

Kinematic Characterization of Marine Wave Energy Devices Based on Immune Particle Swarm Algorithm

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Abstract. This paper explores the optimization of motion characteristics and energy output in an ocean wave energy device. The displacement and velocity of the device in pendant oscillatory motion are explored by simplifying the device model and simulating it using Simulink. Numerical methods are employed to solve the dynamics model. Subsequently, an optimization model for the average output power of the damper is developed based on this exploration. Both the grid search method and particle swarm algorithm are utilized to optimize the damping coefficients. These two methods are compared, revealing the particle swarm algorithm's superior efficiency.

Keywords: Wave Energy Device, MATLAB Simulation, PTO, Particle Swarm Algorithm.

1. Introduction

With increasing environmental, energy, demographic and economic pressures, ocean wave energy is receiving increasing attention as a renewable energy source with high energy flow density and low cost. This study focuses on the energy conversion efficiency of wave energy devices, especially involving the motion models of floats and oscillators as well as the optimization of energy output systems (PTOs). By modeling the motion of floats and oscillators under wave excitation force, this paper aims to optimize the damping coefficient to maximize the average output power of the PTO [1,2].

2. Overview of ocean wave energy

2.1. Energy Density and Availability

The oceans cover about 71% of the Earth's surface, and this vast area of coverage provides us with a huge resource of wave energy. Wave energy not only has a high energy density, but also has a relatively uniform spatial distribution, and these characteristics make it a renewable energy source with great potential and application. Compared with other renewable energy sources (e.g., solar and wind), wave energy has non-negligible advantages in terms of stability and availability. Therefore, the rational development and efficient utilization of wave energy is of great significance in alleviating global energy pressure and promoting sustainable development [3].

2.2. Energy conversion process

Wave energy devices come in a variety of designs, but the core components usually include a float, an oscillator, and an energy output system (often called a PTO). Driven by the waves, the float starts to move and further drives the vibrator's movement. This series of actions triggers the damper to perform work, resulting in the efficient conversion and output of energy. Understanding and optimizing this energy conversion process is the key to improving the efficiency of wave energy devices. This study specifically focuses on how to maximize the average output power of a PTO system through damping coefficient tuning and model optimization.

3. Device motion and numerical simulation

3.1. Kinetic equations

1) Selection of devices

Since only the vertical oscillatory motion of the float and the oscillator need to be considered, in this paper all the forces are simplified to those in the vertical direction in **Fig. 1**.

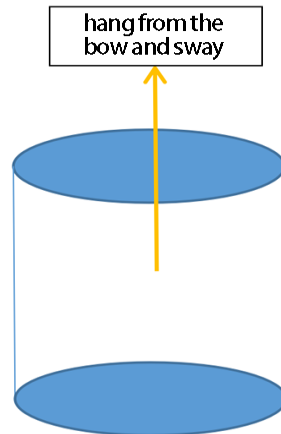


Fig. 1 Simplified device research object

2) Establishment of the coordinate system

When the float and the oscillator are in equilibrium in the water, the state currently is recorded as the equilibrium position, because the motion is one-dimensional motion, so take the center of the device currently as the origin, and the vertical direction as the z direction. When the device moves under the action of waves, let the displacement of the float away from the equilibrium position be z_1 and the displacement of the vibrator away from the equilibrium position be z_2 .

3) Force analysis

Any take a certain time node during the movement, considering the float movement process by the linear periodic microamplitude wave action and the damping force of the linear damper, consider the device along the vertical direction of the linear oscillatory motion, so only consider the vertical direction of the force.

These seven forces affect the motion of the float due to the presence of wave excitation forces, additional inertia forces, hing wave damping forces, hydrostatic restoring forces, the float's own gravity, the damping force of the damper, and the buoyant force of seawater on the device:

The following force analysis is performed to establish the equations:

Wave Motivation:

Floats are subject to wave excitation forces under the action of linear periodic microamplitude waves, then there are:

$$F_{inspire} = k \cos \omega t \quad (1)$$

Emerging wave damping force:

The wave that rises from the rocking motion generates a wave damping force on the floating body, denoted as F_{Rising} .

From the question, F_{Rising} is proportional to the speed of the rocking motion, and the coefficient of proportionality, k , is given:

$$F_{Rising} = -k_{Rising} v_1 \quad (2)$$

Hydrostatic resilience:

The hydrostatic restoring force is related to the buoyancy force applied to the floating body during its motion, and from the formula for the buoyancy force, Δv is the area of the bottom of the displaced floating body that deviates from the equilibrium position, then there is:

$$F_{hydrostatic} = -\rho g \Delta v = -\rho g S z_1 \quad (3)$$

Spring elasticity and damping force of the damper:

The spring force is proportional to the relative displacement of the oscillator and the float, and the damping force of the linear damper is proportional to the relative velocity of the oscillator and the float, then there:

$$T = k_1(z_1 - z_2) + k_1 x_0 \quad (4)$$

$$f = k_2(v_1 - v_2) \quad (5)$$

Buoyancy of the sea water on the device:

At the initial moment the float and the oscillator are balanced in still water, according to the buoyancy formula and the equations of equilibrium:

$$F_{buoyancy} = F_{buoyancy0} + \Delta F_{buoyancy} = (m_1 + m_2)g - \rho g S z_1 \quad (6)$$

Float's own gravity:

At the initial moment the float and oscillator are balanced in still water, according to the equation of gravity:

$$G = -m_1 g \quad (7)$$

Because the acceleration of the float and the vibrator are different, the kinetic equations are listed separately for the float and the vibrator:

Float:

$$\begin{aligned} k \cos \omega t - k_{Rising} v_1 + (m_1 + m_2)g + \rho g S z_1 - m_1 g - m_2 g - k_1(z_1 - z_2) - k_2(v_1 - v_2) \\ = (m_1 + m_{inertial}) \frac{d^2 v}{dt^2} \end{aligned} \quad (8)$$

Vibrators:

$$k_1(z_1 - z_2) + k_1 x_0 + k_2(v_1 - v_2) - m_2 g = m_2 \frac{d^2 z_2}{dt^2} \quad (9)$$

Where m inertia is the additional inertial mass.

3.2. Simulation and numerical solution

1) Determination of initial conditions

The initial conditions specify the displacements z_1 and z_2 of the float and oscillator away from the equilibrium position at $t = 0$, and the corresponding velocities v_1 and v_2 . It is easy to see that: $z_1 = 0, z_2 = 0, v_1 = 0, v_2 = 0$.

2) Simulation

Simulink simulation is a block diagram design environment, the realization of dynamic system modeling, simulation, and analysis of the software package, to provide dynamic system modeling, simulation, and comprehensive analysis of the integrated environment. It has the advantages of wide adaptability, clear structure and process and fine simulation, close to the actual, high efficiency and flexibility [4].

For the established ordinary differential equations, the following system is established in **Fig. 2**:

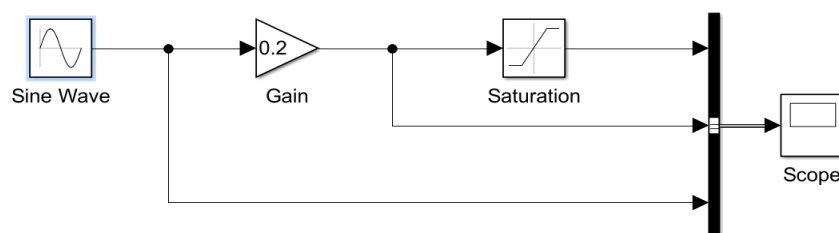


Fig. 2 Simulation system

Sine Wave: Generates a sine wave signal of settable amplitude and frequency, with input parameters such as incident wave frequency (1.4005s⁻¹), amplitude of pendulum excitation force (6250N), etc.

Oscilloscope (scope): displays the waveforms of the signals generated during the simulation process.

The oscilloscope window is popped up as shown in the figure below, and an oscilloscope waveform graph can be obtained, reflecting the fluctuations in the frequency of the incident wave, the amplitude of the pendant excitation force, and other changes in **Fig. 3**:

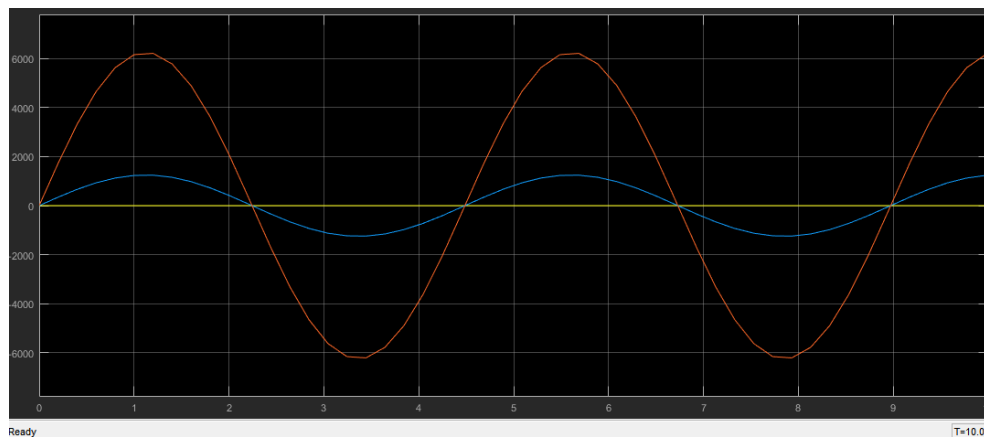


Fig. 3 Simulation waveform diagram

3) Solve the system of differential equations with the help of MATLAB in the form of joint equations

When dealing with the system of differential equations, for general ordinary differential equations, the dsolve function is first considered to solve the analytical solution, which can better explain the essential connection and law between the physical variables, so in this paper, we try to solve the analytical solution of the system of equations with the dsolve function, but due to the system of equations is too complex, MATLAB did not run the results after a long time, and could not solve the analytical solution, and we finally consider to solve the numerical solution with the ode45 function is used to solve the numerical solution. The ode function to solve the system of differential equations is based on the Longe-Kuta method. The Ronger-Kutta method (R-K) is a single-step algorithm for solving numerical solutions of ordinary differential equations, which is derived below based on the Taylor series method in **Fig.4 and 5**:

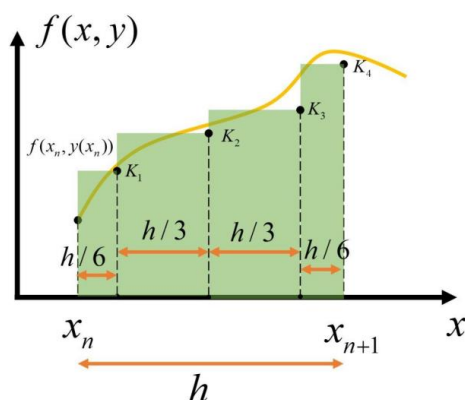


Fig. 4 Schematic diagram of the Ronger-Kutta method (R-K)

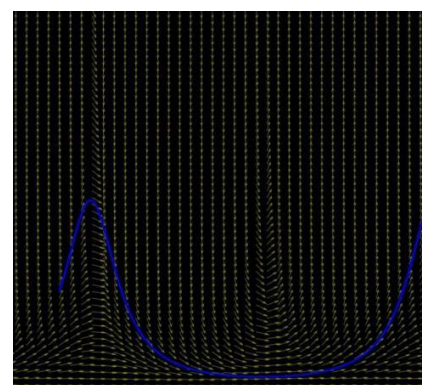


Fig. 5 Integral curve of the Ronger-Kutta method (R-K)

Consider ordinary differential equations:

$$\begin{cases} y = y(x) \\ y' = f(x, y) \end{cases} \quad (10)$$

In the x-y plane, the solution $y=y(x)$ of the above differential equation is called its integral curve; the slope of the tangent line at a point on the integral curve is equal to the value of the function $f(x,y)$. If a directional field is established in the x-y plane according to the function $f(x,y)$, then the direction of the tangent line at each point on the integral curve coincides with the direction of the directional field at that point.

Differential equations have an equivalent integral equation form:

$$y(x_n + 1) - y(x_n) = \int_{x_n}^{x_{n+1}} f(x, y(x)) dx \quad (11)$$

Numerical integration is used to approximate the right end term, which in fact becomes a difference equation at this point:

$$\begin{aligned} y(x_n + 1) - y(x_n) &= \int_{x_n}^{x_{n+1}} f(x, y(x)) dx \\ &\approx h \sum_{i=1}^r f(x_n + \lambda_i h, y(x_n + \lambda_i h)) \end{aligned} \quad (12)$$

Therefore, the basic idea of the R-K method is obtained: to calculate the values of the function of $f(x, y)$ at certain points, make a linear combination of the function values, then construct the approximation formula, and finally compare the approximation formula with the Taylor expansion of the solution, so that the first number of terms are exactly the same, and finally obtain the numerical formula with a certain degree of accuracy (judged by the error).

The construction introduces several parameters:

$$\begin{cases} y_{n+1} = y_n + h \sum_{i=1}^r \alpha_i k_i \\ k_1 = f(x_n, y_n) \\ k_i = f(x_n + \beta_{ij} h, y_n + h \sum_{j=1}^{i-1} \omega_{ij} k_j), (i = 2, 3, \dots, r) \end{cases} \quad (13)$$

The parameters $\alpha_i, \beta_{ij}, \omega_i$ are constants independent of both $f(x,y)$ and the number of steps, and the principle of selection is to make the final approximate solution and the Taylor expansion of the solution to be compared, there are more numbers of exactly the same. Commonly used is more r take 2, 3, 4, also for the convenience of calculation, can be appropriate to choose $\alpha_i, \beta_{ij}, \omega_i$. It is easy to know that the various methods can make the local truncation error of the corresponding calculation formula reach a certain accuracy but cannot further improve the order of the local truncation error. In calculating the function value twice, the highest order of the local truncation error is $O(h^3)$, and to further improve the order, it is necessary to continue to increase the number of times of calculating the function value by the way.

The algorithm is known as the initial value and the form of the derivative of the function to estimate the value of the next step.

Solve the above system of differential equations using ode45 function in MATLAB and make images of velocity and displacement with respect to time. In the velocity image, blue is the float velocity and red is the vibrator velocity. In the displacement image, red is the vibrator displacement and green is the float displacement. The horizontal and vertical axes are in the International System of Units (SIU) (hereafter, abbreviated) as shown in **Fig. 6 to 9**.

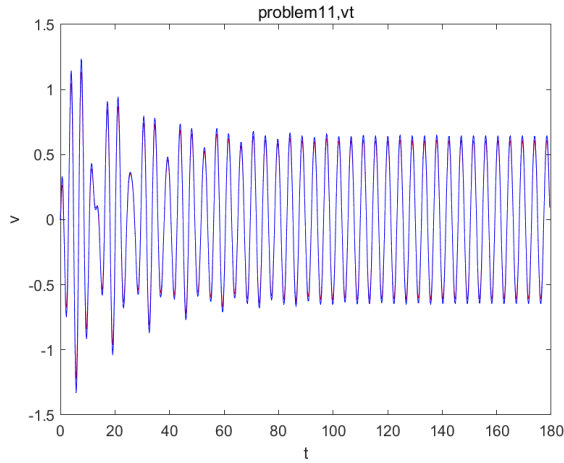


Fig. 6 Graph of a function of speed

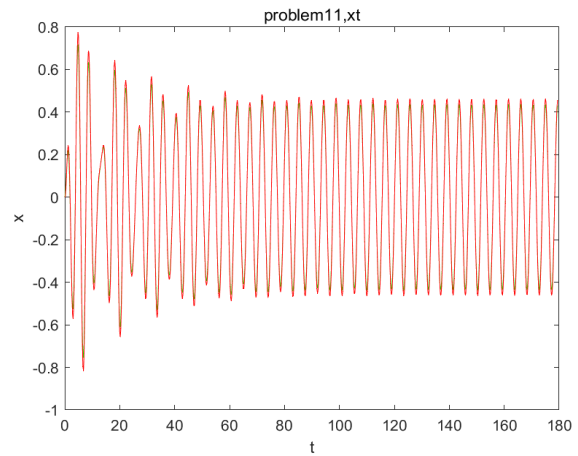


Fig. 7 Graph of a function of displacement

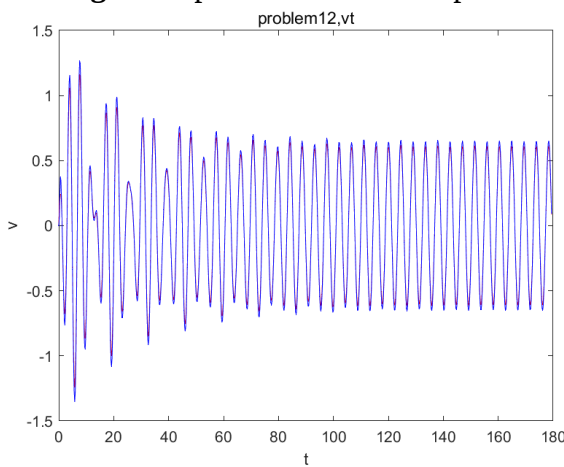


Fig. 8 Graph of velocity as a function of

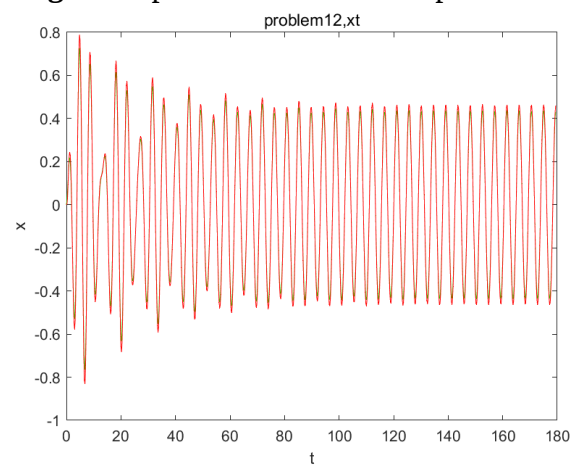


Fig. 9 Graph of a function of displacement

4. Output power optimization

4.1. Objective function construction

The core idea of particle swarm algorithm is to refer to the particles, position, speed, fitness, individual best position, and group best position, and utilize the sharing of information by the individuals in the group to make the whole group move in the problem-solving space, which produces the evolution process from disorder to order, to obtain the feasible solution of the problem. The advantage of PSO is that it is simple and easy to implement and does not have a lot of parameter adjustments. The traditional particle swarm algorithm has problems such as slow convergence speed and easy to fall into local optimization, so the particle swarm algorithm is often mixed with other algorithms to enhance the global exploration ability of the particles and speed up the convergence speed and accuracy. In this paper, the hybrid strategy based on immunization is used [5].

Modeling

$$f = kv \quad (14)$$

$$k_1 = c \quad (15)$$

$$k_2 = c|v|^n \quad (16)$$

k_1 , k_2 are damping coefficients (c , n is constant to be determined) v is relative velocity. Output power:

$$P_1 = \frac{1}{2}kv^2 \quad (17)$$

$$P_2 = \frac{1}{2} c |v|^{n+2} \quad (18)$$

P_1 and P_2 are the output power.

From physical knowledge, the integral of the instantaneous power over time divided by the total time, i.e., the average power, gives:

$$\bar{P} = \frac{\int P dt}{T_{total}} \quad (19)$$

4.2. Grid Search and Particle Swarm Algorithms

For a single-objective optimization model with P_1 as the objective function and k as the objective variable.

A multi-objective optimization model for which P_2 is the objective function and k , c are the objective variables.

The function images and optimal results obtained based on the grid search method are shown in Fig. 10:

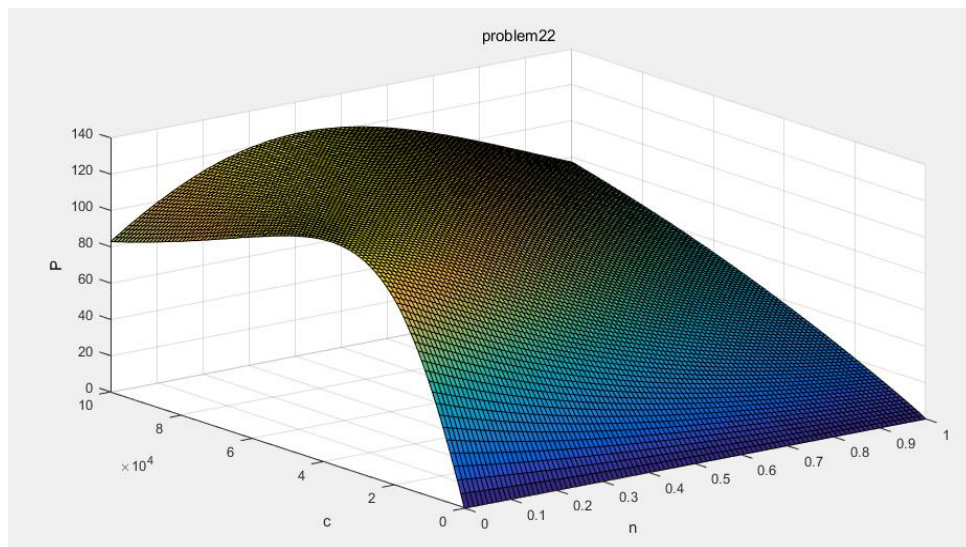


Fig. 10 Function Graphics

The results obtained using the immune particle swarm algorithm are as follows: the maximum output power (P_{max}) is 123.1002, the damping coefficient (c) is 37369.933, and the damping coefficient is proportional to the power of the absolute value of the relative velocity ($P_{max}=122.7245$, $c=98507.23$, $n=0.42$). The comparison demonstrates a high probability of obtaining globally optimal results using the immune particle swarm algorithm.

5. Summary

In this study, MATLAB simulation and various optimization algorithms are used to comprehensively analyze the motion characteristics and output power of an ocean wave energy device. The limitations of the grid search algorithm are mainly reflected in the high-dimensional parameter space and time efficiency, which leads to the limited application of the method in multivariate optimization scenarios. By introducing an optimization strategy based on immune particle swarm, the particle swarm algorithm's shortcoming of easily falling into local optimality is successfully overcome, and the possibility of finding the global optimal solution is greatly improved. Nevertheless, the model in this study still has room for improvement. First, the water environment and influencing factors considered in the model are relatively simple. Subsequent studies can further improve the accuracy and applicability of the model by introducing a more complex linear wave model and considering multidimensional factors such as velocity rank.

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