U.P.B. Sci. Bull., Series D, Vol. 86, Iss. 2, 2024 ISSN 1454-2358

DESIGN AND STRUCTURE ANALYSIS OF OSCILLATING FLOAT WAVE ENERGY POWER GENERATION DEVICE

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With the excessive consumption of energy such as oil and natural gas by countries around the world, humans must develop a renewable and clean energy source to meet energy needs. With the advantages of ocean wave energy (high energy flow density, pollution-free, etc),it has become the focus of scientific researchers. However, for wave energy power generation devices(WEPGD), the technologies have not yet formed a theoretical system, meanwhile there also lack relevant structural analysis. Thus based on the understanding of ocean wave motion and energy generation devices, this paper firstly determines the scheme design of oscillating float Wave energy generation. Then, the structural design of the WEPGD is carried out with the motion characteristics of the oscillating float. Finally, the fluent module and workbench module in the ANSYS finite element software were used for flow field simulation and structural analysis, respectively. Analysis shows that the outer part of the float bears the maximum stress in the upper and lower parts when the device rises and descends. With the impact of horizontal waves, the stress outside the device float is distributed in a sloping stepped pattern, decreasing from top to bottom. Most of all, the maximum stress does not exceed the limiting value of material, so this design device can withstand simulated working conditions and achieve the expected function.

Keywords: Wave energy power generation devices; oscillating float; workbench; Fluent; structural analysis

1. Introduction

After entering the 21st century, the Earth has developed rapidly, and the demand for energy in various countries around the world is increasing. The problem of energy shortage has become a developing barrier around the world. With the large consumption of and the incalculable pollution of non-renewable resource such as oil and natural gas, people urgently need a renewable clean energy to meet the growing energy demand. Thus ocean energy is exploited, and it

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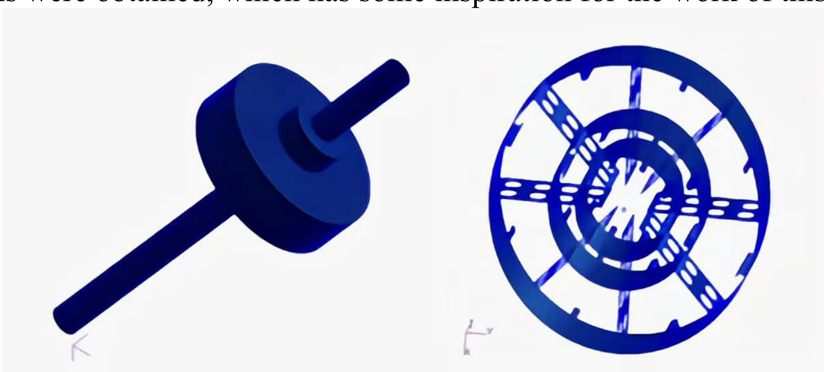
is mainly classified into tidal energy, wave energy, ocean current energy, temperature difference energy, salinity difference energy, etc [1,2]. Wave energy because of the most abundant and high-quality marine energy, it has become the research focus in the world. At present, there are many kinds of WEPGD in the world, mainly including oscillating water column technology, oscillating float technology, etc [3,4]. The latter utilizes the motion of waves to drive the moving parts of the device, and the reciprocating motion drives mechanical systems or hydraulic systems with intermediate media such as oil and water. Then, the energy generation device generates electricity. Due to its advantages of high efficiency, low cost, good reliability and relatively low requirements for the device, the researcher develop the oscillating float WEPGD[5, 6].But there are very few energy generation devices can truly conduct real sea state experiments, what's more fewer can be successfully applied.

Around the world, many scholars have published papers on oscillating float WEPGD. With the following study, a float guided column WEPGD was proposed, and the structural strength analysis of the device was carried out, as shown in Fig.1 [7]. The load conditions of the device under different working conditions were obtained, which has some inspiration for the work of this paper.



(a) float (b) column

Fig. 1. Model of float and guide column

In the Fig. 2, researchers propose a sliding rod float type wave energy generation device, which improved the capture width and good hydrodynamic performance of the float type wave energy generation device to improve efficient. Meanwhile, other scholars improve the structure of the oscillating float, which can effectively protect the device by raising the oscillating float out of the sea when the marine environment is turbulent [8].

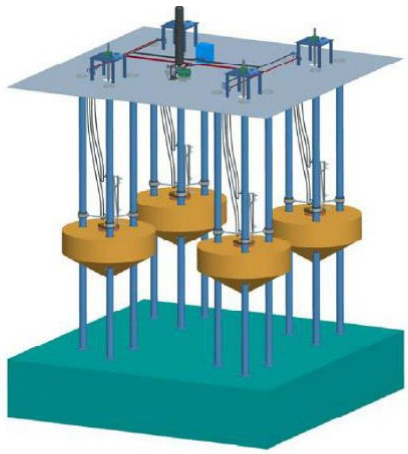


Fig. 2. Oscillating float type device capable of breaking free from the sea surface

A float type WEPGD which consists of rack, gear, ratchet overrunning clutch, hollow sleeve and other component was shown in the paper, it increases the general conversion rate from 30% to 39.3%. What's more, a pendulum oscillating float type WEPGD was proposed, which combines the modified device with the hydraulic transmission. Although more energy is lost in the hydraulic transmission part, the hydraulic transmission can buffer wave energy fluctuations [9]. In the following study, an oscillating float type WEPGD with simple structure was also invented, low construction cost and small energy loss in the conversion process [10].

The oscillating float device designed by scholars of Shanghai Ocean University has improved the conversion efficiency, it obtains a higher capture ratio. In the work, the power output system of the wave energy conversion device was designed, and the draft by comparing the damping of linear and nonlinear power output systems was corrected through analytical algorithms. By comparing the damping of linear and nonlinear power output systems through analytical algorithms, researchers have also designed the power output system of the wave energy conversion device and corrected the draft [11].

Internationally, variation of wave energy in the ocean was proposed to reduce spectral parameters related the transmission and distribution [12]. It can be seen in the Fig.3, research has invented various wave energy converters. For example, when two different WEPGD operate in the ocean, the two upper limits of power P, PA and PB, can be calculated by absorbing a sine wave with a height of H and calculating the period T through an immersed body with a volume of V. If the volume is large enough, the actual absorption power P is close. That is curve PA will increase monotonically, and P can approach monotonically. When the volume is very small, the curve PB is descent. The two dashed lines represent the absorption of power by the oscillation of a finite volume sphere with the best amplitude.

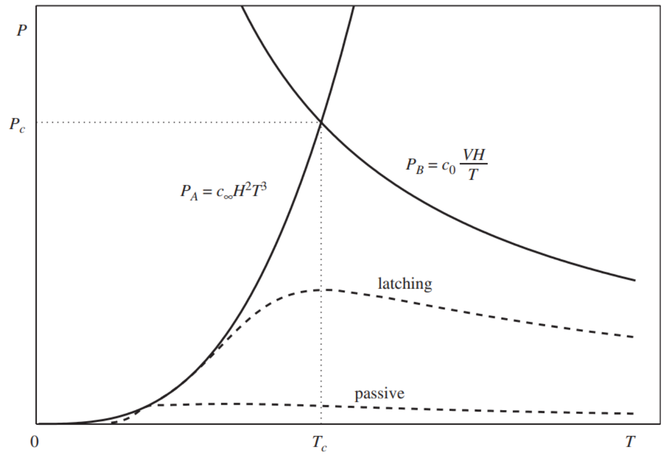


Fig. 3. Relationship between power(W) and period(Hour) of two wave energy generation devices

Researchers from Italy studied the behavior of EDS along sloping beaches at different water depths through laboratory modeling. The results showed that as the water depth decreased, the opposite motion is low dynamic and slow than the upward motion of the float and the forward motion of the paddle [13]. In the following study, different wave energy converters were compared, and a method was proposed to design the generation of innovative and improved structures. While considering the manufacturability of such wave energy converters, the research suggests that volume is not a suitable represented by cost. As these optimized operations result in more complex shapes with multiple parameters: smaller radius characteristics, the surface is more important for the amount of material required rather than volume [14].

The response and energy capture characteristics of WEC under regular and irregular waves under different PTO systems were analyzed, as shown in Fig.4. By evaluating the differences between WECs of different PTOs, research shows that the output power first increases and then decreases with the increasement of the PTO damping coefficient. And at different wave heights, the optimal PTO damping coefficient corresponding to the maximum output energy of the direct driving PTO, and mechanical motion rectifier (MMR) PTO remains unchanged within one wave cycle [15].

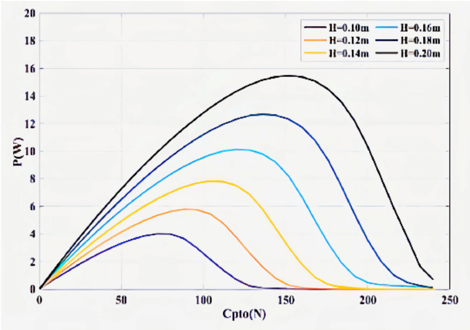


Fig. 4 Mean power as a function of PTO damping coefficient of the WEC with Coulomb PTO.

It can be seen in Fig.5, the study from Iran has compared the efficiency of trapezoidal and circular cross-sections at different wave numbers to identify the influence of cylindrical cross-sections. The results indicate that the efficiency of circular pontoons is higher at low wave numbers [16]. Meanwhile, researchers proposed an improved pendulum wave energy converter, which consists of two parts: a wave energy collector and an energy converter. The wave energy collector includes a swinging device with a triangular cross-section shape, a slope, a support frame, and two side walls. The device utilizes the principles of oscillation, overflow, and it concentrates wave torque to reduce utilization costs and expand application in marine areas [17].

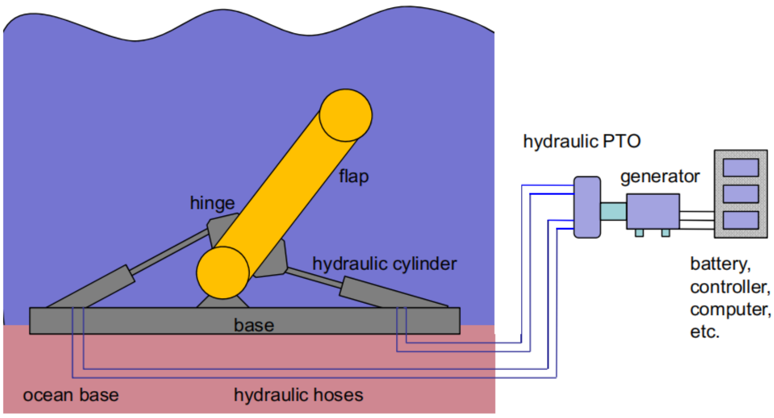


Fig. 5. Zhang Wan's Conceptual Model of an Improved Pendulum Wave Energy Converter

What's more, a new type of oscillating float type ocean WEPGD was proposed in the work [18]. With the adjustments between the vibrator and the output power (torque) of the generator, the vibration captures the maximum power of wave energy in resonance state (Fig. 6).

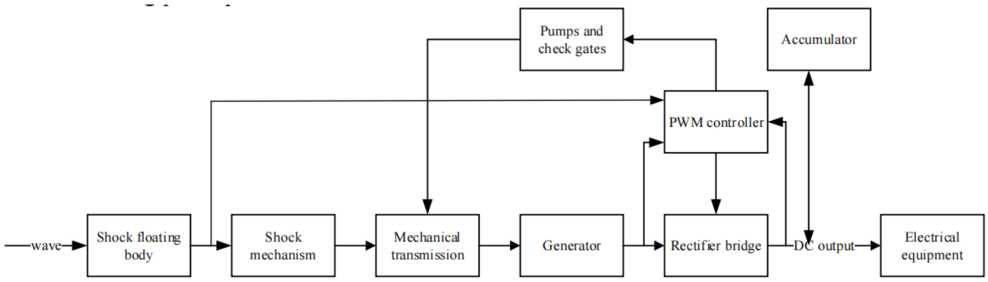


Fig. 6. The working principle flowchart of the oscillating float type wave energy generator

Chinese study found that oscillating float WEC integrates into the breakwater can obtains more efficiently wave energy [19]. In order to evaluate the parameter effect of power take-off system (PTO) on the integrated system of oscillating float WEPGD and pile constrained floating breakwater, the Coulomb resistance model and linear damping model were established and compared. The results show that the Coulomb resistance model has good performance in wave energy capture efficiency and coastal protection [20].

In Conclusion, although many kinds of wave power generation technologies were design in the world at present, there are few can be successfully applied in the ocean experiments. Especially most of them possess the conversion rate is between 30% and 40%, it is necessary to improve the conversion efficiency. Thus, this paper firstly design the structure of the device based on the research of wave energy and oscillating float motion characteristics. Secondly, the flow field of working condition was simulated by the Fluent module in the ANSYS software, then it was applied to the numerical model for structure analysis. The wave energy generation device can be designed efficiently and economically with the research, meanwhile the safety and reliability of the wave energy generating device can be verified.

2. Scheme design

Due to the irregular and unpredictable motion characteristics of waves, the device should operate normally in complex marine environments with minimal energy loss. Thus it is necessary to limit the direction and trajectory of the float, and the device should be operated controllable and computable. Therefore, the scheme design of this paper adopts the oscillating float WEPGD of upslope type, which can effectively mitigate the impact of waves and use the wave energy. Under the wave forces of different sizes and directions, the float can always perform vertical upward and downward cyclic motion with the fixed central rod and slider. This design not only protects the float but also limits the movement, which making it more stable and consuming less energy during work. The hydraulic circuit design is adopted below the float, so that the pressure generated by the float during operation can be effectively transmitted to the hydraulic device and completed the power generation work.

2.1 Mathematical Model of Wave Force

When waves move, the path of water quality points is elliptical and closed-loop in the vertical direction. The particles of seawater continuously horizontally move back and forth along the seabed direction. The pressure exerted by waves on the device can be divided into two types: static seawater and moving seawater. To simplify the problem of the force exerted by waves on the device, this paper assumed that the motion of seawater particles is slow. Meanwhile, the depth of the seawater at the location of the device is much greater than the amplitude of the wave, and the waves are micro amplitude (linear waves). What's more, the fluid is taken as an ideal perfect fluid without viscosity, compressibility and turbulence, and the pressure on the water surface is constant and uniformly distributed. Then the wave force P_Z is:

$$P_Z = -\rho g z + \rho g \frac{H}{2} \frac{\cosh[k(z+h)]}{\cosh(kh)} \cos(kx - \omega t) \qquad (1)$$

Where h is the depth of seawater, η is the wave surface, H is the wave height, λ is the wavelength, T is the period of the wave, c is the propagation speed of the wave, and $c= \lambda/ T$. Also commonly used frequency $\omega= 2 \pi/T$, wave number $k=2 \pi/ \lambda$ to represent the properties of waves. Generally speaking, any specific wave train can be represented by the parameter H, λ ,h or H, T, h to determine [21].

2.2 Mathematic Model of Floating Body Force

When the waves in the ocean make a sinusoidal motion and transmit to the oscillating float type WEPGD, it will generate an exciting force on the oscillating float to make it moves up and down, the mechanical model is shown in Fig.7. The oscillating float WEPGD uses the slide rail to fix and limit the movement of the sliding block inside the float, so that the sliding block only vibrates up and down. When there are no waves, the device is equilibrium on the sea surface, and its gravity is equal to the support force of the seawater. Therefore, the entire system of the device can be seen as a damping slider elastic system. The device works with the excitation force, spring force and damping force generated by wave action on the device. If the wave excitation force is sinusoidal, the Equations of motion of the slider is:

$$m\frac{d^2y}{dx^2} + c\frac{dy}{dx} + fx = P_Z \sin(\omega t + \varphi) \qquad (2)$$

Where m is the mass of the float, x is the displacement, c is the damping coefficient, f is the spring constant, and P_Z is the excitation force, ω is the Angular frequency, t is the time and φ is velocity potential function. When calculating P_Z based on different wave conditions, the damping coefficient c under different conditions can be selected, the optimal solution can be selected and the above two functional equations can be obtained, so that the output power of the device can be calculated finally.

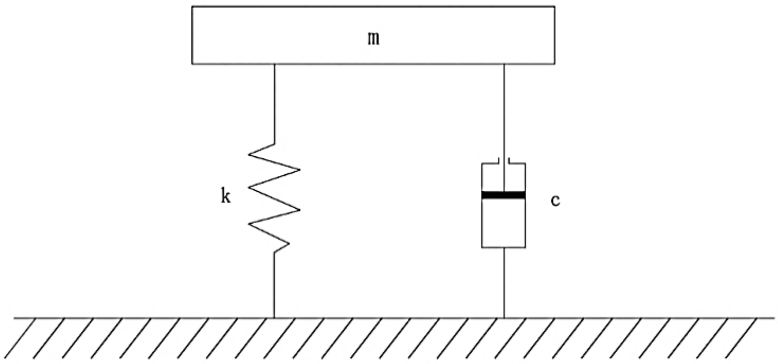


Fig. 7. Mechanical model

2.3 Structure Design

The device designed in this paper is mainly consists of five parts: the shell, intermediate rod, hinge rod, slider, and slide rail. The upper part of the shell is designed as a dome shape to bear the impact of waves and pressure, while the dome shape doesn't generate outward thrust. With the aim of maximizing internal space and resisting wave corrosion, the central of the shell is cylindrical. The lower part of the shell is designed in a sloping shape, and its inner side bears the pressure generated by the operation of the slider and slide rail in the device. Meanwhile, the outer part forms a structure that is similar to a slope, which enhances the resistance of the lower part of the device. The float is fixed on the middle rod, and both sides of the float are connected to the slide rail. The slide rail is connected and fixed to one end of the two pairs of fixed rods, and the other end of the two pairs of fixed rods is connected and fixed to the shell. When the device rises, the slider inside the float will maintain its original state due to inertia and generate relative displacement between itself, thus pressure exerts downwards on the hydraulic circuit. When the device descends, the float moves vertically downwards due to maintaining its original acceleration, which causing relative displacement between the float. The hydraulic oil then withdrawns from the oil tank to complete the circulation, the structure is shown as Fig. 8.

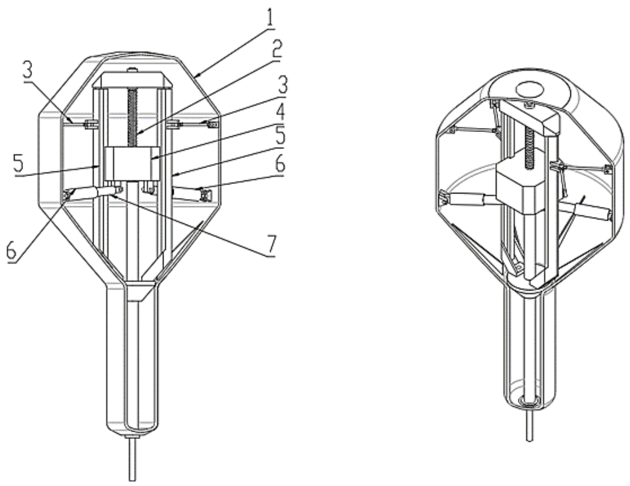


Fig. 8. 3D structural diagram of the device：1-Shell 2- Intermediate rod 3- Hinge rod 4- Slider 5- Slide rail 6- Piston 7- Piston rod

3. Device Structure Analysis

3.1 Material Properties

To prevent the corrosion, the stainless steel is used inside the device. Considering the wave force and low temperature effects of seawater, the upper part of the device shell is made of Q345DE steel. And the rest of the device casing adopts a PET plastic for easy recycling. The upper part of the device casing is coated with 4000HD paint to resist UV corrosion, meanwhile the remaining parts of the device casing are coated with 5054HD paint in three stages to resist seawater corrosion. The mechanical properties of the device shell material are shown in Table 1 below, and the statics calculation only models its linear elastic stage.

Table 1

Material parameters

Material	Density （t/mm3）	Elastic modulus (GPa)	Poisson's ratio	yield strength （MPa）
Q345DE steel	7.85e-9	210	0.3	400
PET	1.38e-9	4	0.4	200

3.2 Solid Modeling

Due to the device is composed of multiple parts, force transfer between each part is required when subjected to external loads. Therefore, contact pairs must be created at the connection points between each part. The establishment of contact pairs is shown in Figure 9, and the model contains a total of 16 sets of connections.

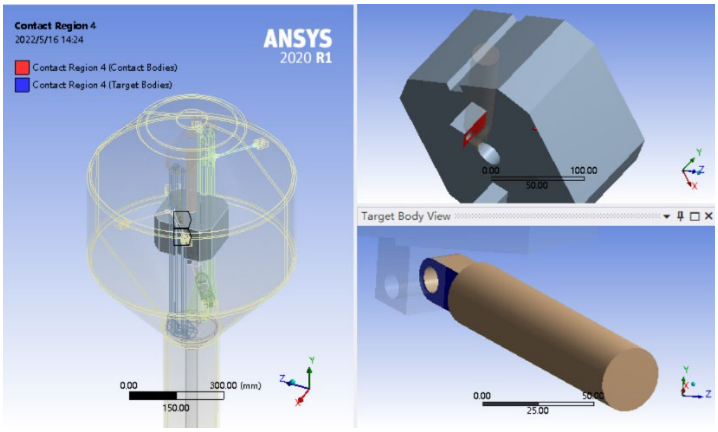
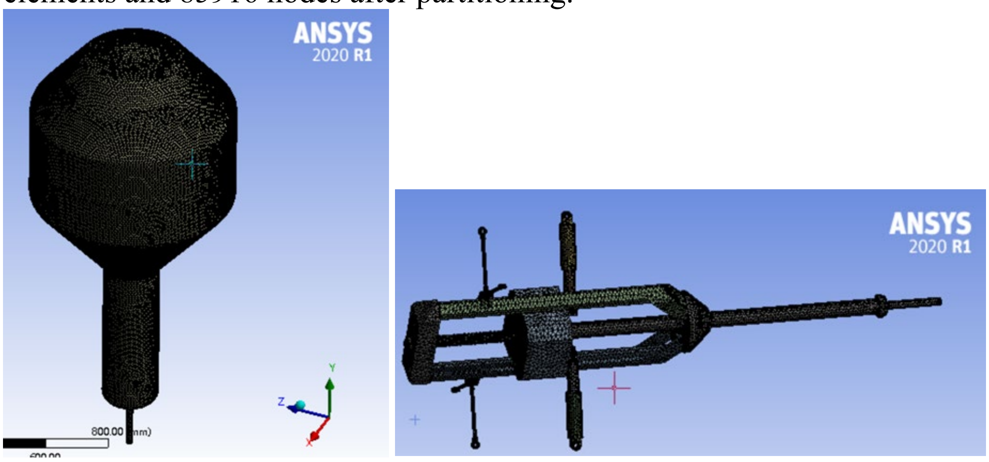


Fig. 9. Connection diagram

3.3 Grid Partition

Due to the complex characteristics of the structure, tetrahedron elements are selected to discrete the geometric modeling, then it is mapped into the finite element model. The overall unit size is controlled at around 4mm, and local small features are refined. In the Figures 10, the model consists of 303447 tetrahedral elements and 85916 nodes after partitioning.



(a) outside (b)inside

Fig. 10. The finite element model of the overall grid division outside and inside the device

3.4 Wave Model

In the load calculation of oscillating float type WEGPD, the fluent module in ANSYS workbench is used to simulate the flow field. The implementation idea is as follows: design a water tank model with a length, width, and height of 40m, 20m, and 20m respectively (Fig 11); divide it into grids with a unit of 0.6m; set up water inlet and outlet, water tank wall, air contact surface (Fig.12).

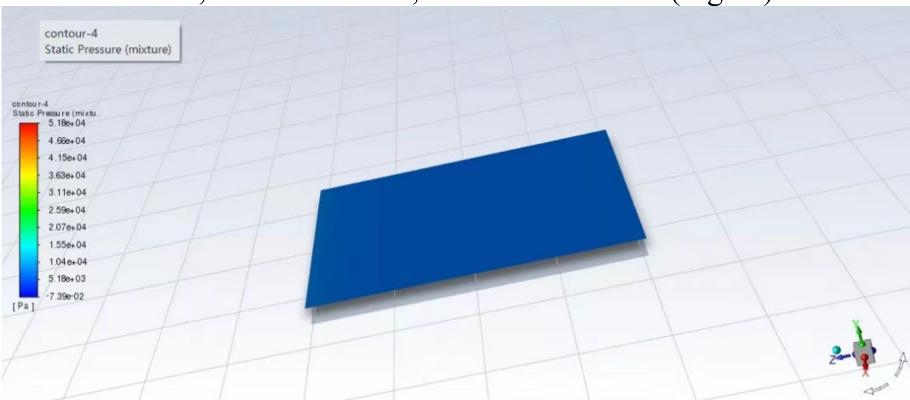


Fig. 11. Finite element model at the isosurface when waves are stationary

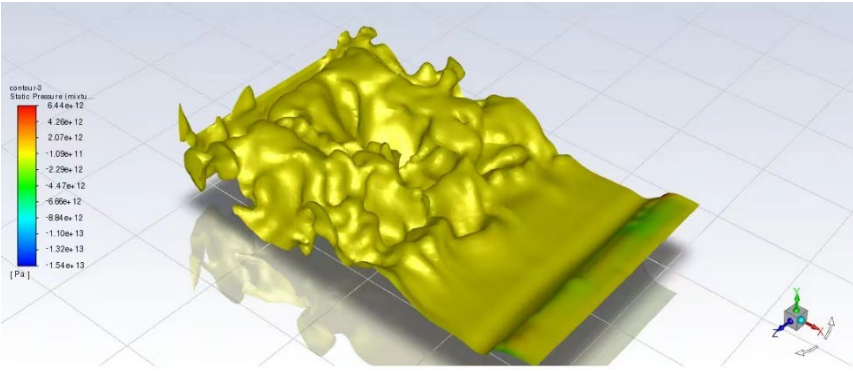


Fig. 12. The finite element model at the isosurface after 300 calculations when the waves begin to move

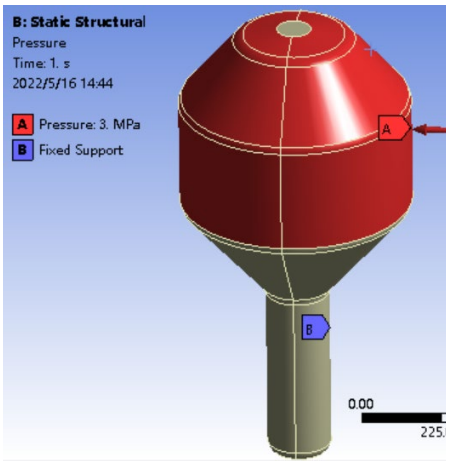
3.5 Applying Boundary Conditions and Loads

This paper calculates the stress situation of the shell under X and Z directions of force, as well as the pressure on the outer cover. The boundary conditions constrain the lower fixed rod, and the working conditions are defined according to the stress situation in Table 2. The load and boundary conditions applied under various working conditions are shown in Figure 13.

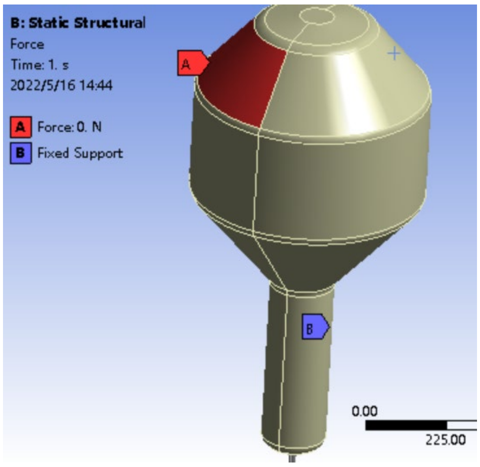
Table 2

Design Condition

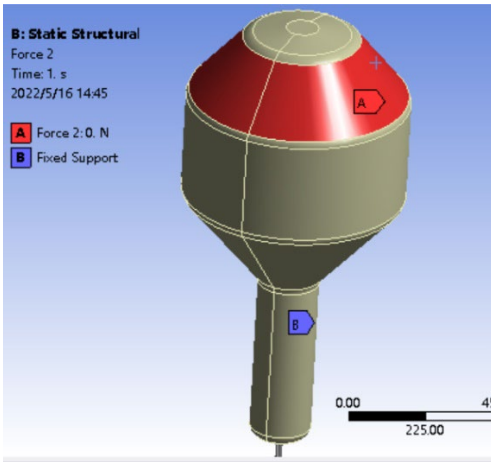
working condition	Overall pressure of the outer cover	The force on the outer cover in the X direction	The force on the outer cover in the Z direction
1	3Mpa	0	0
2	0	30kN	0
3	0	0	30kN



(a) working condition1



(b) working condition2



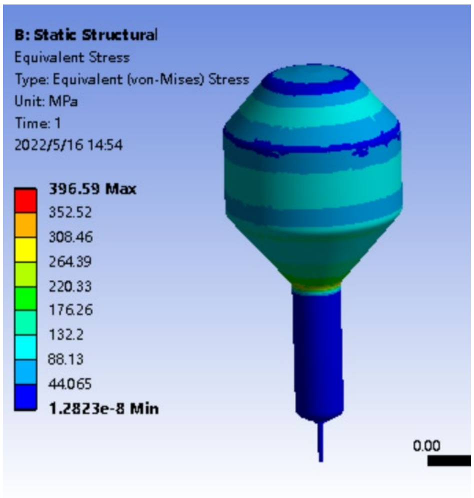
(c) working condition3

Fig. 13. Load and boundary conditions

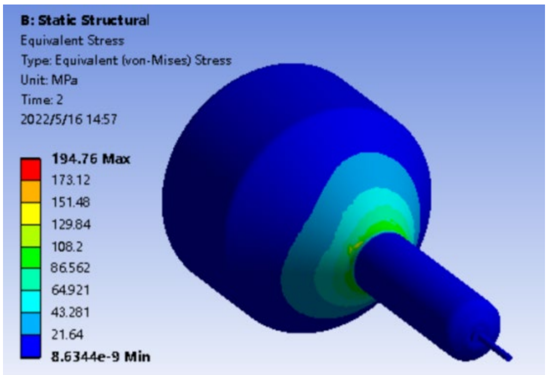
4. Simulation Result And Structural Analysis

4.1 Stress Analysis

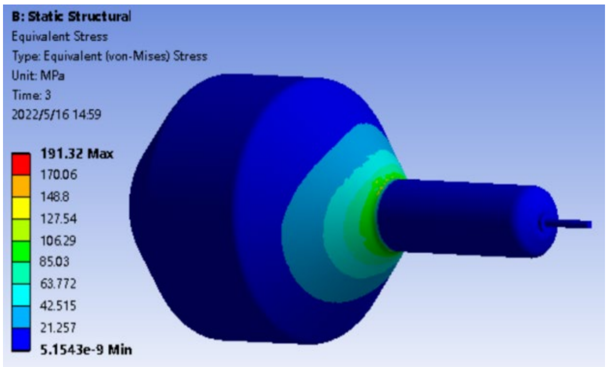
After applying the load, the workbench modulus in the ANSYS software is used to analyze the structure of the device and observe the stress cloud diagram, the results are shown in the figure 14,



(a) working condition1

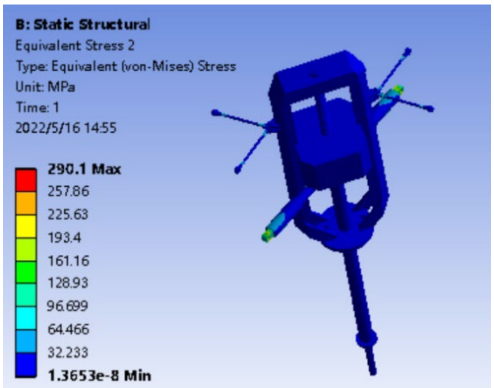


(b) working condition2

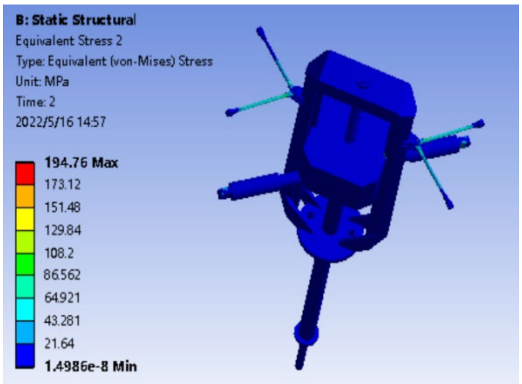


(c) working condition3

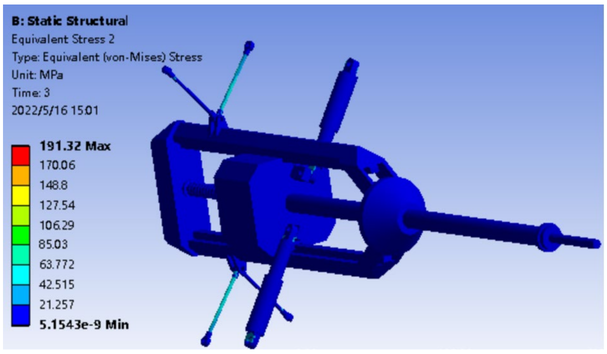
Fig. 14. External stress cloud diagram



(a) working condition1



(b) working condition2



(c) working condition3

Fig. 15. Internal stress cloud diagram

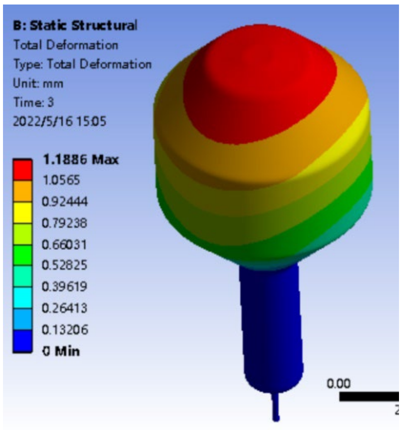
When the device works under condition 1 when the device sinks with waves, the external middle and lower parts of the float part of the device receive the most concentrated stress. As shown in Figure 14 (a), the stress relatively concentrates at the lower part of the device and stepping spreads along the upwards direction. The reason may be the small area of the lower root, which leads to high pressure under the same pressure and problem of stress concentration. Inside the float of the device, the part where the piston is connected to the float receives the most concentrated stress, as shown in Figure 15 (a). During the declining process of the device, the piston withstands a lot of stress that effectively protects the operation of the slider.

When the device operates under condition 2 when the device is pushed by waves parallel to the seabed, the external middle and lower parts of the float part of the device receive the most concentrated stress From Figure 14 (b), it can be seen that the stress is only concentrates at the lower part of the device. In the internal part of the float of the device, the stress received by the part connected to the float by the hinge is the most concentrated, which corresponds to the situation when the device is impacted by waves. In the Figure 15 (b), the hinge effectively bears the horizontal stress and protects the stability of the sliding rail during the impact of waves on the device.

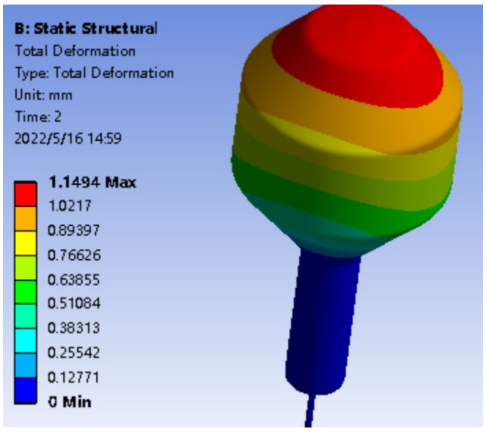
When the device operates under condition 3 when the device rises with waves, the stress received by the outer middle, lower, and upper parts of the float part of the device is the most concentrated. Figure 14 (c) shows that the stress is similar with condition 2. From Figure 15 (c), it can be seen that the stress inside the float of the device is the also same as Figure 15 (b).

4.2 Deformation Analysis

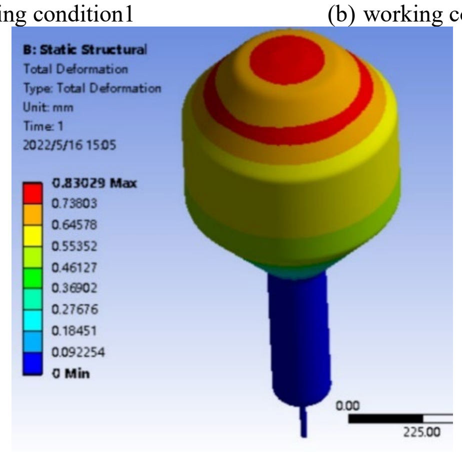
When the device rises, seawater will impact the upper part of the float in a vertical direction, as shown in Figure 16 (a). The deformation of the top and upper circular arches of the float is most serious, which appears a stepped distribution from top to bottom.



(a) working condition1

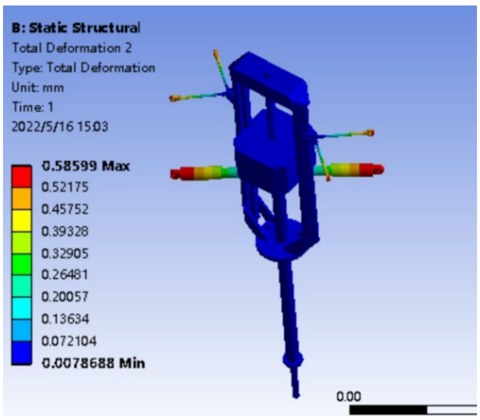


(b) working condition2

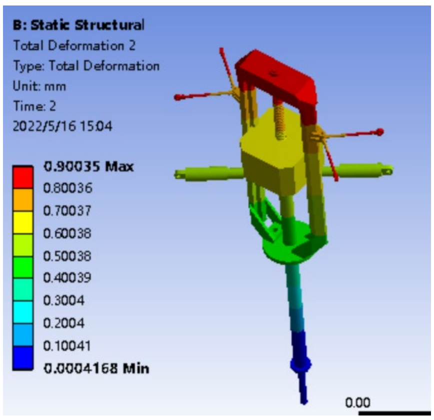


(c) working condition3

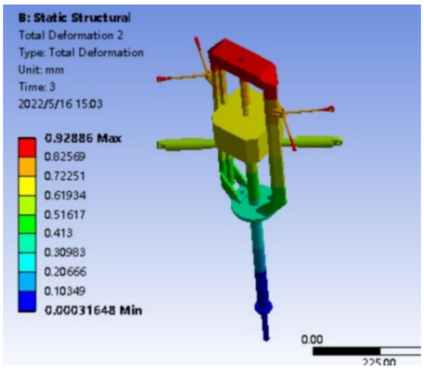
Fig. 16. External deformation cloud diagram



(a) working condition1



(b) working condition2



(c) working condition3

Fig. 17. Internal deformation cloud diagram

Figure 17 (a) shows the deformation cloud inside the device float, it can be seen that the position where the hinge rod and piston connected to the float is born the most severely deformed.

When the device is hit by waves in the horizontal direction, seawater will compress the float in the horizontal direction. As shown in Figure 16 (b), under the action of wave forces in the horizontal direction, the deformation presents an inclined shape with a stepped shape from top to bottom. Figure 17 (b) shows that under the action of wave forces in the horizontal direction, the maximum deformation locates at the upper section of the sliding rail inside the float and the hinge rod of the fixed sliding rail.

When the device descends, seawater will compress the float upwards in the vertical direction. Because of surface tension and inertia of seawater, it will cause a slap on the top of the device after entering the water from the air at the top of the float. As a result, severe deformation at the top of the device in the deformation cloud diagram, shown in Figure 16 (c). At the same time, there is also significant deformation at the slope of the upper part of the device due to the compression of seawater. From Figure 17 (c), it can be seen that the deformation situation inside the float of the device is the same as in Condition 2.

4.3 Influence of Working Conditions on Structural Analysis

Through the stress cloud diagram by the Workbench modulus, the wave pressure on the device shell is mainly reflected externally at the slope of the upper half of the shell, and a small portion concentrated on the outer wall in the condition 1. Internally, the piston inside the device bears the pressure. When the device situates in the condition 2, due to the movement and compression of wave protons in seawater, a pressure distribution cloud is similar to a ladder field inside the external shell of the device. Meanwhile, the pressure mainly concentrated on the sliding rail and the fixed rod of the specified sliding rail internally. In condition 3, the pressure inside the device will be transmitted from the intermediate rod to the hydraulic device, which will convert wave energy into usable energy.

Table 3

Structural statistics table

working condition	maximum stress （MPa）	Maximum deformation （mm）
1	396.59	0.83
2	194.76	1.15
3	191.32	1.19

From the Table 3, it can be seen that the maximum stress experienced by the device under condition 1 is 396.59 MPa, the value less than the yield strength of the upper material of the device shell (400 MPa). The maximum stresses under conditions 2 and 3 are 194.76 MPa and 191.32 MPa, respectively, which are lower than the yield strength of the remaining materials of the device shell of 200 MPa.

5. Conclusion

Based on the understanding of ocean wave motion characteristics and power generation devices, this paper design the scheme design of oscillating float WEPGD. With the fluent and workbench module of ANSYS software, the structure analysis of device model was completed, the results are as follows:

(1) When the device rises, the maximum stress located in the upper part of the external float of the device, and the deformation is also most significant. Inside the float, the hinge rod and piston of the fixed slide rail bear the maximum stress.

(2) When the device is impacted by waves in the horizontal direction, the stress outside the device float is distributed in an inclined stepped trend, which decreases from top to bottom. At the same time, due to the small action area and strong pressure at the root of the device, the stress at the root is more concentrated compared to the external wall stress in the vertical direction.

(3) When the device descends, the stress is most concentrated on the lower part the external float, and the deformation is also the most significant. And the similar condition is located on the beam at the top of the internal slide rail.

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