Research on Hydrodynamic Characteristics of Wave Energy Power Plant

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Abstract. Ocean energy is a kind of high-quality renewable energy. Therefore, it will not be exhausted and has attracted wide attention. China's coastline is 18,000 kilometers long, so China has abundant ocean energy. In order to realize the utilization of wave energy, the research on wave energy power generation technology has never stopped. Wave energy generation refers to the use of wave motion to generate electricity, first converting wave energy into intermediate energy through a conversion device, and then converting intermediate energy into electrical energy. Combining with China's actual situation, China's research on wave energy devices mainly has three types: oscillating water column, pendulum, sink and float. Due to the huge difference in sea conditions and the characteristics of China’s offshore waves with short periods and relatively low energy density, wave energy conversion devices must be independently developed, and hydrodynamic behavior research is the basic work. In this paper, through the theoretical analysis and numerical calculation research methods, the hydrodynamic behavior characteristics of the wave energy conversion device are studied, and the simulation analysis is performed using the hydrodynamic software AQWA.

1. Introduction

In recent years, with the excessive consumption of coal, oil, natural gas and other traditional fossil energy, the stock of fossil energy is decreasing, and it caused serious environmental pollution, especially severe smog, which worsened the ecological environment, affected the health of animals and humans, and posed a great threat to the sustainable development of human society. Therefore, energy and environmental issues are highly concerned by governments and international organizations, and the development of pollution-free renewable energy has become a global consensus. The search for new energy is imminent. There are many new energy sources, such as wind energy, ocean energy, nuclear energy, and geothermal energy. Many countries have begun to study how to use these energy sources. Among the energy contained in the ocean, wave energy is one of them, and the resources of wave energy are very rich. Therefore, wave energy power generation technology has very good development prospects and research significance. If the wave energy can be used properly, it will make it a high-quality renewable energy source.

In this regard, in order to improve the research technology of wave energy power generation devices in China, it is necessary to analyze their hydrodynamic performance. This paper combines the specific parameter formula of an oscillating wave power generation device and uses a large hydrodynamic analysis software AQWA to perform hydrodynamic analysis on the device, which provides the necessary theoretical basis for the research of wave power device.
2. Hydrodynamic analysis method

In order to solve the hydrodynamic parameters of the wave energy power generation device, the device needs to be modeled and numerically simulated. The displacement, velocity and acceleration of the floating body caused by the wave, the additional mass and radiation damping generated by the wave radiation force, and the wave excitation force caused by the incident wave are the performance of the float’s hydrodynamic performance.

2.1 Wave force

In the flow field, according to the linearized Bernoulli equation, the dynamic pressure distribution in the flow field can be calculated.

\[ p = -\rho g z - \rho \frac{\partial \phi}{\partial t} \]  

(1)

The wave forces and moments experienced by the floating body in the six-direction motion mode field are as in the follow.

\[ F_n = \iint p n_j dS, n = 1,2,3 \]  

(2)

\[ M_n = \iint p n_j dS, n = 4,5,6 \]  

(3)

In the formula, \( n_j \) represents the generalized external normal vector in each direction of motion. Bring formula (1) into the follow formula.

\[ F_n = \iint (-\rho g z - \rho \frac{\partial \phi}{\partial t}) n_j dS, n = 1,2,3 \]  

(4)

The wave force in the above formula consists of two parts, one is the wave force caused by the velocity potential, and the other is the hydrostatic pressure in the flow field.

Since the velocity potential is composed of three parts: the incident potential, the radiation potential, and the diffraction potential, the three parts of the wave force can be solved by the velocity potential and formula (4).

\[ F = F^I + F^D + F^R \]  

(5)

\[ F^I = \rho iw \iint \Phi^I n_j dS \]  

(6)

\[ F^D = \rho iw \iint \Phi^D n_j dS \]  

(7)

The three terms on the right side of formula (5) represent the forces and moments generated by the different hydrodynamic components in the wave on the floating body. \( F^I \) is the wave incident force. \( F^D \) is the wave diffraction force. It is the force of the wave diffraction caused by the existence of the floating body on the floating body. The combined force of \( F^I \) and \( F^D \) is called the exciting force of the wave force, represented by \( F^E \). \( F^R \) is the wave radiation force. The floating body is moved by the action of the wave, and the reaction force generated by the wave of the floating body moving outwards on the floating body is related to the additional mass of the hydrodynamic coefficient and radiation damping.

2.2 Hydrodynamic Coefficient

The pressure generated by the floating body due to the wave radiation potential is as follow.

\[ p = -\rho \frac{\partial \phi^R}{\partial t} \]  

(8)

Integrating along the wet surface of the floating body, the total hydrodynamic pressure of the radiation potential of the floating body is as follow.

\[ F^R = -\rho \iint (\rho \frac{\partial \phi^R}{\partial t}) n_j dS \]  

(9)
In formula (9), \( F_i \) represents the wave force experienced by the float at the \( i \)th degree of freedom, \( i = 1, 2, 3 \ldots 6 \). Combining the radiation potential expression and the boundary conditions, the following can be solved.

\[
F_i^R = \text{Re} \left\{ -\rho \omega^2 x_i \int \Phi_i^R n_j dS \right\} \\
= \text{Re} \left\{ -\rho \omega^2 x_i \int \frac{\partial \Phi_i^R}{\partial n} dS \right\}
\]  

(10)

In formula (10), \( x_i \) is the movement displacement of the modal \( i \) of the floating body; \( \Phi_i^R \) is the radiation velocity potential of \( i \) modal; \( n_j \) is the \( j \) degree of freedom normal vector.

\[
\mu_{ij} + \frac{i \lambda_{ij}}{\omega} = \int \Phi_i^R \frac{\partial \Phi_i^R}{\partial n} dS
\]  

(11)

Therefore, the radiated wave force is as follow.

\[
F_i^R = \text{Re} \left\{ -\rho \omega^2 x_i \left( \mu_{ij} + \frac{i \lambda_{ij}}{\omega} \right) \right\} \\
= -\ddot{x}_{\mu_{ij}} - \dot{x}_{\lambda_{ij}}
\]  

(12)

In formula (12), \( \mu_{ij} \) is the additional mass, and \( \lambda_{ij} \) is the radiation damping.

According to the above method, by integrating the free surface, the additional mass and radiation damping of the floating body can be obtained, so the radiation wave force can also be obtained.

3. Device dynamics analysis

In this paper, the oscillating float type wave energy power generation device is taken as the research object. The oscillating float type wave power generation device mainly captures wave energy through the relative movement of the float and the pontoon. Therefore, the movement characteristics of the float and the pontoon have an important influence on the energy conversion characteristics of the device. This scheme uses a cylindrical float as a wave energy absorption device. The size and weight of the float are important influencing factors. In this paper, the hydrodynamic analysis software AQWA is used to study the hydrodynamic performance of the float. The focus is on the response of the float in the z-axis direction.

3.1 Float motion model

For a float moving under the action of a wave, it is known from the theory of potential current that the action of the wave on the float can be decomposed into an incident potential, a radiation potential, and a diffraction potential. The total velocity potential is expressed as formula (5).

The force of the float can be decomposed into several parts: the Froude-Krylov force caused by the incident potential, the diffractive force caused by the diffusive potential, the radiant force caused by the radiant potential, the restoring force of the static water caused by the heave motion of the float and the rear end Load (PTO), where Froude-Krylov force and diffraction force are collectively called wave excitation force.

The wave excitation force can be solved by Haskint's formula, and the radiation force is solved based on the radiation potential. The restoring force of still water is due to the change in the position of the free surface relative to the free surface during the movement of the float, but the gravitational force remains unchanged, resulting in a force and moment similar to elastic recovery, mainly related to the shape, scale and draft of the object. The energy output load is combined by the transmission system and the power generation system.

From the law of motion and Bernoulli's equation, under the premise of linearization, the equation of motion of the float's heave direction is expressed as follows.
\[ m\ddot{a} = \rho g S\dot{x} = -\rho \int \frac{\partial \phi}{\partial \tau} \hat{n}dS - Cu \]  

(13)

In formula (13) \( a \) is the acceleration of float motion; \( u \) is the speed of the float; \( C \) is the load damping coefficient.

By calculating the above formula, you can get as follow.

\[ mRe\{-\omega^2\dot{x}e^{-i\omega t}\} + \rho g SRe\{\dot{x}e^{-i\omega t}\} = -\rho \int Re\{-i\omega(\phi + \phi^D + \phi^R e^{-i\omega t})\hat{n}dS - CR\{e^{-i\omega e^{-i\omega t}}\} \]  

(14)

The complex modulus values in the above formula should be equal to each other, so we can get as follow.

\[ -\omega^2 (m + A)\ddot{x} - i\omega(B + C)\ddot{x} + \rho gS\ddot{x} = F_e \]  

(15)

\[ \ddot{x} = \frac{F_e}{-\omega^2 (m + A)\ddot{x} - i\omega(B + C)\ddot{x} + \rho gS} \]  

(16)

In equations (15) and (16), \( x \) is the motion amplitude of the float; \( B \) is the damping coefficient; \( A \) is the additional mass; \( F_e \) is the wave excitation force of the float.

According to formula (16), the motion response of the float under wave action depends on various factors such as wave excitation force, additional mass, damping coefficient, load.

3.2 Analysis of hydrodynamic coefficient of float

In the working state of the wave energy generating device, the wave load on the float and the buoy is different. The wave load referred to in this article is the combined force of the diffraction force caused by diffraction and the incident force of the wave. Since the other five degrees of freedom of heave have almost no effect on the operation of the wave energy generator, only the influence of the heave load on the float is considered. The heave wave force experienced by the float is shown in Figure 1.

![Figure 1. Heave wave force on the float](image)

The vertical wave force received by the float will change with the change of the wave frequency, and this relationship is shown in Figure 1. From Figure 1, we can see that with the wave frequency increases, the wave force of the float gradually decreases, and it is a nonlinear relationship, and the slowing speed becomes slower.
3.3 The hydrodynamic coefficient of the float

Figure 2 describes the variation characteristics of the radiation damping coefficient of the float in the heave state with the wave frequency. The radiation damping coefficient is an important parameter to measure the damping force of the float in the wave. From Figure 2, we can get the following conclusions; if you want the radiation damping coefficient of the float to be 0, you must keep the wave frequency at 0, that is, there is no incident wave. The radiation damping coefficient of the float changes regularly. When the frequency of the float increases, the radiation damping coefficient of the float shows a trend of "increasing first and then decreasing", and the maximum value is reached when the frequency value is 1.5 rad/s.

3.4 Analysis of the influence of float's draught

In this paper, a cylindrical float is used as a wave energy absorption device. The size and weight of the float are important influencing factors. RAO is the dimensionless response amplitude operator of the device's motion response, which is defined as follows.

\[
\text{RAO} = \frac{\text{structural response amplitude}}{\text{regular wave amplitude}}
\]

The coupling between the float and the wave is closely related to its own weight. A cylindrical float with a diameter of 1.8 m and a height of 1.2 m is used as the model. Change the weight of the float to make the initial draughts 0.4 m, 0.6 m and 0.8 m respectively. Figure 3 shows the numerical simulation results of the motion response in the z-axis direction under three different draughts. It can be seen from Figure 3 that as the weight increases, the resonance frequency gradually decreases; the greater the weight, the smaller the resonance frequency, and the larger the amplitude of motion, which is more in line with the requirements of practical applications, but the movement changes more drastically with frequency. The float with a small weight has a large resonance frequency, but the energy absorption effect in the full band changes more smoothly. Therefore, on the premise of ensuring a wide energy absorption band of the float, a float with a small resonance frequency, a large motion range, and relatively stable motion should be selected.
4. Conclusion
As an important structure for the development and utilization of wave energy, oscillating float-type power generation devices have the advantages of simple structure, wide frequency response range, and high conversion rate. Therefore, they have become a hot spot for academic research and development. Based on the potential current theory, this paper uses AQWA to establish a hydrodynamic model of wave power generation equipment, and calculates the hydrodynamic parameters of the device, including additional mass, radiation damping, wave excitation force and RAO, etc. The hydrodynamic parameters of floats with different parameters are compared. After analysis, this paper believes that, on the premise of ensuring a wide energy absorption band of the float, the float with a small resonance frequency, a large motion range, and relatively stable motion should be selected.

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