

# Mechanical Analysis and Optimal Design of Wave Energy Device

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**Abstract.** At present, the global energy problem is serious. Wave energy is the kinetic energy and potential energy of waves on the ocean surface. Because of its high energy density, wide distribution, and long continuous operation of the device, it has become the focus of academic research. The key problem to be solved urgently for the large-scale application of wave energy is how to optimize the energy conversion efficiency of wave energy devices. This paper starts from the Newtonian dynamic equation, analyzes the motion state of the wave energy device in different wave environments, and studies the optimization and control of its power output. This paper first adopts the analysis method of first whole and then isolation, and establishes a one-dimensional coordinate system with the zero point of sea level. Then, the force analysis of the system is carried out, the dynamic differential equation is established, and the initial draft of the system is solved through the initial balance equation. Since the dynamic equation is a second-order linear ordinary differential inhomogeneous linear equation, the fourth-order Runge is used. The Kutta method is used to solve the problem, and the numerical solution for the position and velocity of the float is obtained. Secondly, the movable coordinate system is established with the float as the reference system, and the force analysis of the oscillator is carried out to obtain its relative dynamic equation. Then, the initial relative position of the oscillator is solved through the initial balance equation, and the relative dynamic differential equation is obtained by using the fourth-order Runge-Kutta method to obtain the numerical solution of the relative position and relative velocity of the oscillator with respect to time. Finally, the numerical solution of the absolute position and absolute velocity of the oscillator with respect to time is obtained through coordinate transformation.

**Keywords:** Exhaustive method, fourth-order Runge-Kutta, bivariate optimization.

## 1. Introduction

At present, the global energy problem is serious, and achieving sustainable energy development, optimizing energy utilization efficiency and reducing pollution are the problems that the world is trying to solve. Wave energy is the kinetic energy and potential energy of waves on the ocean surface. Because of its high energy density, wide distribution (compared to other renewable energy sources such as wind and solar energy), and the advantages of long continuous operation of the device, it has become the focus of academic research. The key problem to be solved urgently for the large-scale application of wave energy is how to optimize the energy conversion efficiency of wave energy devices. [1]

Considering a common wave energy device, the two ends of the spring and the linear damper are respectively fixed on the vibrator and the central axis base, the central axis base is fixed at the center of the partition, and the vibrator reciprocates on the central axis. The damping force of the linear damper is proportional to the relative speed [2] of the float and the vibrator, and its proportional coefficient is the damping coefficient of the linear damper. It is assumed that the float only performs heaving motion in the ocean waves, and the float and the oscillator are balanced in still water at the initial moment. This paper mainly considers the following two states to calculate the heave displacement and velocity of the float and the oscillator under the action of the wave excitation force with a time interval of 0.2s in the first 40 wave cycles. Heaving velocity and displacement at 100s. [3]

## 2. Problem Hypothesis

- 1) The wave motion is a simple harmonic motion, and the wave force on the float body changes sinusoidally;
- 2) The system is only affected by waves, not affected by other factors such as wind;
- 3) The immersion surface of the float is approximately horizontal
- 4) Only the mass of the float and vibrator is considered, and other masses are ignored;
- 5) There is no loss in the energy transfer process;
- 6) The spring is deformed within its elastic limit;
- 7) The rotation center of the system for pitch motion is its geometric center.

## 3. Problem Formulation and Algorithm

### 3.1. Preliminaries

- Newton's second law:

The magnitude of the acceleration of an object is proportional to the force, inversely proportional to the mass of the object, and proportional to the reciprocal of the mass of the object; the direction of the acceleration is the same as the direction of the force.

- Archimedes' Law [4]:

An object immersed in a fluid (gas or liquid) experiences a buoyant force equal to the weight of the fluid displaced by the object, directed vertically upward and through the centroid of the displaced fluid.

- Hydrostatic Resilience:

A floating body that performs heaving motion in waves will be subjected to a force that returns the floating body to its equilibrium position, which is called the hydrostatic restoring force. The hydrostatic restoring force is caused by the change in the buoyancy of the floating body during heaving motion. Therefore, we regard the still water restoring force as the change of the buoyant force when the floating body is heaving relative to the buoyancy force when it is stationary in still water. Therefore, it is proposed in the following text that  $F_b$  is already the sum of the buoyancy and the restorative force at rest.

### 3.2. Algorithm

Taking the sea level as the zero point of the reference system, the Z-axis is established, and the system is taken as the research object, and the force analysis on it is shown in Figure 1. The motion of the system is shown in Figure 2. [5]

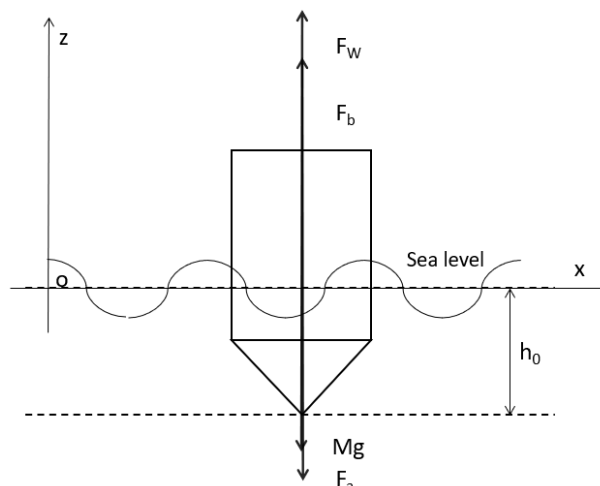
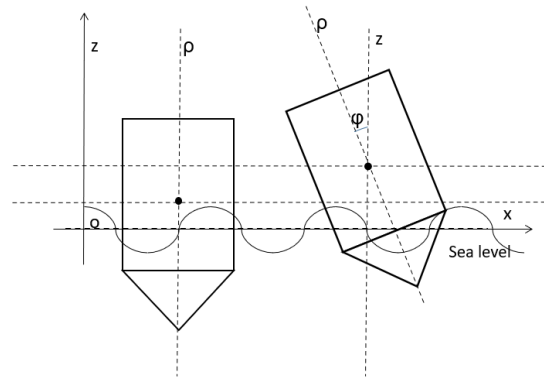


Figure 1. System stress analysis diagram



**Figure 2.** Schematic diagram of float movement

The dynamic equation of the system is listed according to Newton's second law as follows [6]:

$$(M + M') \frac{d^2 z}{dt^2} = F_t \tag{1}$$

Where  $M$  is the mass of the system, because it is assumed that the total mass of the device is approximately the sum of the masses of the float and the vibrator, and  $z$  is the displacement of the system relative to the initial moment (upward).  $M'$  is the positive direction,  $F_t$  is the resultant external force on the system:

$$F_t = F_b + F_{w\perp} - Mg - F_a \tag{2}$$

Where  $F_b$  is the buoyancy of the system:

The wave excitation force can be expressed as follows:

$$F_{w\perp} = F \cos \omega t = F \cos(2\pi ft) \tag{3}$$

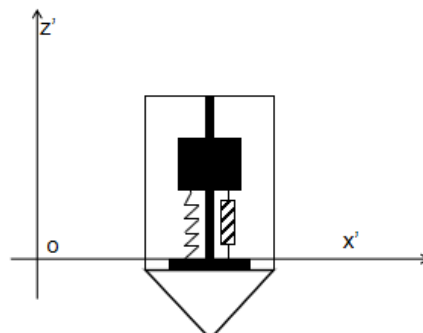
Where  $F$  is the amplitude of the wave excitation force,  $\omega$  is the wave frequency, and  $f$  is the wave frequency.

Wave damping can be expressed as follows:

Because the question only considers the heave motion of the system, the heave motion has no angular velocity, and the wave-making damping force is proportional to the speed of the heave motion, and the direction is opposite, the proportional coefficient is called the wave-making damping coefficient, so the wave-making resistance is set as  $k_a$ , the wave-making damping force  $F_a$  can be expressed as follows:

$$F_a = k_a \frac{dz}{dt} \tag{4}$$

Then, as shown in Figure 3, with the float as the active reference system and the base of the central axis as the zero point, establish the axis.



**Figure 3.** Active coordinate system

Finally, our algorithm analysis and steps can be summarized as follows. If the absolute heave displacement and absolute heave velocity of the float and the vibrator in two states are required respectively, the acceleration of the absolute heave motion of the float and the vibrator needs to be calculated, and the acceleration is integrated to obtain the absolute heave displacement and absolute heave speed [7].

It is assumed that the float only performs heaving motion in the ocean waves, and the float and the oscillator are balanced in still water at the initial moment. The absolute heave displacement and absolute heave velocity of the float are required, in order to simplify the calculation. First, taking the sea level as the fixed reference frame, the float and the vibrator are regarded as a system for force analysis, and the resultant external force on the system is obtained. Secondly, according to Newton's second law [8], the absolute acceleration of the system can be obtained. Then, the absolute heave velocity and absolute heave displacement of the system (that is, the float) can be obtained by integrating the absolute acceleration once and twice. To find the absolute heave displacement and absolute heave velocity of the vibrator, take the float as the active reference frame, carry out the force analysis on the vibrator, obtain the resultant external force on the vibrator, and find it according to Newton's second law in the non-inertial reference frame. The relative acceleration is then integrated to obtain the relative displacement and relative velocity of its heave motion. Finally, convert its relative motion into absolute motion through coordinate transformation, and then the absolute velocity and absolute displacement of the oscillator heave motion can be obtained [9].

### 3.3. Results

In this subsection, we will show the structure of our algorithm. We see Table 1-Table 4 for the heave displacement and velocity of the float and oscillator at 10s, 20s, 40s, 60s, and 100s. It can be seen from the results in Tables 1-4 that our algorithm can solve this problem very well.

**Table 1.** Heave displacement and velocity of float (Case 1)

| Time (s)         | 10      | 20      | 40      | 60      | 100     |
|------------------|---------|---------|---------|---------|---------|
| Displacement (m) | 0.0063  | 0.0022  | -0.0097 | -0.0108 | -0.0089 |
| speed (m/s)      | -0.0254 | -0.0406 | -0.0352 | -0.0198 | -0.0109 |

**Table 2.** Heave displacement and velocity of oscillator (Case 1)

| Time (s)         | 10      | 20      | 40      | 60      | 100     |
|------------------|---------|---------|---------|---------|---------|
| Displacement (m) | -1.3054 | -1.3087 | -1.3185 | -1.3187 | -1.3156 |
| speed (m/s)      | 0.0923  | 0.0808  | 0.0889  | 0.1054  | 0.1177  |

**Table 3.** Float heave displacement and velocity (Case 2)

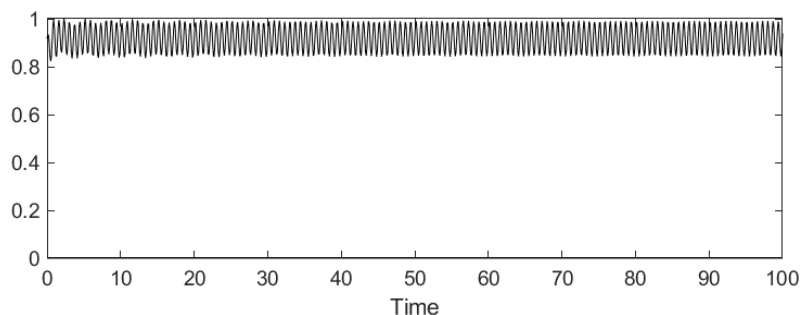
| Time (s)         | 10      | 20      | 40      | 60      | 100     |
|------------------|---------|---------|---------|---------|---------|
| Displacement (m) | 0.0063  | 0.0022  | -0.0096 | -0.0107 | -0.0089 |
| speed (m/s)      | -0.0254 | -0.0406 | -0.0352 | -0.0198 | -0.0109 |

**Table 4.** Heave displacement and velocity of oscillator (Case 2)

| Time (s)         | 10      | 20      | 40      | 60      | 100     |
|------------------|---------|---------|---------|---------|---------|
| Displacement (m) | -1.3149 | -1.3180 | -1.3279 | -1.3282 | -1.3249 |
| speed (m/s)      | 0.1156  | 0.1071  | 0.1203  | 0.1415  | 0.1624  |

### 3.4. Algorithm Robustness Analysis

Give a 5% perturbation to the damping coefficient R or the proportional coefficient r, get a new damping coefficient r, bring r into the model of problem 1, and solve the change rate of the displacement and velocity of the float and the vibrator after the perturbation. From Figure 4, by observing the rate of change before and after the disturbance, it can be found that the ratio is mainly stable around 1, indicating that our algorithm is not sensitive to the change of the damping coefficient. That is, our algorithm can be more widely applied to other problems.



**Figure 4.** Displacement after disturbance and before disturbance

## 4. Conclusion

This paper is devoted to solving the mechanical analysis and optimization problems of wave energy devices accurately. In order to solve this problem, the algorithm in this paper adopts the enumeration method [10], which is simple and easy to prove the correctness of the results, which can better simulate the motion process and energy output of the wave energy device. Furthermore, we use the fourth-order Runge-Kutta method to solve the differential equation, which has high accuracy. In future work, we will simplify the problem assumptions and consider more realistic factors, such as the vulnerable influence of the actual working state of the wave energy device, the quality of some components, the influence of energy dissipation on the output power, and the sea surface is regarded as the level, etc.

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