INTRODUCTION

Energy consumption has increased dramatically with the growth of the global economy, resulting in increasing social concern over environmental matters. The emergence and utilization of low-carbon and renewable energy is becoming the focus of energy development. In response to this situation, attention has been directed toward the oceans. Wave energy is a major type of marine energy, with total reserves theoretically totaling approximately 3 billion kW. A third of this amount can be developed by technology, and the theoretical electric production is approximately 8000 TWh/y. Different types of wave energy converters have been given considerable practical use to develop and utilize wave energy. The converters can be classified according to their structure, as oscillating-water column, pendulum, contraction wave channel, and raft types.

Research on design and optimization of the pitching float wave energy converter

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Abstract
Wave power generation has been the object of extensive renewable energy research and development all over the world. Concerning the application of a wave energy converter to the harsh environment of the South China Sea, a study of the shape and internal layout of a pitching float wave energy converter was performed based on the mechanism of the oscillating-float generator. Research methods based on potential flow theory and the use of ANSYS-AQWA software were applied to predict the hydrodynamic performance and energy conversion of the pitching float wave energy converter. The influence of the float shape, width, side radius, and centroid position on the hydrodynamic performance of the float was analyzed. The results show that the pitching performance of the spherical-bottom float was the best among the three basic shapes examined. The width of the float had the greatest impact on the pitching performance of the float, and the effect of the radius of the float on the pitching performance was also significant. The pitching performance of the float was improved with the realization of a larger radius in the pitching direction. The centroid position and rotational inertia also had a great impact on the pitching performance of the float. The wave energy converter designed in this study lays the foundation and provides reference for further research on the novel, efficient, and stable wave energy converter.

KEYWORDS
energy conversion, float, hydrodynamic performance, pitching motion, wave energy

1 INTRODUCTION

Energy consumption has increased dramatically with the growth of the global economy, resulting in increasing social concern over environmental matters. The emergence and utilization of low-carbon and renewable energy is becoming the focus of energy development. In response to this situation, attention has been directed toward the oceans. Wave energy is a major type of marine energy, with total reserves theoretically totaling approximately 3 billion kW. A third of this amount can be developed by technology, and the theoretical electric production is approximately 8000 TWh/y. Different types of wave energy converters have been given considerable practical use to develop and utilize wave energy. The converters can be classified according to their structure, as oscillating-water column, pendulum, contraction wave channel, and raft types.
Various types of wave energy converters have been studied, and some of the research results have been put into commercial application. As early as 1986, the Norwegian Wave Energy Company built a contraction wave channel wave power plant (Tapchan) with an installed capacity of 300 kW.\(^7\) In 2009, the Oyster-2 pendulum device developed by Aquamarine Power was successfully installed at the European Marine Energy Center in Oakney County, Scotland, with a maximum power output of 800 kW.\(^8\) In the same year, the Palami-1 Raft Wave Energy Converter, developed by Scottish Ocean Power Transmission Corporation, was successfully tested in Portugal and has already been connected to the grid for power generation.\(^9\) In 2011, The Mutriku Wave Power Station was built by Spain's EVE Energy Company in Armintza, northern Bilbao, and was connected to the grid with an average annual power generation of 400 MW h.\(^10\)

However, the technical difficulties of wave energy converters that have to be overcome are still significant. The oscillating-water-column wave energy converter is easily affected by terrain,\(^11\) and it has high construction cost and high risk.\(^12,13\) The pendulum wave energy converter is easy to damage\(^14,15\) and is affected\(^16,17\) by waves; furthermore, the maintenance of its power take-off (PTO) is inconvenient.\(^18\) The contraction wave channel converter requires a high wave energy flux density and terrain, which is difficult to achieve. The raft wave energy converter consumes a large amount of material and is difficult to locate the mooring. Furthermore, its large-area valve-body arrangement affects the marine ecosystem, and the impact damage issue is also prominent.\(^19\) By contrast, the oscillating-floating wave energy converter contains small-scale components,\(^20\) low manufacturing cost, high conversion efficiency,\(^21\) and strong environmental resistance.\(^22\) In conclusion, the key to the development of the wave energy converter is to resolve the problems of low efficiency and stability, low safety and reliability, and high cost.

As one of the major methods for capturing wave energy, the float wave energy converter has the characteristics of high conversion efficiency, strong stability, and low cost, which has broad application prospects.\(^23\) Ocean Power Technologies Corporation of the United States has developed a point-absorber wave energy power buoy device. It works by utilizing the mutual heave motion of the inner and outer parts of the buoy\(^24,25\) and has already entered the commercial application stage. China's heaving buoy wave energy converter has been rapidly developed. In 2011, the 20 kW-class direct-drive heave-type wave energy converter “Nezha-I,” developed by Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, was put into operation in Zhuhai.\(^26\) However, for the heaving buoy wave energy converter, there exists a huge impact effect between the stator and rotor, which easily causes structural damage. Amiri et al\(^27\) conducted a comprehensive numerical simulation of the deep-sea double-floating-body wave energy converter, and the results showed that the wave energy conversion efficiency can be significantly improved under certain conditions. Nazari et al\(^28\) conducted a feasibility study on a point absorber at an Iranian port and found that the natural frequency and parameters of the damping coefficient have significant impact on the average heave displacement. Therefore, the energy-capture efficiency can be improved by changing the shape of the converter. However, there has not been much research focused on the effect of the shape and internal layout on the hydrodynamic performance of the converter. In addition, none of the abovementioned studies have involved the application of a wave energy converter to specific sea conditions, especially harsh sea conditions.

The nodding duck device proposed by Stephen Salter of the University of Edinburgh and PS Frog MK5 developed by Lancaster University\(^29\) are representative pitching float wave energy converters. In China, Guangdong Ocean and Fishery Service Center developed a pendulum-type oscillating-float wave energy power generation device, which is also a pitching float wave energy converter.\(^30\) However, these existing converters exhibit poor stability, and the oscillating body of the device comes into direct contact with the sea water, which can easily cause damage to the device.

In addition, predicting the complex hydrodynamic performance of the pitching float wave generator is difficult. Thus, it is a challenge to reasonably determine the structural design according to the wave parameters of the actual sea area, which has been the main obstruction to extending the application of the pitching float wave converter. Furthermore, the pitching float wave converter usually has a large scale; as such, the research methods of experiments, programming, and CFD simulation are costly and time-consuming.

This study considers the application of wave energy under complex sea conditions in the South China Sea as research background. A novel pitching float wave energy conversion device is presented in this paper. The energy conversion structure inside the device does not come into contact with the sea water. Thus, the device exhibits more stable energy conversion and improved safety performance. The shape and internal layout of the pitching float wave energy device were investigated based on the principle of floating oscillatory power generation. A system dynamics model was built for the pitching float wave energy device. Based on potential flow theory and the secondary development of ANSYS-AQWA software, this study established the research methods of hydrodynamic performance and energy conversion for the pitching float wave energy device, providing an economical and time-saving method. The influences of float shape, width, side radius, and centroid position on the hydrodynamic performance of the float were analyzed. The results and research method of this study can provide guidance for the design of the pitching float wave energy converter and similar devices.
2 | INNOVATIVE DESIGN OF THE PITCHING FLOAT WAVE ENERGY CONVERSION DEVICE

2.1 | Working conditions

The specific marine environment determines the design of the float-type wave energy converter to a certain extent. In this study, the float-type wave energy converter is assumed to be located in the South China Sea. In winter, the wave direction is mostly northeast, and the monthly average wave height is between 0.5 and 2.5 m. In summer, the wave direction is mostly southwest, and the monthly average wave height is between 1.0 and 1.5 m. Referring to the real sea conditions in the South China Sea, the wave height is in the range of 0.5-2.5 m, and the wave period is between 5 and 7 s. In addition, the average depth of the water is set as 100 m, and the wind speed is 10 m/s. Other external factors, such as the mooring, are not considered.

2.2 | Principle of energy conversion

The wave energy converter operates through the interaction between the float and the built-in pendulum. The pitching float wave energy converter in this study can be divided into the first-stage energy conversion system, second-stage energy conversion system, and third-stage energy conversion system.

The first-stage energy conversion system consists of the wave and the float, which converts the kinetic energy and potential energy produced by the wave motion into mechanical energy assumed by the float (mainly considering the mechanical energy in the pitching direction). The first-stage energy conversion system is the foundation of the device. The shape design of the float is closely related to the first-stage conversion efficiency, which is particularly important.

The second-stage energy conversion system is composed of the pitching float and pendulum in the float. The relative motion between the built-in pendulum and the float converts the mechanical energy of the float into pendulum mechanical energy. In the entire process of energy conversion, this secondary energy conversion functions as a bridge connecting the first-stage and third-stage energy conversion systems, playing the role of converting unstable energy into stable energy. In addition, the pendulum is placed inside the float, which protects the transfer mechanism from wave impact and greatly improves the safety and stability of the device.

The third-stage energy conversion system consists of the pendulum plate, gear transmission mechanism, and generator. The mechanical energy of the pendulum plate is converted into electrical energy assumed by the generator through the utilization of the regulating function of the gear transmission mechanism. The gear transmission mechanism not only achieves the transfer of energy but also transforms the unstable and changing energy into stable and regular energy, improving the efficiency of power generation.

For the pitching float wave energy converter designed in this study, the energy is finally stored in the battery through the rectifying circuit.

2.3 | Detailed design of the device

The pitching float wave energy converter is fabricated from Q235 steel. The float in the first-stage conversion system has a draft depth of 1 m, length of 3 m, width of 0.9 m, height of 0.6 m above the water line, small radius on the wide side, and fan-shaped bottom.

The general arrangement of the first-stage conversion system is depicted in Figure 1. The generator system includes the energy storage device. The flange is used to connect the upper and lower shells and symmetrically arrange mooring points. The pendulum is a two-stage conversion component. The gear transmission system is used to transmit the mechanical energy of the pendulum and regulate the energy conversion.

The transmission shaft and main parts of the gear transmission mechanism and generator are shown in Figure 2. The
transmission shaft is supported by the platform. The main transmission gear is connected with the two-stage conversion system. The down gear is connected to the left generator, whereas the up gear is connected to the right generator. The generator base is fixed on the inner platform of the float, and the auxiliary transmission gear is connected to the two-stage conversion system. The entire gear transmission mechanism can improve the stability of energy conversion, while at the same time, it has the function of speed regulation.

The pendulum plate and part of the gear transmission mechanism in the two-stage conversion system are shown in Figure 3. The left bracket is used to support the left end of the pendulum plate and is fixed with the support shaft by means of articulation. The left gear is used to transfer the mechanical energy of the pendulum plate. The supporting shaft has the function of transmitting motion and is articulated with the left and right brackets. The right gear is used to transfer the mechanical energy of the pendulum plate. The right bracket is able to support the right end of the pendulum plate and is fixed with the supporting shaft by means of articulation. The pendulum is located at the lower end.

3 | RESEARCH METHODS

3.1 | Dynamic model of pitching float wave energy converter

In this study, the pitching motion of the float with inertia $I_1$ was analyzed under the action of waves. The float converts the energy caused by the wave action into mechanical energy, and the internal damping plate is swung by its inertia. The pendulum with inertia $I_2$ forms a relative motion with the float with inertia $I_1$, such that the mechanical energy can be converted into electricity through the gear transmission system. To facilitate the calculation, an ideal incompressible irrotational flow is assumed, and the viscous impact is neglected in the frequency domain approach. Additionally, the damping system between the float and pendulum plate (PTO system) is assumed to exhibit a linear output, that is, the PTO force is a linear function of the relative rotation angle and relative rotational angular velocity of the float and pendulum plate. The impact of the PTO is considered by the secondary development of AQWA in Fortran. The mooring force passes through the centroid, and the elastic coefficient is zero when only the pitching motion is considered. Figure 4 illustrates a model of the mechanics of the pitching float wave energy converter, where $K_1$ and $K_2$ are both zero and $C_2 = C_{PTO}$.

In Figure 4, the coupled motion of the pitching float $I_1$ and waves is a first-stage energy conversion system. The main parameters include inertia $I_1$, damping coefficient $C_1$, float rotation angle $\theta_1$, relative rotation angle $\theta_2$ of the pendulum plate and float, and damping coefficient of PTO $C_{PTO}$. The built-in pendulum plate $I_2$ and pitching float $I_1$ are secondary energy conversion systems. The main parameters include the inertia $I_2$ of the pendulum plate, relative rotation angle $\theta_2$ of the pendulum plate and the float, and damping coefficient of PTO $C_{PTO}$.

This treatment only considers the motion in the pitching direction, and the frequency domain motion equation of the pitching float can be given as follows:

$$
(I_1 + \mu_{55}) \ddot{\theta}_1 (t) + \lambda_{55} \dot{\theta}_1 (t) + C_{55} \theta_1 (t) = m_{55}
$$

where $I_1$ is the pitching inertia of the float, $\mu_{55}$ is the added inertia caused by the pitching of the float, $\lambda_{55}$ is the damping coefficient caused by the pitching of the float, and $C_{55}$ is the hydrostatic

![FIGURE 3](image-url)  
**FIGURE 3** Pendulum plate and part of gear transmission system

![FIGURE 4](image-url)  
**FIGURE 4** Mechanics model of pitching float wave energy converter
restoring coefficient, and \( m_{55} \) is the wave excitation moment caused by the pitching of the float. Because of the moment \( m_3 \) generated by the pendulum pitching on mass block \( m_2 \), the equivalent force exerted on float \( m_1 \) is denoted as \( f_{13} \), which is given by

\[
f_{13} = C_{13} \left( \dot{\theta}_1 (t) - \dot{\theta}_3 (t) \right) \tag{2}
\]

where \( C_{13} \) is the damping coefficient caused by the pitching motion of the pendulum acting on the float.

The moment of the force imposed on the float caused by the mooring system is denoted as \( M_1 \), which can be expressed as:

\[
M_1 = k' \dot{\theta}_1 (t) \tag{3}
\]

where \( k' \) is the stiffness coefficient of the mooring system.

Substituting Equation (2) and Equation (3) into Equation (1), the following equation was obtained,

\[
\begin{align*}
(I_1 + \mu_{55})^{-1} \dot{\theta}_1 (t) + \lambda_{55} \dot{\theta}_1 (t) + C_{13} (\dot{\theta}_1 (t) - \dot{\theta}_3 (t)) + C_{55} \theta_1 (t) + k' \dot{\theta}_1 (t) &= m_{55} \\
I_3^{-1} \ddot{\theta}_3 (t) &= C_{31} (\ddot{\theta}_3 (t) - \ddot{\theta}_1 (t))
\end{align*} \tag{4}
\]

The moment balance equation of the pendulum is

\[
I_3^{-1} \ddot{\theta}_3 (t) = C_{31} (\ddot{\theta}_3 (t) - \ddot{\theta}_1 (t)) \tag{5}
\]

where \( C_{31} \) is the damping imposed on the pendulum body produced by the pitching motion of the float.

The equation system is

\[
\begin{align*}
(I_1 + \mu_{55})^{-1} \dot{\theta}_1 (t) + \lambda_{55} \dot{\theta}_1 (t) + C_{13} (\dot{\theta}_1 (t) - \dot{\theta}_3 (t)) + C_{55} \theta_1 (t) + k' \dot{\theta}_1 (t) &= m_{55} \\
I_3^{-1} \dot{\theta}_1 (t) &= C_{31} (\ddot{\theta}_1 (t) - \ddot{\theta}_1 (t))
\end{align*} \tag{6}
\]

where \( \ddot{\theta}_1 \) and \( \ddot{\theta}_3 \) are the angular accelerations of the float and pendulum, respectively, whereas \( \dot{\theta}_1 \) and \( \dot{\theta}_3 \) are the angular velocities of the float and pendulum, respectively.

The amplitude response of the float is related to the wave forces through

\[
-\omega^2 \begin{bmatrix} M \end{bmatrix} \{ \xi \} - i \omega \begin{bmatrix} B \end{bmatrix} \{ \xi \} + \begin{bmatrix} K \end{bmatrix} \{ \xi \} = \{ f \} - M g n_3 + \{ f z \} \tag{7}
\]

where \([ M ]\), \([ B ]\), and \([ K ]\) are the mass matrix, damping matrix, and stiffness matrix of the float, and \([ f ]\) and \([ f_z ]\) are the action forces of the wave loaded on the float and the external system loaded on the float, respectively.

Unlike diffraction theory, the Froude–Krylov hypothesis states that for a float sufficiently small so as to not affect the pressure field due to an incident wave, the wave force acting on the float is

\[
F = C F_K \tag{8}
\]

where \( C \) is the coefficient of the diffraction force. \( F_K \) is defined by

\[
F_K = \rho \overline{V}_0 (\frac{dv}{dt}) \tag{9}
\]

where \((dv/dt)\) is the average acceleration and \(\overline{V}_0\) is the drainage volume.

Referring to the calculation of the potential flow, the fluid viscous force is calculated in the form of added damping, \(33\) which can be expressed as

\[
C_{ij} = x \ast 2 [(M + \Delta M) \ast K]^{0.5} \tag{10}
\]

where \( x \) is the percentage of added viscous damping, \( M \) is the float mass matrix of the float, \( \Delta M \) is the added-mass matrix of the float, and \( K \) is the hydrostatic stiffness matrix of the float.

### 3.2 Optimization method of pitching float wave energy converter

This treatment mainly investigates the first-stage and second-stage energy conversion system. For the first-stage energy conversion system, the effect of the shape of pitching float on the energy absorption efficiency necessitates investigation. The control variable method is applied to optimize the shape of the pitching float. In the optimization process, the displacement and draft depth remain constant. The float shape is firstly determined. The float width, which has the greatest influence on the wave energy-capture efficiency, is secondly optimized.

Then, the length and radius of the float are optimized in turn to design the optimal shape of the pitching float. In the optimization process, the AQWA-LINE module of the ANSYS-AQWA software is used to solve the hydrodynamic parameters, such as the amplitude response operator (RAO), wave excitation force, radiation damping, and added mass of the float in the pitching direction. The optimal float can be determined according to the simulated hydrodynamic performance.

For the second-stage energy conversion system, the coupled motion equation between the pitching float and the built-in pendulum plate is addressed. The influence of the design parameters of pendulum plate on the power generation efficiency is determined for the interaction of the float with the pendulum plate. The size, layout, and shape of the pendulum plate are optimized, and the second-stage conversion system with the best conversion efficiency is determined.

### 3.3 Numerical Model Verification

This work calculated the hydrodynamic data of the float RAO with the AQWA-LINE module. Figure 5A shows the
**FIGURE 5** Floating frequency domain calculation model. (A) APDL grid model; (B) AQWA hydrodynamic model

**FIGURE 6** Comparison between simulated RAO heave and the results of Liu34 for different float-bottom shapes

**FIGURE 7** Three floats with different bottom shapes. (A) Platform bottom; (B) Conical bottom; (C) Spherical bottom

**FIGURE 8** RAO of three floats with different bottom shapes

**TABLE 1** Sizes of floats for the three bottom shapes

| Bottom shape | $D$ (m) | $h$ (m) | $d$ (m) | Displacement (t) | $I_{xx}$ (kg m$^2$) | $I_{yy}$ (kg m$^2$) | $I_{zz}$ (kg m$^2$) | Centroid coordinates (m) |
|--------------|---------|---------|---------|-----------------|-------------------|-------------------|-------------------|-------------------------|
| Platform     | 1.8     | 0.6     | 0.4     | 2.1             | 1414              | 1414              | 1392              | (0, 0, −0.115)          |
| Cone         | 1.8     | 0.6     | 0.4     | 1.9             | 1071              | 1071              | 1163              | (0, 0, −0.044)          |
| Sphere       | 1.8     | 0.6     | 0.4     | 2.0             | 1262              | 1262              | 1308              | (0, 0, −0.075)          |
grid drawn by ANSYS-APDL, and the generated data file is connected to AQWA. Figure 5B shows the AQWA frequency domain hydrodynamic calculation model.

To verify the accuracy of the numerical model, the simulated data of the RAO heave were compared with the results obtained by Liu,\textsuperscript{34} who compared the RAO heaves of floats of different bottom shapes. As shown in Figure 6, the change in the RAO heave with angular frequency is very consistent with the change described in Liu.\textsuperscript{34} Therefore, the numerical model developed in this study is adequate for predicting the hydrodynamic characteristics of the pitching float wave energy converter.

4 | RESULTS AND DISCUSSION

4.1 | Motion response of floats with different shapes

Hydrodynamic performances were calculated for the floats of three common shapes, namely platform bottom, spherical bottom, and conical bottom. The models for the floats of these three shapes are shown in Figure 7. The dotted line in Figure 7 represents the waterline. The specific size is listed in Table 1. Based on the hydrodynamic calculation results of the floats with these three shapes, a parametric optimization scheme for the shape of floats was constructed. The three shape parameters—float width $D$, width radius $R_1$, and length radius $R_2$—were investigated. The three constraints were $d + h = 1$ m, molded depth $h + h + h = 1.6$ m, and displacement weight $w = 2$ t, where $d = $ draft, $h = $ molded depth, and $w = $ displacement weight. In the optimization procedure of the pitching float wave energy converter, the RAO performance is the first important standard for appraisal, as the RAO performance is directly related to the power generation. The wave excitation force, radiation damping, and added mass are secondary considerations.

The optimal float-bottom shape was determined by comparing the values and trends of the pitching RAO of the different float-bottom shapes. As can be seen (Figure 8), for an
angular frequency between 0 and 2.5 rad/s, the pitching RAO of the spherical-bottom float is the largest, the platform-bottom float is slightly smaller, and the conical-bottom float is the smallest. However, after 2 rad/s, the pitching RAO of the platform-bottom float has passed the peak and begins to decrease rapidly compared with the other two types of floats. In the angular frequency range of 2.5-4 rad/s, the RAO of the conical-bottom float gradually increases to the peak and exceeds those of other two types of floats. Regarding the entire trend of the curve, the pitching RAO peak of the cylindrical-spherical-bottom float is the largest. At most frequencies, the RAO of the spherical-bottom float is larger than those of the other two types of floats. Therefore, for the pitching RAO, the pitching response performance of the spherical-bottom float is the best.

The optimal bottom shape of the float was confirmed by comparing the wave excitation force, radiation damping, and

| Float number | D (m) | L (m) | R (m) | I_{xx} (kg m²) | I_{yy} (kg m²) | I_{zz} (kg m²) | Centroid coordinates (m) |
|---------------|-------|-------|-------|----------------|----------------|----------------|--------------------------|
| 1             | 0.81  | 3.4   | 1.945 | 756            | 2502           | 2189          | (0, 0, −0.063)           |
| 2             | 0.857 | 3.2   | 1.78  | 791            | 2339           | 2041          | (0, 0, −0.065)           |
| 3             | 0.88  | 3.1   | 1.701 | 803            | 2243           | 1954          | (0, 0, −0.066)           |
| 4             | 0.908 | 3     | 1.625 | 824            | 2166           | 1887          | (0, 0, −0.067)           |
| 5             | 1.032 | 2.6   | 1.345 | 911            | 1864           | 1634          | (0, 0, −0.072)           |
| 6             | 1.11  | 2.4   | 1.22  | 966            | 1725           | 1532          | (0, 0, −0.076)           |
| 7             | 1.2   | 2.2   | 1.105 | 1044           | 1617           | 1468          | (0, 0, −0.080)           |
| 8             | 1.3   | 2     | 1     | 1120           | 1498           | 1403          | (0, 0, −0.087)           |
| 9             | 1.35  | 1.8   | 1.212 | 1438           | 1179           | 1355          | (0, 0, −0.122)           |
| 10            | 1.42  | 1.8   | 0.905 | 1220           | 1394           | 1372          | (0, 0, −0.094)           |
| 11            | 1.56  | 1.6   | 0.82  | 1344           | 1302           | 1376          | (0, 0, −0.104)           |
| 12            | 1.73  | 1.4   | 0.745 | 1512           | 1227           | 1431          | (0, 0, −0.117)           |
| 13            | 1.928 | 1.2   | 0.68  | 1708           | 1151           | 1525          | (0, 0, −0.132)           |
| 14            | 2.18  | 1     | 0.625 | 2011           | 1103           | 1736          | (0, 0, −0.151)           |
| 15            | 2.48  | 0.8   | 0.58  | 2406           | 1058           | 2053          | (0, 0, −0.174)           |
| 16            | 2.86  | 0.6   | 0.545 | 3004           | 1029           | 2589          | (0, 0, −0.202)           |
| 17            | 3.15  | 0.8   | 0.416 | 2727           | 769            | 2392          | (0, 0, −0.093)           |

**TABLE 2** Sizes of floats for width optimization

**FIGURE 11** RAO curves of float width optimization

**FIGURE 12** Mean value and extremum value of RAO vs the width of the float. (A) Mean value of RAO; (B) Extremum value of RAO
added mass. As can be seen from Figure 9A, the overall trend of the three curves for the wave excitation force with angular frequency are consistent. Among them, the platform-bottom float is subjected to the largest wave excitation force, followed by the spherical-bottom float. The wave excitation force of the conical-bottom float is the smallest. Figure 9B shows that the radiation damping of the floats with the three shapes all increase in angular frequency between 0 and 1.5 rad/s, and the growth trend is basically the same. Among them, the radiation damping of the conical-bottom float is basically the smallest, the spherical-bottom float is slightly larger, and the platform-bottom float is the largest. As shown in Figure 9C, the overall trend of the three curves for the added mass with the angular frequency are consistent. Among them, the conical-bottom float has the largest added mass, platform-bottom float takes second place, and spherical-bottom float has the smallest.

In conclusion, the spherical-bottom float has a better pitching RAO than the other two types of floats at the same angular frequency. Meanwhile, the added mass, radiation damping, and wave excitation force of the spherical-bottom float are also better. Thus, the spherical-bottom float is chosen as the basis for further research and optimization.

4.2 | Motion response of the floats with different widths

Based on the optimized spherical-bottom float, the displacement remained unchanged. The width of the float is taken as the design variable, and other structural dimensions change with the width of the float. The hydrodynamic calculation of the floats with different widths was conducted. The pitching response performance was analyzed to determine the optimal relative width. Figure 10 depicts the calculation sketch of the pitching float wave energy converter. This optimization procedure does not consider the radius of the float. The constraints are as follows: $h = 0.6 \text{ m}$, $d = 1 \text{ m}$, and $w = 2 \text{ t}$. The size information is listed in Table 2.
The optimal width of the float can be determined by comparing the values and trends of RAO in the pitching direction of the width-differing floats. As shown in Figure 12, the trend of extremum value and mean value of RAO with the width of the float is basically the same. As the float width increases from 0, the RAO extremum and mean of the float first fluctuate and then reach a peak at a width of 0.908 m (referring to the fourth float in Table 2 and fourth curve in Figure 11); then, the RAO extremum and mean fall sharply over the peak. As shown in Figure 12, the RAO peak value and frequency of the peak vary with the float width, which indicates the major influence of the float width on the pitching performance of the float. In summary, the fourth float has the best pitching motion response performance and is far superior to the other floats.

By comparing the wave excitation force, radiation damping, and added mass, the float with optimal width was determined. As shown in Figure 13A, the curves for 17 groups of wave excitation forces show a similar trend. The curve of the 16th float is higher than other curves, which means that the 16th float suffers the greatest wave excitation force. As can be seen from Figure 10, the 16th float also exhibits better pitching response performance and belongs to the trend of extremum value and mean value of RAO with the width of the float is basically the same. As the float width increases from 0, the RAO extremum and mean of the float first fluctuate and then reach a peak at a width of 0.908 m (referring to the fourth float in Table 2 and fourth curve in Figure 11); then, the RAO extremum and mean fall sharply over the peak. As shown in Figure 12, the RAO peak value and frequency of the peak vary with the float width, which indicates the major influence of the float width on the pitching performance of the float. In summary, the fourth float has the best pitching motion response performance and is far superior to the other floats.

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| Float number | $R_1$ (m) | $R_2$ (m) | $I_{xx}$ (kg m$^2$) | $I_{yy}$ (kg m$^2$) | $I_{zz}$ (kg m$^2$) | Centroid coordinates (m) |
|-------------|----------|----------|----------------|----------------|----------------|------------------------|
| 4           | 0        | 0        | 824           | 2166           | 1887           | (0, 0, −0.067)         |
| 18          | 1500     | 0        | 807           | 2063           | 1810           | (0, 0, −0.049)         |
| 19          | 2000     | 0        | 800           | 2050           | 1800           | (0, 0, −0.050)         |
| 20          | 3000     | 0        | 816           | 2110           | 1836           | (0, 0, −0.063)         |
| 21          | 2000     | −200 000 | 773           | 2024           | 1752           | (0, 0, −0.059)         |
| 22          | 2000     | −100 000 | 761           | 2066           | 1735           | (0, 0, −0.059)         |
| 23          | 2000     | −70 000  | 751           | 1992           | 1720           | (0, 0, −0.059)         |
| 24          | 2000     | −40 000  | 800           | 2288           | 1982           | (0, 0, −0.068)         |
| 25          | 2000     | −35 000  | 729           | 1961           | 1689           | (0, 0, −0.059)         |
| 26          | 2000     | 30 000   | 857           | 2136           | 1870           | (0, 0, −0.060)         |
| 27          | 2000     | 40 000   | 844           | 2127           | 1857           | (0, 0, −0.059)         |
| 28          | 2000     | 50 000   | 832           | 2109           | 1839           | (0, 0, −0.059)         |
| 29          | 2000     | 70 000   | 818           | 2090           | 1819           | (0, 0, −0.059)         |
| 30          | 2000     | 90 000   | 808           | 2074           | 1804           | (0, 0, −0.059)         |
| 31          | 2000     | 200 000  | 796           | 2059           | 1787           | (0, 0, −0.059)         |
high-quality float. The wave excitation force of the fourth float is above the absolute average. Combined with its optimal response operator RAO, the fourth float is also classified as a high-quality float. From Figure 13B, it is found that the radiation damping of the 16th float is the largest, whereas that of the 4th float is relatively small, which means that the fourth float is better than the 16th float in this respect.

Figure 13C presents the added mass of the 17 types of floats with different widths.

The added mass of the first float is the largest. From Figure 11 and Figure 13A,B, the first float has small RAO values and a large radiation damping value. The first float belongs to the nonoptimal pitching float, which is not included in the scope of further study. The added-mass curve of the fourth float conforms to the trend of the general curve, and the curve is located in the middle position, which belongs to the high-quality float. The added mass of the 16th float varies greatly, which indicates that the fluid caused by the float varies greatly. The pitching response performance is poor. The first float is a poorly performing pitching float and was not included in further study. The added-mass curve of the fourth float, located in the middle position, coincides with the trend of general curves, indicating a high-quality float. The added mass of the 16th float fluctuates greatly, which definitely causes the flow pattern around the float to change dramatically; thus, the pitching motion response of the 16th float is poor.

**Figure 18** Shape of the 19th float

**Figure 19** Arrangement optimization of the internal components of the 19th float
In conclusion, the RAO performance of the fourth float is far superior to that of the other floats. Furthermore, the fourth float exhibits the best pitching motion response and favorable wave excitation force, radiation damping, and added mass. The next-level design optimization is implemented accordingly.

### 4.3 Motion response of floats with different side radii

The hydrodynamic calculation of the fourth float was performed for the optimization of the length and width radii, and the pitching motion response was analyzed. The displacement volume, draft, and shape characteristics and the parameters of the fourth float were unchanged. The relatively optimal radius was determined in this section.

#### FIGURE 20
Effect of centroid position and moment of inertia on the RAO

#### FIGURE 21
Effect of centroid position and moment of inertia on the mean value and extremum value of RAO. (A) Mean value of RAO; (B) Extremum value of RAO

#### TABLE 4 Sizes of the floats for internal layout optimization

| Float number | Draft (m) | Displacement (t) | $I_{xx}$ (kg m$^2$) | $I_{yy}$ (kg m$^2$) | $I_{zz}$ (kg m$^2$) | Centroid coordinates (m) |
|--------------|-----------|------------------|---------------------|---------------------|---------------------|--------------------------|
| 19           | 1         | 2                | 800                 | 2050                | 1800                | (0, 0, −0.050)            |
| 32           | 1         | 2                | 779.9               | 1965.7              | 1662.7              | (0, 0, −0.012)            |
| 33           | 1         | 2                | 727.5               | 1913.3              | 1662.7              | (0, 0, −0.055)            |
| 34           | 1         | 2                | 782.6               | 2036.7              | 1765.8              | (0, 0, −0.059)            |
| 35           | 1         | 2                | 727.5               | 1913.3              | 1662.7              | (0, 0, −0.063)            |
| 36           | 1         | 2                | 730.2               | 1915.9              | 1662.7              | (0, 0, −0.070)            |
| 37           | 1         | 2                | 735.3               | 1921.1              | 1662.7              | (0, 0, −0.077)            |
| 38           | 1         | 2                | 743.1               | 1928.9              | 1662.7              | (0, 0, −0.085)            |
| 39           | 1         | 2                | 747.9               | 1933.7              | 1662.7              | (0, 0, −0.088)            |
| 40           | 1         | 2                | 753.5               | 1939.2              | 1662.7              | (0, 0, −0.092)            |
| 41           | 1         | 2                | 755.9               | 1941.6              | 1662.7              | (0, 0, −0.093)            |
| 42           | 1         | 2                | 756.6               | 1928.8              | 1649.1              | (0, 0, −0.094)            |
| 43           | 1         | 2                | 759.6               | 1945.4              | 1662.7              | (0, 0, −0.096)            |
| 44           | 1         | 2                | 766.4               | 1952.2              | 1662.7              | (0, 0, −0.099)            |
| 45           | 1         | 2                | 770.9               | 1937.8              | 1642.3              | (0, 0, −0.101)            |
| 46           | 1         | 2                | 790.7               | 1976.4              | 1662.7              | (0, 0, −0.110)            |
| 47           | 1         | 2                | 432.2               | 841.2               | 614.7               | (0, 0, −0.590)            |
As shown in Figure 14, \( R_1 \) is the radius of the width arch, and \( R_2 \) is the radius of the length arch. Here, a positive value indicates that the length is convex outward, and a negative value indicates that the length is concave inward. The controlling variable method was adopted to optimize the width radius \( R_1 \) of the float (referred to the data for the 18th to 20th floats in Table 3). After the determination of \( R_1 \), the length radius \( R_2 \) is optimized (referred to the data for the 21st to 31st floats in Table 3).

By comparing the values and trends of the pitching RAO of floats with different side radii, the optimal side radius for a float was obtained. Figure 15 shows that the extremum value and mean value of the RAO vary significantly with the side radius. The RAO extremum values and mean values of the 18th, 19th, 20th, and 21st floats are greater than those of the 4th float, with the RAO value of the 19th float serving as the maximum. Figure 16 shows that the peak values of RAO varies with side radii. However, the frequency corresponding to the peak value of RAO is basically the same, as is the trend for all the curves, which indicates that the side radius of the float has less influence on the pitching motion performance of the float than does the width of the float.

The optimal radius float was confirmed by comparing the wave excitation force, radiation damping, and added mass. As shown in Figure 17A, the wave excitation force curves almost coincide. The 24th float exhibits the optimal performance for the largest wave excitation force. However, recalling the RAO curve of the 24th float, its pitching amplitude response is not favorable; thus, the 24th float is not a high-quality float. The 19th float exhibits the optimal RAO and a similar performance to the other floats in terms of the wave excitation force. Thus, the 19th float is on the list of high-quality floats. Figure 17B further shows that the 24th float demonstrates the largest radiation damping, which impedes the pitching motion of the float, whereas the 19th float has the smallest radiation damping value. The fourth float also has a large radiation damping. As can be seen from Figure 17C, the added masses of the different floats show little difference, except the 24th and 4th floats, which have values that are slightly larger. Therefore, the optimization of the side radii for a float has a negligible impact on the added mass.

In conclusion, the 19th float exhibits the best pitching motion response performance and demonstrates the final shape.
of the float, as shown in Figure 18. The relevant parameters are listed in Table 3.

4.4 Effect of centroid position and moment of inertia on the motion response of the floats

Based on the adjusted 19th float, this section further optimizes the centroid position and moment of inertia of the 19th float, with the shape of the float unchanged, by adjusting the layout of the inner components of the float and the thickness of the platform to improve the pitching performance. The corresponding analysis and calculation were carried out. Note that when the internal structure of the float was optimized, the detailed layout inside the float was not displayed; rather, the appropriate corresponding center of mass positions and inertias were determined to compute the hydrodynamics of the float.

As shown in Figure 19, the generator, platform, and pendulum plate inside the float are simplified as mass block 1, mass
block 2, and mass block 3, respectively. The centroid position and moment of inertia are optimized through the arrangement of the mass block. The parameters are listed in Table 4.

The optimal centroid position of the float was determined by comparing the values and trends of the pitch RAO of floats with different centroid positions. Figure 20 shows that the RAO extremum and mean of a float increase with the increase in the centroid position or the moment of inertia of the float. The 34th float has the largest RAO extremum and RAO mean; however, the 19th float has larger ones than most floats. The RAO extremum and mean of the 34th float are better than those of the 19th float. According to Figures 20 and 21, the peak value of RAO varies slightly by altering the centroid position and moment of inertia, and the frequency of the peak are all close to 2.5 rad/s. The 34th float exhibits the best RAO curve and pitching amplitude response performance.

The best centroid position of a float was confirmed by comparing the wave excitation force, radiation damping, and added mass. As shown in Figure 22A, except for the wave excitation force curve of the 47th float, the other curves coincide closely with each other. The wave excitation force of the 47th float is the largest; however, according to the RAO curve of the 47th float in Figure 18, the 47th float has a poor pitching amplitude response and is, therefore, excluded from the high-quality float list. The wave excitation force curve of the 34th float coincides closely with the other float curves. Additionally, the 34th float has the best RAO curve and is, therefore, classified as a high-quality float. In Figure 22B,C, the radiation damping and added-mass curves of floats are very close, except the curve of the 47th float, which indicates that a small change in the centroid position or moment of inertia has little impact on the radiation damping or added mass.

The comprehensive optimization of the shape, width, side radius, and centroid position of the float demonstrates that the 34th float has the best pitching motion response performance. The final float layout is shown in Figure 23.

4.5 | Performance of the optimized device

After optimization, the RAO value of the pitching float wave energy conversion device is shown in Figure 24A-F. As seen from the figure, the pitch RAO value is much greater than the RAO values in the other directions, indicating that the pitch performance of the device is good. The pitching peak frequency appears near 2.5 rad/s, and the maximum RAO reaches 130 deg/m. The rolling, yawing, and swaying responses are very small, and the RAO amplitude is within one. The maximum amplitude of the surging response reaches four, and the peak frequency is approximately 2.5 rad/s. According to the “Classification Specification for Offshore Mobile Platforms (2012)”35 when the RAO amplitude is less than five, the stability is excellent. Therefore, the hydrodynamic performance of the converter is excellent.

As shown in Figure 25, the optimized pitching float wave energy generator uses the relative motion of the built-in pendulum and the float body to generate and improve the stability and safety of the device. The capture width ratio is approximately 12%, and the energy-capture efficiency is high.

A regular wave was selected to verify the hydrodynamic performance of the float in the time domain. Typical South China Sea working conditions were adopted, in which the wave period was 6 seconds, wave height was 1.6 m, wave angle was 0°, and mooring point was at the center of mass. As shown in Figure 26, the float exhibits excellent surge and pitch movement and is stable in the other directions.

5 | CONCLUSIONS

By optimizing the configuration and internal layout of the pitching float wave energy converter, a pitching float wave energy converter was designed in this study, exhibiting good hydrodynamic performance, high wave energy capture efficiency, simple structure, and safe mooring. The designed float has a total length \( L = 3.0 \) m, width \( B = 0.9 \) m, depth \( D = 1.6 \) m, draft \( d = 1.0 \) m, displacement weight \( W = 2.0 \) t, radius of the round bottom \( R = 1.625 \) m, radius of the width arc \( R = 2000 \) m, centroid coordinate \((0, 0, -0.059)\), float inertia \( I_1 = 2036.7 \) kg/m², and an angle-line mooring system was used. The mooring point is settled at the centroid position. The following conclusions are determined:

1. ANSYS-AQWA was used to analyze the hydrodynamic performance of floats with three common shapes, namely spherical bottom, conical bottom, and platform bottom. A parametric shape optimization scheme was formulated to optimize the shape of the float. Through a comparative analysis, it is concluded that the spherical-bottom float exhibited the best pitching performance.
2. The width of the float had a great influence on the pitching performance. A larger side radius of the float in the pitching direction contributed to better pitching performance. The pitching performance of the float increased with increasing inertia $I_{zz}$ through the adjustment of the thickness of the platform plate or arrangement of the internal structure.

3. The pitching float wave power converter generated electricity by the relative motion of the built-in pendulum and float. The design was found to not only reduce the wave impact and enhance the wave energy-capture efficiency but also improve the stability and safety of the device, laying the foundation and providing reference for further study of the novel, efficient, and stable wave energy converter.

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