Research on the Sea Surface Vertical Spar Buoy Power Installation Driving by Double-Sided Rack

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Abstract. Based on the analysis of engineering examples of current domestics and foreign wave energy conversion device and wave energy power generation principle, in this paper, a buoy wave power device was proposed and the principles were explored. The device mainly uses mechanical transmission devices for wave energy conversion to mechanical power. In the paper, the overall design of the buoy wave power device was carried, and directional reversing gearbox was developed, it can convert the vertical reciprocating movement of the wave to unidirectional rotation. According to Froude-Krylov hypothesis method, the paper analyses the perpendicular wave force of the vertical cylinder and the action of the ups and downs of displacement under the force. On the basis of the above work, the overall design of the device was completed.

1. Introduction

Energy is an essential material basis of human survival and development. At the same time, energy consumption also contributes to the deterioration of the ecological environment. It seriously threatens the sustainable development of human society. Now the growing shortage of fossil energy has gradually become a worldwide problem. Ocean accounts for 71% of the earth's surface. Therefore, the wide ocean contains enormous energy. If marine renewable energy can be developed and utilized efficiently, it will ease the pressure on energy supplies and contribute to the sustainable development of the society. Energy problem becomes the most concerned problem. In order to solve the problem of human demand for energy, the countries have begun to study the wind energy, solar energy, ocean energy and other renewable energy [1].

"Nodding duck" wave energy conversion device is a new type of wave energy conversion device proposed by Salter in 1974, because its shape resembles a duck named [2] The oscillating water column wave power device is one of the more mature devices of domestic and overseas. Japan in such type of wave energy devices progresses rapidly, becoming the first country that applied this device to the commerce successfully, providing electricity for the maritime navigation device [3]. Several marine power generation equipment above is expensive and the efficiency is not high. So this paper designs a power generating device using floating wave as power sources [4].

2. The typical wave theory and Froude- Krylov hypothesis methods

2.1. Typical wave theories
For linear wave theory, because the assumption of linearity is set up under the condition of small amplitude (relative to the wavelength), and therefore the linear wave theory, also known as a slight wave theory, or small amplitude gravity waves [5]. For the nonlinear wave theory, including finite amplitude wave theory advanced by Stokes (1874) [6], also known as Stokes wave theory [7]; The elliptical cosine wave theory advanced by Korteweg and De Vries (1895) [8] and solitary wave theory proposed by Rusell (1834) [9].

2.2. Froude-Krylov hypothesis method
In this paper, the Froude-Krylov hypothesis method was used to calculate the effect on the buoy. This assumption method is widely used in engineering practice. This method is an approximate method, but it is simple, and based on the model test of a certain degree of precision.

The so-called Froude-Krylov hypothesis method (F-K, for short) [10] assumes that in the case of the presence in the floating body or submerged body, the wave pressure of the incident wave does not change from its arbitrary point. Therefore, the wave force can be calculated on the floating body acted by wave pressure in the absence of submerged body (force F-K, for short). And then it will be corrected through multiplied force F-K by the diffraction coefficient $C$. The diffraction coefficient means virtual mass effect. It can be obtained by conducted such models test.

Using F-K hypothesis method, the wave force that submerged body is suffered can be expressed as:

$$ F = C F_k $$  \hspace{1cm} (1)

In equation (1), $C$ is the diffraction coefficient, $F_k = \rho V_0 (dv/dt)$, it is represented by $F_k (dv/dt)$. Refers to the initial acceleration of the water body when buoy to submerge within the volume of the water on the condition that there are no floating bodies. And then the wave force can be obtained acting on the buoy by calculating the integral for water area that is submerged by the buoy. Wave force can be divided into horizontal force and vertical force. The expression is:

$$ F_h = C_h \int_S P_d S $$  \hspace{1cm} (2)

$$ F_v = C_v \int_S P_v dS $$  \hspace{1cm} (3)

In the above equation, $P_h$ is wave forces of the undisturbed incident wave in the horizontal direction at any point on the surface of the submerged body. $P_v$ is wave forces of the undisturbed incident wave in the vertical direction at any point of the surface of the submerged body. $S$ is the total surface areas of water submerged body; $C_h$ is level diffraction coefficient; $C_v$ is vertical diffraction coefficient.

When the incident wave is linear wave, the wave pressure in the surface of the buoy acted by undisturbed incident waves can be expressed as:

$$ p = \frac{\rho g h}{2} \cos(\frac{k(z+h)}{\cos(h)}) \left\{ \cos(kx - \omega t) + i[\sin(kx - \omega t)] \right\} $$  \hspace{1cm} (4)

In the equation (4), $p$ is wave pressure in any point (N/m$^2$); $\rho$ is the density of the sea waters ($1.025 \times 10^3$ kg/m$^3$); $G$ is the acceleration of gravity; $H$ is height of the wave; $h$ is depth of sea water; $k$ is wave number, satisfied with $k=2\pi/\lambda$; $z$ is undulating displacement of the floating body; $\cosh(x)$ is hyperbolic cosine; $\omega$ is circular frequency of wave (rad$^{-1}$).

The wave force of the buoy was calculated based on the $F-K$ hypothetical method. Substituting the equation (4) into equation (2) and (3), and then integrating, multiplied by the appropriate diffraction coefficient, the wave force of the buoy can be easily obtained.

The wave force acting on the buoy includes the vertical waves force and horizontal wave force two parts. Under the function of the force, buoy moves up and down along the direction of wave movement. In the wave power generation device, buoy motion along the wave is limited by an anchor. The device is mainly used for the vertical waves force to drive the motion of a buoy, namely the effective movement.
towards the buoy is the vertical movement. So the effects of the horizontal wave force can be ignored, only calculating the vertical wave force. Next, let us calculate the vertical wave power of the buoy.

2.3. The vertical wave forces on a vertical spar buoy

It is provided with a spar buoy in h meters of the sea. The basic size of the radius is $R$, the height is $L$, the location of a draft $D$, as showed in figure 1.

![Figure 1. Schematic diagram of vertical spar buoy](image)

Using a cylindrical coordinates system $(r, \theta, z)$ integration method, the cylindrical coordinates of the bottom of the spar buoy at any point is $x = r \cos \theta$, $y = r \sin \theta$, $z = z$. Making, $\theta = \pi / 2 + \phi$, the pressure of the incident wave on the cylindrical surface at any point is:

$$p = \frac{\rho g H}{2} \frac{\cosh[k(z + h)]}{\cos(kh)} \cos(kr \cos \theta - \omega t)$$

$$= \frac{\rho g H}{2} \frac{\cosh[k(z + h)]}{\cos(kh)} [\cos(kx \sin \phi \cos \omega t - \sin(kx \sin \phi) \sin \omega t]$$

(5)

Because of:

$$\cos(kx \sin \phi) = J_0(kr) + 2 \sum_{m=1}^{\infty} J_{2m}(kr) \cos(2m\phi)$$

$$\sin(kx \sin \phi) = 2 \sum_{m=1}^{\infty} J_{2m-1}(kr) \sin[(2m-1)\phi]$$

(6)

Substituting the equation (6) into equation (5) is:

$$p = \frac{\rho g H}{2} \frac{\cosh[k(z + h)]}{\cos(kh)} [\{J_0(kr) + 2J_1(kr) \cos 2\phi\} \cos \omega t - 2\{2J_1(kr) \sin \phi \sin \omega t\}]$$

(7)

$J_0(kr)$, $J_1(kr)$, $J_2(kr)$ represent zero order, first order, second order Bessel function, respectively.

When the value of $H/2R$ is relatively small, the effect of viscosity can be ignore. Substituting $p$ of the equation (7) and $ds = rd\phi dr$ into equation (3), and then integrating, the vertical wave force of vertical spar buoy can express as:

$$F_y = C_y \int_0^h P_z dS$$

$$= C_y \frac{\rho g H \pi L_1}{k} \cos h[k(h - d)] \cos \omega t$$

(8)

When the sea wave height is constant, the size of the vertical wave force of the vertical spar buoys floating in the sea depends on four factors: $C_y$, the relative radius of the cylinder $2\pi R / \lambda$, the relative submergence height $d / R$, the relative water depth $h / R$. When any of the above four parameters are
modified, the force of the vertical cylinder will also be changed. Hogben N. and Standing R.G. got the $C_V$ value [11] of the vertical spar buoy through a model test. The values are given in table 1.

Table 1. The diffraction coefficient of vertical spar buoy

| KR | h/R | d/2R | $C_V$ |
|----|-----|------|------|
| 0.1 | 5 | 0.75 | 1.01 |
| 0.2 | 5 | 0.5 | 1.02 |
| 0.5 | 5 | 0.25 | 1.04 |
| 1   | 5 | 0.75 | 1.43 |

The vertical wave forces can be calculated which acted by the vertical spar buoy, according to the above formula.

3. The design of the power installation driving by double-sided rack

3.1 The structure design of buoy type wave generator

The device driven by the wave force, it can do reciprocate motion in the vertical direction at the sea surface. The reciprocating motion turns to single direction movement towards the overrunning clutch, thus driving the generator, as showed in figure 2. In the figure 2, part 1 is gear speeder, part 2 is seal box, part 3 is cylindrical buoy, part 4 is a double rack, part 5 is generator, part 6 is overrunning coupler, and part 7 is the reverse box.

Figure 2. Schematic diagram of buoy type wave generator

3.2 The working principle of the buoy wave power generation

Pointed out above, the device mainly utilizes the sea fluctuated as power sources, driving the buoy doing reciprocating motion. As shown in figure 2, when the buoy is driven by waves, due to the action of the oriented axis and a guide rail, limiting the movement towards the double-sided rack in the horizontal direction. After reaching the back stroke, the limit baffle plate on the bottom will limit its upward movement so as to achieve the maximum stroke of the float. This design is referenced to the bicycle overrunning clutch principle [12] which will be applied in this device, so that the output powers in a direction can be achieved. As showed in Figure 3.
1-input shaft A 2-output shaft 3-input gear A 4-input gear B5-output shaft B

Figure 3. Principle of gear box

When the rack goes up, the rack turns the input gear A and input gear B to rotate, but the direction of the two gears movement is the opposite. The overrunning clutch assembled in the two gears is opposite, that is, the input gear A move, the overrunning clutch does not exceed, driving the output shaft. At the same time the overrunning clutch in the input gear B exceeds. Gear B is just idle, not driving the input shaft B. Conversely, if the rack is downward movement, the output gears A idle and gear B move, guaranteeing the output shaft is rotated around one direction in this way of operation.

The output shaft drives the gear speed increasing structure and the generator, which are connected to the output shaft, to complete the dynamic process of the whole device. The sealing box which loads gear accelerator, the generator and the toroidal gear box is sunk to the bottom of the sea floor and fixed on the seabed, and the height of the sealing box can be adjusted to meet optimum position of the rack travel.

3.3. Output speed calculations and simulation analysis to the toroidal gear box

As can be seen from the above equation, the input angular velocity is related to wave circular frequency, and it is in inverse proportion to the wave period. Therefore, it should be reasonably chosen the situation that the device installs and reasonably designs the quality and other related parameters of the floating equipment in order to make the device a relatively stable power generation level.

Import the model which has been established into ADAMS, supply constraints and contact. Exert a force constraint on the double - sided rack, as showed in figure 4.

Figure 4. Buoy rack and its connected gear mechanism model

The speed and acceleration curve of the output shaft gear can be obtained by the analysis of its state, as showed in figure 5.
Figure 5. Velocity and acceleration curve of output shaft gear

It can be seen that the output shaft gear drove by the rack, its speed is gradually increased, that is, the faster the rise, the faster the speed of the gear. The change of acceleration is larger, because the rack is repeated up and down. But the gears rotate around one direction generally. It can continue to drive the motor rotation and complete the required power generation.

The mechanism adopts gear meshing as the driving torque, so the gear connected with the rack is analysed using ABAQUS, as showed in figure 6 (a, b). Figure 6(a) shows the stress nephogram of the input gears; figure 6(b) shows the deformation nephogram of the input gears.

Figure 6. The stress and deformation nephogram of the input gears

4. Conclusion

In this paper, the kinetic energy was used to produce by ocean wave’s cyclical fluctuations to obtain electricity generating power, which can be stored and used. After summarizing the various forms of marine energy, establishing the main power source is the fluctuation of the ocean wave. In order to design a buoy that meets the better effects of the floating, this paper designs a cylindrical buoy. The design can better adapt to the waves floating manner. According to the shape of the float, the Froude-Krylov hypothesis can be used to calculate the vertical wave force of the buoy. The power generation device is designed based on the above theoretical calculation and the operation speed of the device is calculated.

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