withstand the maximum impact load is related to the wave period and wave height factors. Its value decreases along with the increase of the wave period. To verify the strength of the roller blades, the wave period $T = 10s$, wave height $H = 1.5m$ of a given parameter sea conditions are to be checked, with the results shown in ‘figure 4’ and ‘figure 5’.

From ‘figure 4’, it is found that the maximum stress value of blades, which comes into contact with the roller, appears in an installation groove position. Under the condition of the selected conditions, the maximum stress value is 5 MPa, far less than the yield strength of the material, complying with the requirements. In ‘figure 5’, the maximum deformation of the blade appears at the end position. The
maximum deformation is about 0.048 mm, and the relative dimensions of the blade are very small, meeting the design requirements.

4. Conclusions
This paper proposes a use of wave energy power generation buoy rolling type power generation device. With the analyses, the following conclusions are shown:

(1) The device is with low dependence of the coast terrain and sea state condition, wide adaptation, simple installation and convenience.
(2) The device can absorb the front and back wave energy which passes over through the internal reversing mechanism, with high energy utilization ratio.
(3) The energy transferring within the device adopts gear drive, featuring a smaller energy loss, and high mechanical transmission efficiency.

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References
[1] Shi, H.D., Cao, F.F., Liu, Z., Qu, N. (2010) Theoretical study on the power take-off estimation of heaving buoy wave energy converter. Renewable Energy, Vol. 865: 441-448.
[2] Mendonca, H., Martinez, S. (2015) A Resistance Emulation Approach to Optimize the Wave Energy Harvesting for a Direct Drive Point Absorber. IEEE Transactions on Sustainable Energy. Vol. 24:3-11.
[3] Falcao, A., Henriques, J. (2015) Oscillating-water-column wave energy converters and air turbines: A review. Renewable Energy, 07:1391-1424.
[4] Wang, X.F., Niu, S.M., Yin, Y.J., et al. (2015) Triboelectric Nanogenerator Based on Fully Enclosed Rolling Spherical Structure for Harvesting Low-Frequency Water Wave Energy. Advanced Energy Materials, Vol. 23:132-136.
[5] Moretti, G., Fontana, M., Vertechy, R. (2015) Model-based design and optimization of a dielectric elastomer power take-off for oscillating wave surge energy converters. Meccanica, No.11 :2797-2813.
[6] Xi, M.M., Wu, Y.W., Tian, W.X., et al. (2015) the influence of ocean conditions on thermal-hydraulic characteristics of a passive residual heat removal system. Progress in Nuclear Energy, Vol. 85:576-587.
[7] Ceballos, S., Rea, J., Robles, E., et al. (2015) Control strategies for combining local energy storage with wells turbine oscillating water column devices. Renewable Energy, Vol. 30:1097-1109.
[8] Sproul, A., Weise, N. (2015) Analysis of a Wave Front Parallel WEC Prototype. IEEE Transactions on Sustainable Energy, No.4:1183-1189.
[9] Mendoza, E., Chavez, X., Carlos, A. (2015) Hydrodynamic behavior of a new wave energy converter: The Blow-Jet. Ocean Engineering, Vol.106:252-260.
[10] Arthur, P., Jens, P.K., Tommy, L. (2012) Design Specifications for the Hanstholm Weptos Wave Energy Converter. Energies, No.5:1001-1017.
[11] Veen, D., Gourlay, T.(2012) A combined strip theory and Smoothed Particle Hydro-dynamics approach for estimating slamming loads on a ship in head seas. Ocean Engineering, Vol.43, No. 4:64-71.
[12] Molin, B., Ferziger, J. h. (2003) Hydrodynamique des Structures Offshore. Applied Mechanics Reviews, Vol.56, No. 2:29-35.