

# Analysis and Optimization on the Flow Ability of Wave Buoy Based on AQWA

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**Abstract.** Wave buoy is a modern ocean observation facility, and the ability of following wave is an important parameter to reflect the measurement accuracy. This article will focus on the study of hydrodynamics on the ability of three common appearance buoys. By using the hydrodynamic calculation software AQWA, this article will study the heaving response of free buoy in regular wave under frequency domain, it combined with the typical Green function method for solving the wave force and the related hydrodynamic coefficients of floating structure, and it applied the three dimensional potential flow theory and based on the single degree of freedom motion equation. According to the features of short period wave in Chinese sea states, this paper will calculate the heaving response RAOs of 25 buoys on different shapes, weight and shape parameters. Hydrodynamics calculation results show that: under the same conditions in the environment load, the flow-ability of ball float 3-2 has better performance than other buoys in working condition. The research methods of this article has provide good scientific basis for the parameter design on ocean data buoy.

## 1. Introduction

With the rapid development of the Marine economy in the world, measurement and collection of Marine environmental data is becoming increasingly important for human exploration and exploitation of Marine resources. Ocean data buoy which has the advantages of all-weather, all-day time, fixed point and reliability is widely used in measuring and collecting Marine environmental data. Description of Marine environment need to measure many parameters, and measurement of wave parameter is an important item. In order to ensure accurate measurement of wave parameters in different frequency ranges, oceanic data buoy should have better flow-ability in wave frequency range as large as possible. Flow-ability of buoy is mainly reflected in the heaving response, so the research of heaving motion under different frequency is of great significance for improving the accuracy.

At present, there are two methods to research the buoy motion characteristics at home and abroad: experimentation and numerical calculation. Wang D J et al. [1] calculated the wave exciting loads on a CALM buoy in water of finite depth with linearized potential wave theory. Leonard et al. [2] studied the coupling effect between buoy and mooring system through three-dimensional coupling analysis. Monroy et al. [3] simulated RAOs(response amplitude operator) of the CALM buoy in the regular and irregular wave by using SWENSE method which can simulate the fully nonlinear effects (including viscous effects) of fluid. Salem et al. [4] studied the linearization method about quadratic damping of the CALM buoy system with the frequency domain analysis method, and estimated the amplitude of pitching by using the linearization method. Zhaozheng Wang et al. [5] designed the disc-shaped data buoy and its mooring system and carried out the related model test. Based on the three dimensional potential flow theory, Quanming Miao et al. [6] calculated the hydrodynamic parameters(additional



added mass, damping and so on) and motion response of the free-floating buoy, and estimated the motion and tension responses of the three anchors buoy system in different depths under extreme sea conditions. Xiutao Fan, Huajie Wang et al. [7, 8] based on ignoring the influence of mooring, studied the heaving and rolling response of large wave buoys with spectral analysis. Jiming zhang et al. [9, 10] modified the roll damping coefficients of buoy by using model test, and simulated the rolling response of buoy with numerical simulation in frequency domain, which also ignored the effect of mooring.

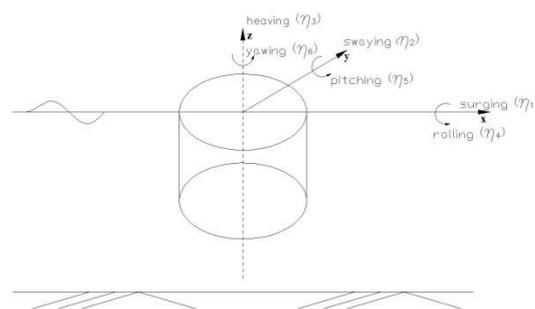
For Marine floating structures, the research priorities of domestic and foreign scholars focused on six degrees motion responses of the floating body and mooring force, but there are few studies on the heaving response which specially reflects the flow-ability of offshore buoy. In this paper, in order to be able to obtain the accurate prediction result of heaving response, the AQWA hydrodynamic calculation model is used to treat the buoy as a large scale component. Therefore, the hydrodynamic coefficients and wave force functions of the buoy are calculated by the three-dimensional potential flow theory. Based on the heave motion equation, the free floating buoy with different shape parameters under regular wave is analysed in frequency domain, and the heaving response amplitude operator (RAOs) is obtained. Compared with the calculation results, it is concluded that the ball float 3-2 has better work performance, which provides reference for the shape design of wave buoy.

## 2. Numerical Simulation

### 2.1. Frequency Domain Analysis under Linear Regular Waves

**2.1.1. Definition of coordinate system.** For convenience of calculations and description, the motion equation of wave buoy with six degree is generally defined as the following two coordinate systems: the reference coordinate system  $oxyz$  and the moving coordinate system  $o_0x_0y_0z_0$ . The origin of reference coordinate system is in the horizontal plane, plane  $oxy$  coincide with static water surface, and the  $z$ -axis is vertically upward. The moving coordinate system which keeps the same motion as the float and defines a coincidence point between initial static surface and float as the origin of coordinates is fixed on the float. The directions of the two frames that are also consistent satisfy the Descartes right-hand rule. The two frames coincide when the float is stationary.

As shown in Figure 1, the wave force under the regular wave that is decomposed into six directions results in the DOF motion which are rolling, pitching, yawing and surging swaying, heaving. Since the Marine data buoy mainly needs to research its flow-ability, the main considerations in this study are heaving response.



**Figure 1.** The DOF motion of float

**2.1.2. The potential flow theory.** Based on the theory of three-dimensional potential flow, the hydrodynamic analysis of float is carried out under regular wave. Need to be satisfied: water is an ideal and incompressible fluid without spinning, the wave is a small amplitude wave. The velocity potential should satisfy the following conditions:

$$\text{Control equation: } \nabla^2 \phi = 0 \quad (1)$$

$$\text{Free surface boundary condition: } -\omega^2 \phi + g \frac{\partial \phi}{\partial z} = 0, \quad z = 0 \quad (2)$$

$$\text{Seabed boundary condition: } \frac{\partial \phi}{\partial n} = 0, \quad z = -h \quad (3)$$

$$\text{Free surface motion condition after linearization: } \frac{\partial \zeta}{\partial t} - \frac{\partial \phi}{\partial z} = 0 \quad (4)$$

$$\text{Free surface dynamic condition after linearization: } \frac{\partial \phi}{\partial t} + g\zeta = 0 \quad (5)$$

In general, the above conditions are solved by using Green function method which establishes the integral equation between the velocity potential and Green function. In solving the integral equation, the boundary element method is used to discrete the object surface for a certain number of units, then to calculate the strength in the center of each unit (called source point) under the boundary conditions, and to obtain the velocity potential at each node with the pulse source distribution.

After the radiation and diffraction velocity potential of the structure are calculated, the first order hydrodynamic pressure can be expressed as:

$$p = -\rho \frac{\partial \phi}{\partial t} \quad (6)$$

The total wave force is obtained by integrating the wet surface of the object:

$$F = \iint_S p n dS \quad (7)$$

Here, S is wet surface of the object; generally speaking, the first wave force consists of three parts:

$$F = F_{HS} + F_R + F_{EX} \quad (8)$$

Here, F is the first wave force;  $F_{HS}$  is rigid hydrostatic restoring force;  $F_R$  is Radiation force;  $F_{EX}$  is the first wave excitation force and moment which are generated in the interaction of wave incidence and diffraction velocity potential.

*2.1.3. The frequency domain control equation.* In the study of the hydrodynamic response of the floating body, it is generally considered to be a rigid body with six degrees of freedom. According to Newton's second law, the buoy maintains a static equilibrium under multiple forces which are the static water restoring force, the inertial force, the damping force and the wave excitation force. Based on the three dimensional potential flow theory, considering the action of hydrostatic restoring force and wave exciting force (summation of the incident and diffraction forces), the boundary element method is used to calculate the buoy motion response in frequency domain, frequency control equation under linear regular wave is given:

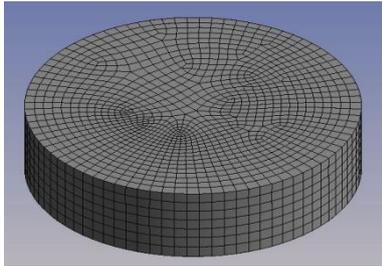
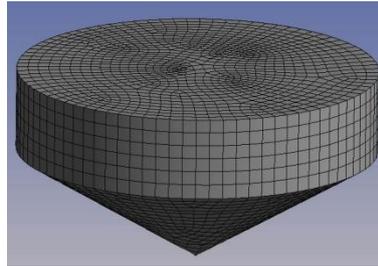
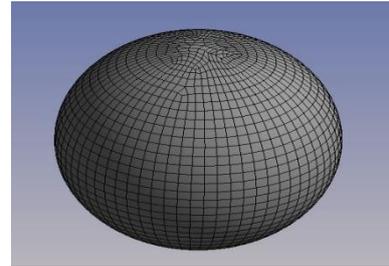
$$(M + \mu(\omega))\ddot{X} + C(\omega)\dot{X} + KX = F(\omega) \quad (9)$$

Here, M is the mass matrix,  $\mu$  is the added mass matrix, C is the damping coefficient matrix, K is the static water restoring stiffness matrix, F is the wave exciting force matrix, X is the motion response matrix. The additional mass  $\mu$ , potential flow damping coefficient C and wave excitation force F can be calculated by the potential flow theory.

## 2.2. Geometric Modeling

*2.2.1. 3-D model.* Using AutoCAD 2011, three kinds of floating models with different shapes (flat cylindrical, conical bottom cylindrical and ball) were established and the shape parameters were changed. Then, respectively import models into the AQWA module in ANSYS 15.0 for frequency domain analysis.

*2.2.2. Mesh generation.* Using AQWA to automatic meshing: the maximum size of the grid element is 0.2m, the defeaturing tolerance is 0.1m, the maximum allowed frequency is 1.314HZ, and the meshing type is selected as combined meshing, and the quadrilateral grid is obtained. It is noteworthy that it is not yet possible to employ symmetry mesh in AQWA. The grid divisions of three kinds of float are shown in Figure 2, Figure 3 and Figure 4.

**Figure 2.**Meshing of flat float**Figure 3.**Meshing of cone float**Figure 4.**Meshing of ball float

At the same time of external environmental load, the heaving responses of floats with different sizes, different weight and different shapes are analyzed by using the AQWA. Comparing the difference between wave amplitude and heaving response amplitude of various floats, the float model which has the best flow-ability and can be used to determine the optimum shape parameters for oceanic wave buoy is obtained.

### 2.3. Calculating Case

The working performance of wave buoy is influenced by many external factors, such as weight, shape parameter, shape, wave factor and so on. Compared with the European waters, the characteristics of Chinese waters is short period and low-height. In order to achieve more accurate detection in offshore waters of China, we need to design the buoy which is suitable for short period and low height. In this paper, in order to determine the relatively superior floating shape, the floats of 25 working conditions (see Table 1, Table 2 and Table 3) are designed to analyze the floating flow-ability with different parameters under the same conditions of external environmental loads. In the table, the submerged depth refers to the height of the bottom of the float to the static water surface.

**Table 1.**Working conditions of flat float

| Model | Height (m) | Diameter (m) | Weight (kg) | Submerged depth (m) | Grid numbers |
|-------|------------|--------------|-------------|---------------------|--------------|
| 1-1   | 0.8        | 3.2          | 1000        | 0.121               | 2874         |
| 1-2   | 0.8        | 3.2          | 1500        | 0.182               | 2904         |
| 1-3   | 0.8        | 3.2          | 2500        | 0.303               | 2958         |
| 1-4   | 0.8        | 3.2          | 3500        | 0.425               | 2791         |
| 1-5   | 0.8        | 3.2          | 5500        | 0.667               | 2791         |
| 1-6   | 0.8        | 2.4          | 2500        | 0.539               | 1919         |
| 1-7   | 0.8        | 4.0          | 2500        | 0.194               | 4225         |
| 1-8   | 1.6        | 3.2          | 2500        | 0.303               | 3295         |
| 1-9   | 2.4        | 3.2          | 2500        | 0.303               | 4142         |

**Table 2.**Working conditions of cone float

| Model | Height (m) | Diameter (m) | Taper (°) | Weight (kg) | Submerged depth (m) | Grid numbers |
|-------|------------|--------------|-----------|-------------|---------------------|--------------|
| 2-1   | 1.6        | 3.2          | 120       | 1000        | 0.677               | 2424         |
| 2-2   | 1.6        | 3.2          | 120       | 2500        | 0.919               | 2631         |
| 2-3   | 1.6        | 3.2          | 120       | 4500        | 1.162               | 2480         |
| 2-4   | 1.6        | 3.2          | 120       | 6500        | 1.389               | 2480         |
| 2-5   | 2.0        | 3.2          | 90        | 2500        | 1.325               | 2571         |
| 2-6   | 1.2        | 3.2          | 150       | 2500        | 0.589               | 2345         |

**Table 3.** Working conditions of ball float

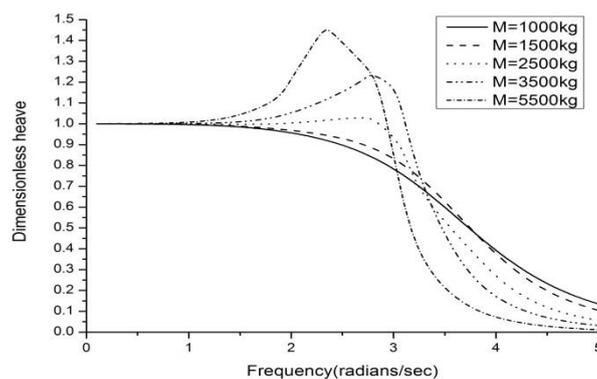
| Model | Diameter (m) | Weight (kg) | Submerged depth (m) | Grid numbers |
|-------|--------------|-------------|---------------------|--------------|
| 3-1   | 3.2          | 1500        | 0.575               | 2616         |
| 3-2   | 3.2          | 2500        | 0.759               | 2897         |
| 3-3   | 3.2          | 4500        | 1.059               | 3078         |
| 3-4   | 3.2          | 7500        | 1.443               | 3202         |
| 3-5   | 3.2          | 11500       | 1.933               | 3195         |
| 3-6   | 3.2          | 16500       | 2.716               | 2464         |
| 3-7   | 2.4          | 2500        | 0.935               | 1813         |
| 3-8   | 2.8          | 2500        | 0.832               | 2329         |
| 3-9   | 3.6          | 2500        | 0.704               | 3360         |
| 3-10  | 4.0          | 2500        | 0.661               | 3909         |

### 3. Result and Analysis

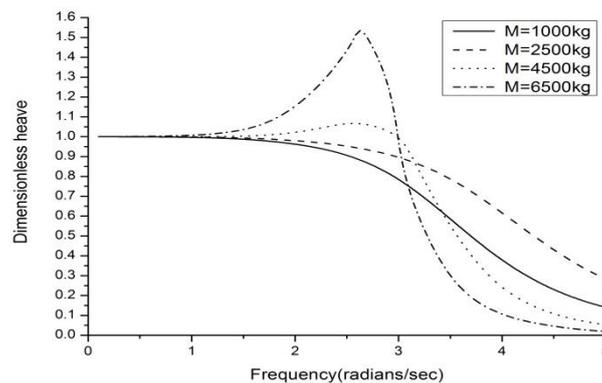
Set the sea water depth to  $h = 15m$ , seawater density to  $\rho = 1025 kg/m^3$ , the gravity acceleration to  $g = 9.8 N/kg$  and the wave frequency which is calculated to  $\omega = 0 \sim 5 rad/s$ . And set the wave amplitude to 1m. The RAOs (amplitude response operator) about heaving of each float in different wave frequency is calculated by using AQWA.

#### 3.1. The Influence of Float Weight

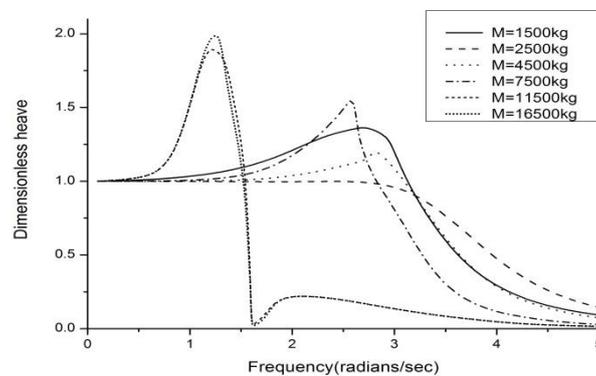
Select model 1-1, 1-2, 1-3, 1-4 and 1-5 to analyze the effect of float weight on the heaving motion of the flat-bottomed float, and the RAOs about heaving varies with frequency are shown in Figure 5. When the wave frequency is less than 1 rad/s, the amplitude of the heaving motion of different weight float is consistent with the wave amplitude (1m). But when the wave frequency is between 1 ~3rad/s, only the model 1-3 is still close to the wave amplitude, has better flow-ability and more accurate monitoring of wave data. The more the weight is in the high frequency range, the more likely it is to resonate.

**Figure 5.** Effect of mass on heaving amplitude of flat float

As shown in Figure 6, model 2-1, 2-2, 2-3 and 2-4 are used to analyze the effect of mass on heaving motion of the cone bottom floater. The tendency of the RAOs varies with the wave frequency is the same as flat bottomed float. When the wave frequency is 1 ~ 3rad/s, only the model 2-2 is still relatively close to the wave amplitude, and the flow-ability is better than others.



**Figure 6.** Effect of mass on heaving amplitude of cone float



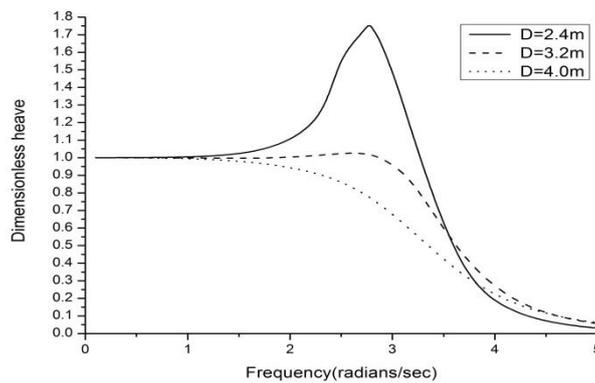
**Figure 7.** Effect of mass on heaving amplitude of ball float

As shown in Figure 7, model 3-1, 3-2, 3-3, 3-4, 3-5 and 3-6 are chosen to analyze the effect of mass on heaving motion of ball floater. The over-weight ball float resonates with wave in the low frequency region. When the wave frequency is 1 ~ 3rad/s, only the model 3-2 is relatively close to the wave amplitude, and the flow-ability is better than others.

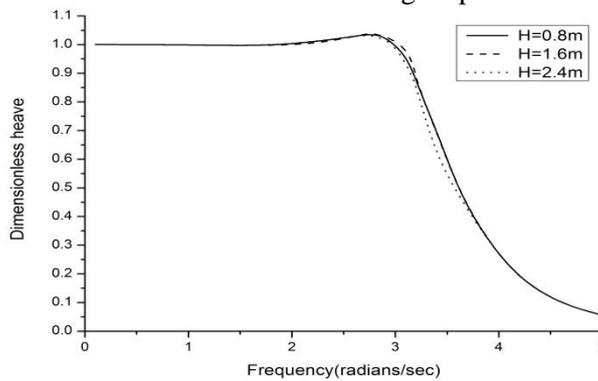
According to the above analysis shows: when the float hydrostatic surface were of round cross-section, whatever shape of the floating bottom are, the trend of float work performance with the weight change rule is roughly same under the same wave frequency, that is to say, the trend of float heaving amplitude with weight is the same. The larger the difference between float amplitude with wave amplitude is, the more inaccurate the buoy monitoring data is. Therefore, the buoy whose heaving amplitude is the closest to the wave amplitude can be chosen, its flow-ability is the best and the motion is relatively stable. Compared with the working performances of 15 selected models, model 1-3, 2-2 and 3-2 are better than others.

### 3.2. The Influence of Float Shape Parameters

The influence of float diameter on the heaving motion is analysed by selecting model 1-3, 1-6 and 1-7, and the RAOs about heaving varies with frequency are shown in Figure 8. Under the condition of the same quality, the smaller float diameter is, the greater heaving amplitude in high frequency range is, and the more unstable heaving motion is. Float whose diameter is lager is easy to resonate with wave, resulting in inaccurate measurement results. When the wave frequency is less than 2.5 rad/s, the amplitude of a model with a diameter of 3.2m is the closest to wave, and the monitoring result is the most accurate.



**Figure 8.** Effect of diameter on heaving amplitude of flat float

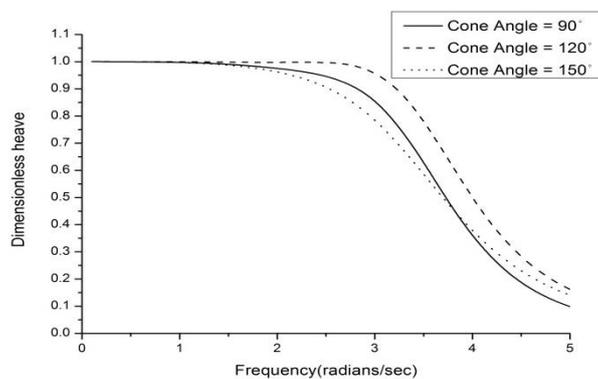


**Figure 9.** Effect of height on heaving amplitude of flat float

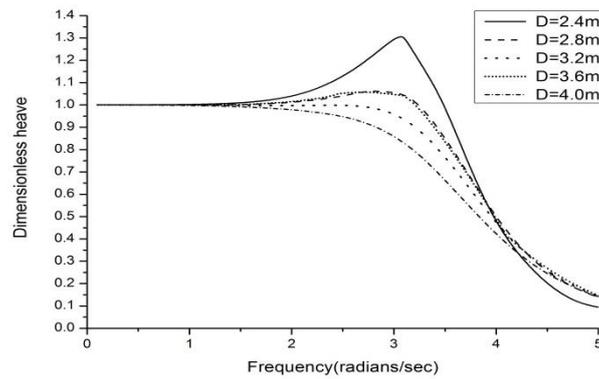
The influence of the float height on the heaving motion is analysed by selected model 1-3, 1-8 and 1-9, and the RAOs about heaving varies with frequency are shown in Figure 9. With the same diameter and quality, the tendency that heaving amplitude of flat float with different heights varies with the wave frequency are roughly coincide. When wave frequency is less than 3 rad/s, calculated results shown that all models are close to wave and monitoring are more accurate. Therefore, the effect of height on float flow-ability can be ignored.

The influence of the float cone angle on the heaving motion is analysed by selecting model 2-2, 2-5 and 2-6, and the results were shown in Figure 10. When wave frequency is 0 ~ 2.8 rad/s and the cone Angle is 120 °, the heaving amplitude is the closest to wave.

The influence of spherical diameter on the heaving motion is analysed by selecting model 1-2, 1-7, 1-8, 1-9 and 1-10, and the results are shown in Figure 11. When the wave frequency is less than 3.0 rad/s, the amplitude of a model with a diameter of 3.2m is the closest to wave, and the monitoring result is the most accurate.



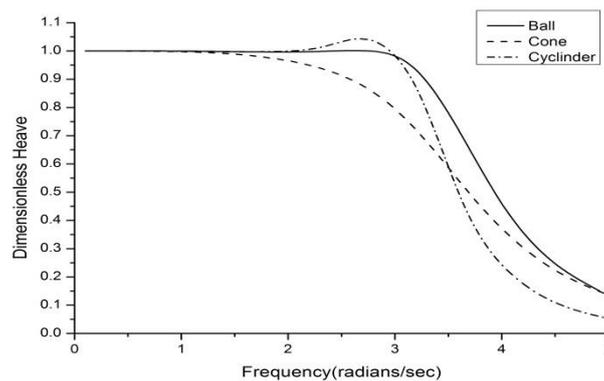
**Figure 10.** Effect of angle on heaving amplitude of cone float



**Figure 11.**Effect of diameter on heaving amplitude of ball float

3.3. *The Influence of Float Shape*

Select model 1-3, 2-2 and 3-2 to analyze the effect of float shape on the heaving motion, as shown in figure 12. The distribution curve of floating heaving amplitude with different shapes changing with wave frequency is roughly the same, and the amplitude decreases with the increase of wave frequency. However, the heaving amplitude of 3-2 is more similar to the wave amplitude in the longer frequency range, that is to say, it is more accurate to monitor wave data in short period.



**Figure 12.**Effect of shape on heaving amplitude of float

3.4. *Results Summary*

According to the above analysis, the heaving amplitude of each float that is compared with wave amplitude (this paper is set as 1m) when the wave frequency is 2.8rad/s, the results are shown in Table 4, and these results are took as a sign to determine which has better flow-ability (the smaller the difference between heaving motion and wave is, the better flow-ability is) under the high wave frequency.

**Table 4.**The relative amplitude of each float model

(The relative amplitude refers to the difference between the heaving amplitude and the wave amplitude)

| Model | Heaving amplitude | The relative amplitude | Model | Heaving amplitude | The relative amplitude | Model | Heaving amplitude | The relative amplitude |
|-------|-------------------|------------------------|-------|-------------------|------------------------|-------|-------------------|------------------------|
| 1-1   | 0.85              | 0.15                   | 2-1   | 0.85              | 0.15                   | 3-1   | 1.33              | 0.33                   |
| 1-2   | 0.90              | 0.10                   | 2-2   | 0.92              | 0.08                   | 3-2   | 1.00              | 0.00                   |
| 1-3   | 1.04              | 0.04                   | 2-3   | 1.08              | 0.08                   | 3-3   | 1.14              | 0.14                   |
| 1-4   | 1.24              | 0.24                   | 2-4   | 1.24              | 0.24                   | 3-4   | 1.20              | 0.20                   |
| 1-5   | 1.27              | 0.27                   | 2-5   | 1.92              | 0.92                   | 3-5   | 0.16              | 0.84                   |

|     |      |      |     |      |      |      |      |      |
|-----|------|------|-----|------|------|------|------|------|
| 1-6 | 1.72 | 0.72 | 2-6 | 0.85 | 0.15 | 3-6  | 0.16 | 0.84 |
| 1-7 | 0.78 | 0.22 |     |      |      | 3-7  | 1.23 | 0.23 |
| 1-8 | 1.04 | 0.04 |     |      |      | 3-8  | 1.07 | 0.07 |
| 1-9 | 1.04 | 0.04 |     |      |      | 3-9  | 1.07 | 0.07 |
|     |      |      |     |      |      | 3-10 | 0.91 | 0.09 |

The statistics of the above table show that: five models (model 1-4, 1-5, 1-6, 2-4 and 2-5 ) resonate with wave frequency of about 2.5 rad/s and two models (model 3-5 and 3-6) resonate with wave frequency of about 1.2 rad/s, leading to the inaccuracy of measuring the wave data. And only model 3-2 has the smallest relative amplitude in the wave frequency of 2.8 rad/s. Considering the float height has no influence on the heaving amplitude, so the model 3-2 with the best stability is chosen as the initial selection of the oceanic data buoy.

#### 4. Summary and Prospect

This paper selected the float model for biaxial symmetry structure, and the motion of other degrees has no coupling effect on heaving. The single degree of heaving model can accurately describe the heaving response. In this paper, frequency domain analysis of float was carried out under the regular wave with the AQWA hydrodynamics calculation model and the potential flow theory, and the heaving amplitude were calculated by using numerical analysis method. 25 models with three shapes are chosen as examples to carry on the numerical simulation, is used to analysis the effect of float weight, diameter, height, taper angle and shape on the heaving amplitude.

The results show that: the larger the float is, the larger the heaving amplitude is, but the overall trend is roughly the same; the influence of float diameter and bottom taper angle on heaving amplitude is larger, and the variation rule is nonlinear; the performance of float is not influenced by float height; in comparison, model 3-2 has better flow-ability in the longer wave frequency range, which is more suitable for the measurement of China sea with short period wave.

According to the analysis results, this paper completed the preliminary selection of wave data buoy, and laying the foundation for the optimization of the shape parameters.

In this paper, the heaving motion characteristics of float are studied under regular wave, but the real marine condition is extremely complicated. Therefore, it is necessary to further simulate the working performance of float under irregular waves. In addition, this paper only analysed the motion characteristics of free-float in regular wave, without considering the coupling effect of buoy and mooring system.

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