Research on Motion Modeling and Numerical Solution for Float-Oscillator Systems in Wave Energy Devices

Keyang Liu, Xiaoyang Shi, Mindong Liu*

* jaguartiger@just.edu.cn

School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212100, China

Abstract: This study formulates a coupled second-order non-homogeneous differential equation system for the float and oscillator by integrating Newton's second law with wave excitation forces. For the two damping cases of linear and nonlinear, the equation system is transformed into a fourth-order differential equation system, and the fourth-order Runge Kutta method is used to perform numerical iterative calculations with a time step of 0.02s. The heave displacement and velocity of the first 40 wave cycles at a time interval of 0.2s are obtained, and specific parameters at specific times are extracted. The results showed that under both damping conditions, displacement and velocity fluctuated over time and gradually stabilized. At some moments, such as 10 seconds, under linear damping, the float displacement was -0.1905185m and the velocity was -0.6398664m/s, while under nonlinear damping, the displacement was -0.2057268m and the velocity was -0.6511330m/s. Selecting 0.002 as the smaller step length for testing, it was found that the difference between the obtained results and the original step size calculation results was small, indicating that the model results have high reliability.

Keywords: Wave energy converter; Float-oscillator system; Equation of motion; Fourth-order Runge-Kutta method; Numerical solution; Linear and nonlinear damping

1. Introduction

Wave energy, as an important marine renewable energy source, has the characteristics of wide distribution and abundant reserves. Growing worldwide energy needs and pollution challenges have intensified focus on wave energy deployment [1]. The wave energy device achieves efficient energy utilization by converting the mechanical energy of waves into electrical energy. In addition, the efficiency of its energy conversion constitutes a key concern for the large-scale deployment of this technology [2]. This device usually consists of a float, an oscillator, an energy output system, etc. It drives the internal oscillator to produce relative motion through the movement of the float under wave action, and then outputs energy by doing work through a damper [3]. Studying the motion characteristics and energy output efficiency of wave energy devices is of great significance for optimizing device design and improving energy utilization efficiency [4].

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In the motion analysis of wave energy devices, the interaction between fluid and structure needs to be considered. Under the assumption of non viscosity and non rotation, seawater will experience various hydraulic effects such as wave excitation force, additional inertial force, wave making damping force, and static water recovery force when floating in waves [5]. What the additional inertial force reflects is the supplementary force that must be applied to drive the movement of the floating body and the surrounding fluid; The wave damping force is derived from the wave radiation effect caused by the motion of the floating body, and its direction is opposite to the velocity of the motion; The static water recovery force is caused by the change in buoyancy when the floating body deviates from the equilibrium position, and has a tendency to bring the floating body back to equilibrium. The accurate modeling of these forces is the foundation for analyzing the dynamic behavior of the device.

Energy output systems typically include springs and dampers, where the design of dampers directly affects energy conversion efficiency. Damping force can have a linear or nonlinear relationship with relative velocity, and its coefficient needs to be optimized to maximize the average output power [6]. In addition, the device may involve multiple motion modes such as heave, pitch, etc., further increasing the complexity of system dynamics modeling and optimization. By establishing a multi degree of freedom motion equation and numerically solving the response under different wave excitations, a theoretical basis can be provided for the performance evaluation and optimization of the device.

The core objective of this article is to establish a motion model of the float and oscillator under wave excitation, and to solve their displacement and velocity. Based on Newton's second law, the coupled motion of the float and oscillator can reformulated as a second-order differential system. By conducting force analysis on the system, taking into account additional inertial forces, wave damping forces, static water recovery forces, as well as spring and damping forces in the PTO system, the motion model of the float and oscillator can be derived.

2. Modeling the Motion Behaviors of Floating Components and Oscillators in Wave Excitation Environments

This article establishes the motion model of the float and oscillator under wave excitation, and solves their displacement and velocity. By virtue of Newton’s second law, a system of second-degree non-homogeneous differential equations for floating components and oscillatory components was constructed by analyzing the forces acting on the system, taking into account various forces such as wave excitation force and additional inertial force. For both linear damping and nonlinear damping scenarios, the equation system is transformed into a fourth-order differential equation system, and the fourth-order Runge Kutta method is used to perform numerical iterative calculations with a time step of 0.02s. The heave displacement and velocity with a time interval of 0.2s during the first 40 wave cycles are obtained, and specific parameters at specific times are extracted [7]. The results showed that under both damping conditions, displacement and velocity fluctuated over time and gradually stabilized. At some moments, such as 10 seconds, under linear damping, the float displacement was -0.190518509m and the velocity was -0.639866499m/s, while under nonlinear damping, the displacement was -0.205726826m and the velocity was -0.651133016m/s. Selecting 0.002 as the smaller step size for testing, it was found that the difference between the obtained results and the original step size calculation results was small, indicating that the numerical error of the model is controllable and the model results are reliable.

2.1 System Description and Model Parameters

System composition. The wave energy device mainly consists of a float, a oscillator, a central axis, and an energy output system (PTO). Among them, Featuring a cylindrical shell and a conical shell that have uniform mass distribution, the float is equipped with a partition at the interface of the two shells, serving as a bearing surface where the central axis can be mounted; The oscillator is a cylindrical body mounted on the central axis, connected to the central axis base through a PTO system, which includes a spring and a linear damper. One end of the spring and linear damper is fixed to the oscillator, and the other end is fixed to the central axis base, which is fixed at the center of the partition. Meanwhile, the quality and various frictions of the central axis, base, partition, and PTO were ignored during the analysis process.

Sports form. In terms of motion form, the float only performs vertical oscillation motion under wave action, while the oscillator performs reciprocating motion along the central axis. The two drive the linear damper to do work through relative motion, thereby achieving energy output. At the initial moment, the float and oscillator are in equilibrium in still water and begin to move under the action of wave excitation force fcos ω t (where f is the amplitude of the wave excitation force and ω is the wave frequency). In the analysis, seawater is treated as non-viscous and irrotational fluid; when subjected to linear, periodic, micro-amplitude wave loads, the float bears four separate forces: wave-induced excitation force, additional inertial force, wave-making damping force, and hydrostatic recovery force.

Known data. Table 1 contains specific parameter information required for analysis, such as incident wave frequency, additional heave mass, heave induced damping coefficient, and heave excitation force amplitude.

Table 1. Wave energy converter parameters

Parameter category	Numerical value	Unit
Incident wave frequency	1.4005	s^{-1}
Hanging additional mass	1335.535	*kg*
Damping coefficient of oscillation induced wave	656.3616	N·s/m
Amplitude of oscillation excitation force	6250	N
Amplitude of pitch excitation torque	1230	N·m

2.2 Coordinate system establishment and variable definition

Establish a one-dimensional coordinate system in the vertical oscillation direction with the equilibrium position taking the location of the float component and oscillator unit in still water as the origin, and specify upward as the positive direction [8].

In this coordinate system, the heave displacement of the float is represented by $x_1(t)$, and its first derivative with respect to time is the float's $\dot{x}_1(t)$ heave velocity, while its second derivative $\ddot{x}_1(t)$ is the float's heave acceleration; The displacement of the oscillator during reciprocating motion along the central axis is represented by $x_2(t)$, and the corresponding velocity and acceleration are $\dot{x}_2(t)$ and $\ddot{x}_2(t)$, respectively.

The relative motion between the float and the oscillator drives the damper to do work, introducing relative displacement $x_{rel}(t)=x_2(t)-x_1(t)$ and relative velocity $\dot{x}_{rel}(t)=\dot{x}_2(t)-\dot{x}_1(t)$. These relative quantities will be directly used to describe the magnitude of spring force and damping force in the PTO system.

At the same time, the system is subjected to wave excitation force following the form of fcos ω t, where f is the amplitude of the excitation force, ω is the frequency of the wave circle, and t is the time variable. These parameters, together with the additional inertial force, wave damping force, and static water recovery force acting on the float, constitute the external force term of the system's motion equation [9- 10].

The additional inertial force is represented by F_{add}, and its magnitude is related to the heave acceleration and heave additional mass ma of the float; The wave making damping force is denoted as $F_{,w}$, determined by the heave wave making damping coefficient B (ω) and the heave velocity of the float; The static water recovery force is $F_{restore}$, which is proportional to both the hydrostatic recovery force coefficient k_z and the float's heave displacement; The spring force in the PTO system is represented by F_k, which depends on the spring stiffness k and relative displacement, while the linear damping force is represented by F_c, and the related variables are defined as shown in Table 2.

Table 2. Descriptions of Key Variables in the Study

Force Category Division	symbol	related parameters
Supplementary Inertial Resistance Force	F_{add}	Float oscillation acceleration, oscillation additional mass m_a
Wave-induced Attenuating Force	F_w	Vertical oscillation damping coefficient B (ω), float vertical oscillation velocity
Static water Restitution Force	$F_{restore}$	Static water recovery coefficient kz, float heave displacement
spring force	F_k	Spring stiffness k, relative displacement
Linearized Damping Force	F_c	Damping coefficient c, relative velocity

2.3 Force analysis

Force analysis under equilibrium state. In equilibrium, there is no relative motion between the float and the oscillator, and they can be considered as a whole. At this point, gravity and buoyancy are equal:

$$(m_1+m_2)g=\rho g^{\gamma} \tag{1}$$

By substituting the numerical values, the volume of the float underwater can be calculated as v, which is approximately 7.12m^3. Further calculations show that the float has a draft depth of 2.8m, and the conical part is entirely underwater.

Force analysis under pendulum motion state. The PTO system force F_{PTO} incorporates linearly-defined spring-derived force Fk as well as linearity-dependent damping force Fc, with corresponding mathematical expressions formulated as:

$$F_{PTO}=F_{\mathrm{k}}+F_{\mathrm{e}} \tag{2}$$

The linear damping force Fc bears a direct proportional relationship to the relative velocity of the float oscillator, with the damping coefficient C serving as the proportionality factor. Thus, algebraic expression relevant to linearity-bound retarding Impetus can be derived as follows:

$$F_c = -c(\dot{x}_1 - \dot{x}_2) \tag{3}$$

There are two types of linear dampers:

(1) Damping coefficient is a constant

(2) The damping coefficient is proportional to the power of the absolute value of the relative velocity: $c = 10000 \cdot |\dot{x}_2 - \dot{x}_1|^{0.5}$, where $\dot{x}_2 - \dot{x}_1$ is the relative velocity between the float and the oscillator.

The linear spring force Fk is proportional to the relative displacement between the oscillator and the float, and can be expressed as:

$$F_k = -k(x_1 - x_2) \tag{4}$$

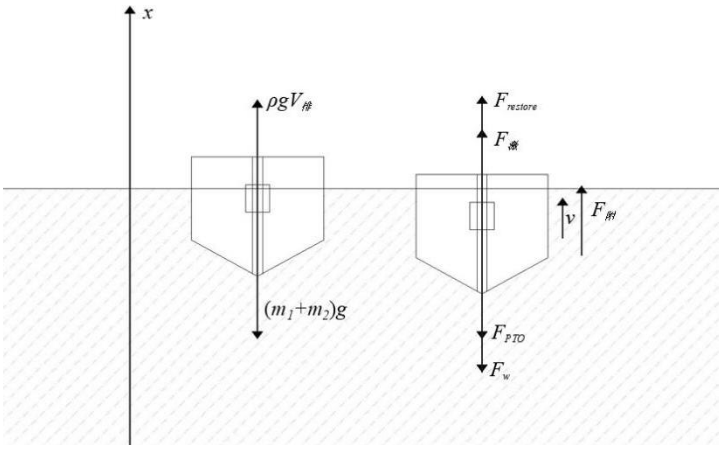

Fig. 1. Schematic diagram of force analysis for vertical oscillation motion

As shown in Figure 1, force analysis was conducted pertaining to the floating body and oscillating unit individually. It can be seen that when the device only performs vertical oscillation motion, the buoyancy module is acted upon by wave-derived excitation load, supplementary inertial impetus, wave-driven retarding force, and static-water restoring resistance, and PTO system force; The oscillation component is acted upon by the force generated by the PTO mechanism.

2.4 Analysis of the force condition of the float

For a float, the combined external force it receives is the sum of wave excitation force, additional inertial force, wave damping force, static water recovery force, PTO system spring force, and damping force.

Wave excitation force. Theews excitation force of waves on the float is a periodic force, expressed as:

$$F_3 = f \cos a\, t \tag{5}$$

The direction is consistent with the oscillation direction, where f is the amplitude of the excitation force, ω is the frequency of the wave circle, and t is time.

Additional inertia force and inertia resultant force. According to the definition of additional inertial force, its magnitude is proportional to the heave acceleration of the float and opposite in direction. The formula is:

$$F_{add} = -m_a \vec{\chi}_1 \tag{6}$$

Where ma is the additional mass of the float's heave, and $\ddot{x}_1$ is the heave acceleration of the float.

The total mass of the float needs to consider its own mass and the additional mass of the pendulum, therefore its inertial resultant force is:

$$F_i = -(m_1 + m_{\mathrm{al}})\tilde{\chi}_1 \tag{7}$$

Wave damping force. The resistance generated by the rising waves during the movement of the float is proportional to and opposite to the heave velocity, expressed as:

$$F_w = -b_w \dot{x}_1 \tag{8}$$

Among them, bw being the damping coefficient associated with the oscillatory wave, and $\dot{x}_1$ is the oscillation velocity of the float.

Static water recovery force. The restoring force that acts on the float to retrieve its static equilibrium position is proportional to and opposite to the heave displacement, and the formula is:

$$F_{reserve} = \rho g S x_1 \tag{9}$$

among which, $s = \pi r^2$, $k_h = \rho g s$ AAx1 represents the positional deviation generated by the heave motion of the float module when placed in static water recovery coefficient.

In summary, according to Newton's second law, the motion equation of the float can be obtained as follows:

$$F_j + F_i + F_{restore} + F_w + F_{\mathrm{T}TO} = 0 \tag{10}$$

2.5 Analysis of the load-bearing situation corresponding to the vibratory element

This oscillatory unit is acted upon solely by the elastic spring resistance and retarding impetus of the PTO system, whose direction is contrary to that of the relevant force exerted on the buoyancy-bearing component. According to Newton's second law:

$$m_2 \ddot{x}_2 + F_{PTO} = 0 \tag{11}$$

In summary, the model for the heave motion of the float and oscillator under wave excitation is established as follows:

$$\begin{cases} F_j + F_{\mathrm{restore}} + F_w + F_{\mathrm{T}TO} = -(m_1 + m_{sl})\dot{x}_1 \\ F_{\mathrm{T}TO} = -m_2 \dot{x}_2 \\ F_f = f \cos\theta\, t \\ F_w = -b_w \dot{x}_1 \\ F_{restore} = \rho g \pi r^2 z_1 = k_h z_1 \\ F_{\mathrm{T}TO} = F_k - F_c \\ F_k = -k(\dot{x}_1 - \dot{x}_2) \\ F_c = -c(\dot{x}_1 - \dot{x}_2) \end{cases} \tag{12}$$

Float oscillator motion model under linear damping. The damping coefficient is a constant, and by substituting it into the above formula, the motion equation of the float is obtained:

$$f\cos\alpha\, t + k_k\dot{x}_1 - b_w\dot{x}_1 - k(x_1 - x_2) - c(\dot{x}_1 - \dot{x}_2) = -(m_1 + m_{a1})\ddot{x}_1 \tag{13}$$

The equation of motion for the oscillator:

$$c(\hat{x}_1 - \hat{x}_2) + k(x_1 - x_2) = m_2\hat{x}_2 \tag{14}$$

Namely:

$$\begin{cases} f\cos\alpha\, t + k_1\hat{x}_1 - b_w\hat{x}_1 - k(x_1 - x_2) - c(\hat{x}_1 - \hat{x}_2) = -(m_1 + m_{a1})\hat{x}_1 \\ c(\hat{x}_1 - \hat{x}_2) + k(x_1 - x_2) = m_2\hat{x}_2 \end{cases} \tag{15}$$

Float oscillator motion model under nonlinear damping. The expression for damping coefficient is:

$$c = 10000\,|\tilde{x}_2 - \tilde{x}_1|^{0.5} \tag{16}$$

The motion equation system of the float oscillator is:

$$\begin{cases} f\cos\omega\, t + k_k x_1 - b_w\dot{x}_1 - k(x_1 - x_2) - 10000|\dot{x}_2 - \dot{x}_1|^{0.5}(\ddot{x}_1 - \ddot{x}_2) = -(m_k + m_{a1})\ddot{x}_1 \\ 10000|\dot{x}_2 - \dot{x}_1|^{0.3}(\ddot{x}_1 - \ddot{x}_2) + k(x_1 - x_2) = m_2\ddot{x}_2 \end{cases} \tag{17}$$

2.6 Model solution

Runge Kutta method. The Runge Kutta method is a commonly used numerical approach for solving ordinary differential equations (ODEs), suitable for both linear and nonlinear equations. The float oscillator system in this article is described by second-order differential equations, which call for conversion into an equivalent-form system of first-order ordinary differential equations first, and then solved using numerical methods.

When using the Runge Kutta method, initial conditions must be given. This article sets the commencement moment when the float and the oscillator remain motionless at at the equilibrium position, with zero displacement and velocity, to ensure the uniqueness of the equation solution.

The fourth-order Runge Kutta method achieves high accuracy and stability by performing multi-point estimation and weighted averaging of derivatives within each integration step, and can effectively calculate the dynamic response of floats and oscillators under wave excitation.

Fourth order Runge Kutta method formula. Solve the ODE equation in the form of:

$$\frac{dy}{dt} = f(t, y), y(t_0) = y_0 \tag{18}$$

If the step size is h and y_n corresponds to tn, the formula for calculating y_{n+1} is as follows:

$$\begin{cases} k_1 = f(t_\pi, y_\pi) \\ k_2 = f(t_\pi + \frac{k}{2}, y_\pi + \frac{k}{2}k_1) \\ k_3 = f(t_\pi + \frac{k}{2}, y_\pi + \frac{k}{2}k_2) \\ k_4 = f(t_\pi + \frac{k}{2}, y_\pi + hk_3) \end{cases} \tag{19}$$

$$y_{n+1} = y_n + \frac{k}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{20}$$

Among them, k_1 is the slope of the current point; k_2 and k_3 are half step slopes; k_4 is the slope of the next step; y_{n+1} is the next approximate value after weighted averaging.

First order processing of differential equations with second-order characteristics. When through the application of the fourth-order Runge Kutta method to solve differential equations, the algorithm itself is developed specifically for differential equations of the first order. Therefore, the differential equation of the second order involving two variables system should be rewritten as a quaternary first-order differential equation system.

Writing of First Order Differential Equations:

$$\dot{z} = f(t,z) = \begin{bmatrix} f_1(t,z) \\ f_2(t,z) \\ f_3(t,z) \\ f_4(t,z) \end{bmatrix} = \begin{bmatrix} x_3 \\ x_4 \\ -\frac{f\cos\alpha - k_k x_1 + b_w x_3 + k(x_1-x_2) + c(x_3-x_4)}{m_1+m_{21}} \\ \frac{c(x_3-x_4)+k(x_1-x_2)}{m_2} \end{bmatrix} \tag{21}$$

Determine initial value. At the beginning, Both the float and the oscillator maintain equilibrium under still water conditions, in a state of equilibrium, and can be obtained as follows:

$$x_1 = 0, x_2 = 0, x_3 = 0, x_4 = 0 \tag{22}$$

RK4 formula iterative calculation. The fixed step size h is 0.02, traversing 40 wave periods. Given the current step tn and the state vector:

$$z_n = \left[x_{1,n}, x_{2,n}, x_{3,n}, x_{4,n}\right]^T \tag{23}$$

Use the RK4 formula to calculate four slope vectors k1,n, k2, n, k3, n, k4, n (each a 4x1 vector), and then substitute them to calculate the next corresponding discrete value:

$$z_{n+1} \propto z(t_n + h) = z_n + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{24}$$

Expand the four components separately to obtain the updated formula, and obtain the state variables for the next time step in sequence:

$$\begin{cases} x_{i,n+1} = x_{i,n} + \frac{\hbar}{6}(k_{1,1}, k_{2,1}, k_{3,1}, k_{4,1}) \\ x_{2,n+1} = x_{2,n} + \frac{\hbar}{6}(k_{1,2}, k_{2,2}, k_{3,2}, k_{4,2}) \\ x_{3,n+1} = x_{3,n} + \frac{\hbar}{6}(k_{1,3}, k_{2,3}, k_{3,3}, k_{4,3}) \\ x_{4,n+1} = x_{4,n} + \frac{\hbar}{6}(k_{1,4}, k_{2,4}, k_{3,4}, k_{4,4}) \end{cases} \tag{25}$$

Through gradual iteration, the displacement and velocity sequences of the float and oscillator oscillation motion with a time interval of 0.2 s were obtained for the entire 40 cycle calculation interval.

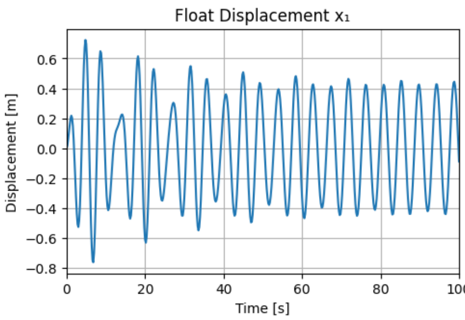

Fig.2. Drift displacement of float with constant damping coefficient

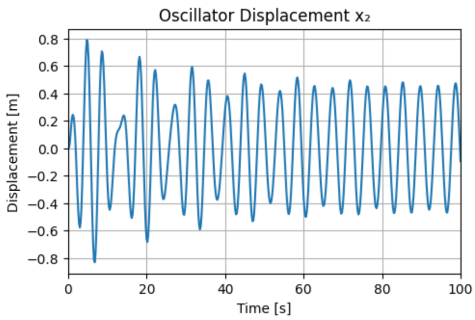

Fig. 3. Vertical displacement of oscillator with constant damping coefficient

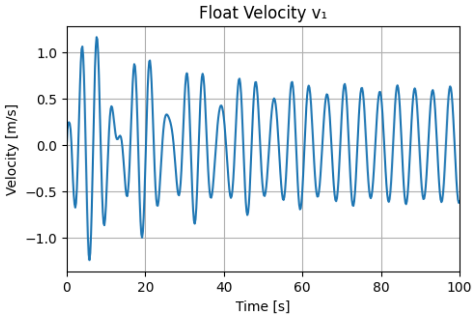

Fig. 4. Drifting velocity of float with constant damping coefficient

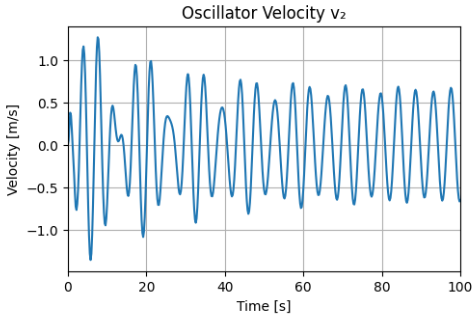

Fig. 5. Vertical oscillation velocity of oscillator with constant damping coefficient

Figures 2, 3, 4, and 5 respectively show the vertical displacement and velocity changes of the float and oscillator during the first 40 wave cycles with a time interval of 0.2 seconds when the linear damper is a constant coefficient. The fluctuation of displacement and velocity over time can be visually observed from the figures, and the floating interval decreases over time and tends to stabilize.

Select the calculation results at t=10s, 20s, 40s, 60s, and 100s, and list the heave displacement and velocity data of the float and oscillator as shown in Table 3:

Table 3. Calculation results of heave Positional deviation and movement speed of the float module and oscillatory unit

Time (s)	float		oscillator	
	Displacement (m)	Speed (m/s)	Displacement (m)	Speed (m/s)
10	-0.190518509	-0.639866499	-0.211451880	-0.693543019
20	-0.590379698	-0.240353045	-0.634059472	-0.270450852
40	0.285450499	0.313944087	0.296654134	0.333461334
60	-0.314400061	-0.478875555	-0.331354832	-0.515139791
100	-0.083576966	-0.603944545	-0.084055158	-0.642847557

Table 3 presents the specific data of the heave displacement and velocity of the float and oscillator at t=10s, 20s, 40s, 60s, and 100s in the first 40 cycles when the linear damper is a constant coefficient. At 10s, the float displacement is -0.190518509m and the velocity is -0.639866499m/s, while the oscillator displacement is -0.211451880m and the velocity is -0.693543019m/s.

3. Conclusions

This article focuses on the motion characteristics and related parameter calculations of the float and oscillator when the float only performs vertical oscillation motion. Firstly, the system composition and motion form were clarified. The wave energy device mainly consists of a float, an oscillator, a central axis, and a PTO system. The float only undergoes vertical oscillation motion under wave action, while the oscillator undergoes reciprocating motion along the central axis. Based on Newton's second law, a force analysis is conducted on the float and oscillator, considering wave excitation force, additional inertial force, wave damping force, static water recovery force, and spring and damping forces of the PTO system. The construction of a motion model adopts the form of a second-order differential equation.

For two damping scenarios, the damping coefficient is a constant of 10000N·s/m and is proportional to the absolute value of the relative velocity to the power of 0.5, with a proportionality coefficient of 10000. Differential formulations of second order undergo conversion into an equivalent set of primary-order ordinary differential equations, and numerical solution is carried out through the fourth-order Runge-Kutta approach. By setting initial conditions, the float and oscillator are stationary at the equilibrium position with zero displacement and velocity. With a time step of 0.02 seconds, the heave displacement and velocity during the first 40 wave cycles are iteratively calculated, and the results at 10 seconds, 20 seconds, 40 seconds, 60 seconds, and 100 seconds are extracted.

3.1 Limitations of the Study

While the established model provides insights into the system's dynamic response, several limitations should be acknowledged:

Model Simplifications: The analysis assumes ideal conditions, including non-viscous and non-rotating fluid, and neglects the mass and friction of components like the central axis and PTO mounting. These simplifications may lead to discrepancies compared to real-world scenarios where viscous damping and mechanical losses are present.

Motion Constraints: The study is restricted to the heave motion of the float. In practice, wave energy devices often experience coupled multi-degree-of-freedom motions (e.g., pitch, surge), which could significantly influence the energy capture and system dynamics.

Wave Excitation Idealization: The wave excitation is modeled as a single-frequency, periodic force. Real ocean waves are irregular and multi-directional, which this model does not account for.

Scope of Analysis: The current work focuses solely on kinematic responses (displacement and velocity). It does not proceed to quantify the output power or evaluate the energy conversion efficiency, which is the ultimate metric for device performance.

3.2 Future Work

Based on the findings and limitations of this study, the following directions are suggested for future research:

Model Enhancement: Incorporate more physical factors into the model, such as viscous drag, mechanical friction, and the coupled effects of multi-mode motions (pitch, heave). Extending the analysis to irregular wave spectra using stochastic models would improve realism.

Power Output and Optimization: The natural next step is to utilize the obtained velocity and relative motion data to calculate the instantaneous and average power output of the PTO system. Subsequently, optimization algorithms (e.g., genetic algorithms as initially indicated) can be applied to key parameters (like damping coefficient c, spring stiffness k, or float geometry) to maximize the average output power, aligning the research with the initial objective of optimal design.

Experimental Validation: Building a physical scale model for wave tank testing is crucial to validate the numerical predictions of this study and calibrate the model parameters against experimental data.

Control Strategy Integration: Future work could explore the implementation of active or passive control strategies for the PTO system to adapt to varying wave conditions and further enhance energy extraction efficiency.

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