Optimal design of wave energy maximum output power based on simulated annealing algorithm

Xin Lv [1], Zheyu Shang [2,*]

[1] College of Science, China University of Petroleum (East China), Qingdao, China

[2.]Bachelor of Mechanical Engineering, Taiyuan institute of technology, Taiyuan, China

* Corresponding Author Email: animal1917117@163.com

Abstract. As one of the largest new energy sources, wave energy has received a lot of attention from governments in various countries. In recent years, researchers in various countries have done a lot of work on the collection and conversion of wave energy, and the utilization of wave energy is getting higher and higher. The problem of further optimizing the wave energy harvesting device can be solved by using optimization algorithms, which need to be intelligent due to the complexity of the problem. The simulated annealing algorithm is a classical intelligent optimization algorithm that can perform global optimization of the objective function with excellent results. In this paper, the output power of float-vibrator type wave energy devices is optimized using the simulated annealing algorithm, and the optimal values of important parameters are obtained, which play a reference significance for practical development.

Keywords: Simulated annealing algorithm, Wave energy power, Optimization, Differential equation.

1. Introduction

In the past few centuries, the main fuels utilized by mankind were fossil fuels, such as oil, coal, and natural gas. However, the use of fossil fuels can be extremely damaging to the environment, and although humans are still heavily dependent on fossil fuels, the environmental impact caused by fuels is receiving increasing attention worldwide [1]. And the development of new energy industry helps to solve fossil energy depletion, environmental problems, and create jobs, so countries have started to develop tethered energy technologies [2]. In recent years, many scientific research efforts for the development of new energy technologies have focused on renewable energy sources, such as wind, solar, biomass, wave energy, etc. [3-5].

Since the earth's oceans are very large, wave energy is one of the most important renewable energy sources in the world. If wave energy is utilized well, human beings will be much less dependent on fossil fuels, which will help curb carbon emissions. A large number of researchers have already conducted research on wave energy harvesting, and there are already many practical applications of wave energy. To improve the wave energy harvesting efficiency, energy harvesting devices and concepts have been continuously updated. Yikai Zhu et al. recently proposed a multi-modal energy harvesting device using a beam structure to further improve the harvesting efficiency [6], while Lin-Chuan Zhao et al. proposed a new concept: mechanical intelligent energy harvesting, which can be used to harvest energy more simply [7]. The main application of wave energy is currently power generation, and nearly half of China's energy supply can be obtained from the borders of the Yellow Sea and Bohai Sea using wave energy [8].

In order to better utilize wave energy and alleviate the pressure of environmental degradation, it is important to improve the efficiency of wave energy utilization. In this paper, the principle of float-vibrator type wave energy device is analyzed using the laws of physics, and the output power of the wave energy device is optimized using a simulated annealing algorithm, and the optimal coefficients of the dampers in the device are obtained in order to expect the best configuration in this type of wave energy device and to improve the harvesting efficiency.

2. Materials and Methods

2.1. Data acquisition and pre-processing

The wave energy device targeted in this paper is a float-vibrator wave energy device, the structure of which is the same as that shown in problem a of the 2022 China Student Mathematical Modeling Competition, and some of the device data used in this paper are also adopted from the data given in that problem (http://www.mcm.edu.cn/html_cn/node/ 5267fe3e6a512bec793d71f2b2061497.html).

2.2. Introduction to the method

2.2.1 Analysis of the collection principle of the device

The float-vibrator type wave energy device is shown in Figure 1 below, consisting of a float, a vibrator, a center shaft and an energy output system (PTO, including a spring and a damper), with a rotary damper and a torsion spring installed on the rotating shaft, and a linear damper and a rotary damper working together to output energy. Among them, the oscillator, the center shaft and the PTO are sealed inside the float; the float consists of a cylindrical shell and a conical shell with uniformly distributed masses; the two shells are connected with a compartment that serves as a support surface for mounting the center shaft; the oscillator is a cylinder threaded on the center shaft and connected to the center shaft base through the PTO system.

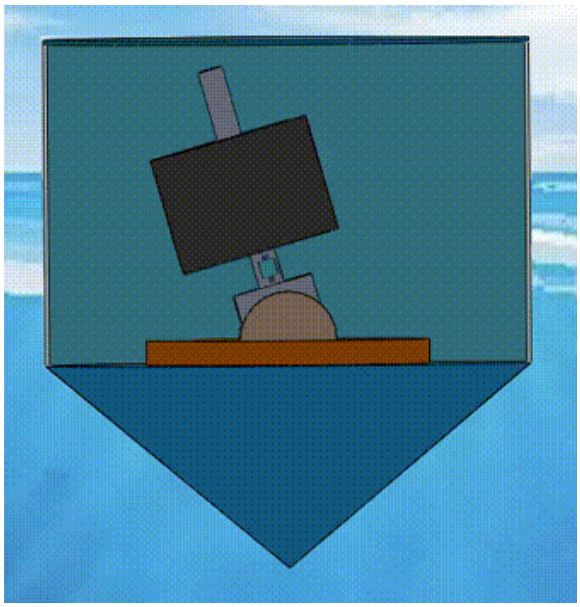


Figure 1. Schematic diagram of wave energy device

(http://www.mcm.edu.cn/html_cn/node/ 5267fe3e6a512bec793d71f2b2061497.html)

In this paper, we consider that the seawater is viscous and spinless, and the float is subjected to wave excitation (moment), additional inertia (moment), wave damping (moment) and hydrostatic recovery (moment) under the action of linear periodic micro-amplitude waves. Next, we consider the vertical and longitudinal motion of the float, which is a one-dimensional up-and-down motion, and the longitudinal motion is an angular rotation.

2.2.2 Analysis of the dangling motion

For the pendular motion, a one-dimensional coordinate system needs to be established for the analysis [9] as follows Figure 2.

In the following, F_W denotes the periodic wave excitation force, F_{r1} denotes the additional inertia force, F_{r2} denotes the hinged wave damping force, F_{PTO} denotes the spring and damper force, and F_b denotes the hydrostatic recovery force. With R denoting the radius of the float bottom, r denoting the radius of the oscillator, h_1 denoting the height of the cylindrical part of the float, and h_2 denoting the height of the conical part of the float.

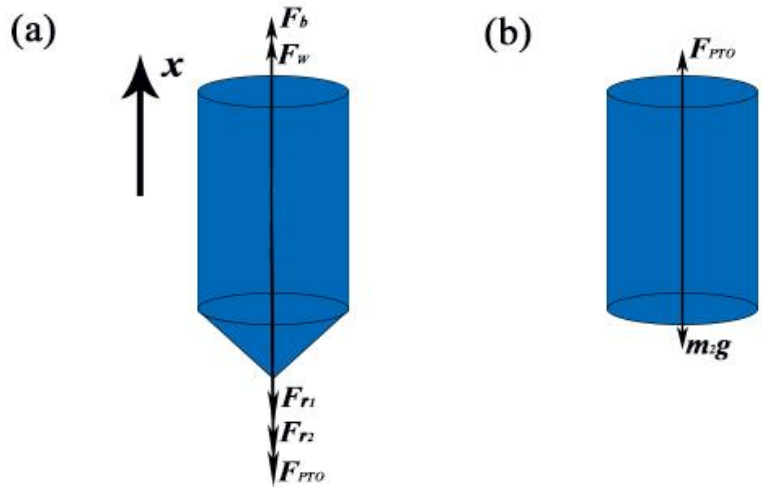


Figure 2. Float force analysis (a) and oscillator force analysis (b)

To simplify the problem, the wave excitation force is expressed as

$$F_W = cos\omega t \tag{1}$$

The analysis of the additional inertia force by Newton's second law gives

$$\mathrm{F_{r1}} = -\mathrm{m_a a_1} \tag{2}$$

Wave damping force for the floating body in the seawater to do the dangling motion, will raise the wave, thus creating resistance to the floating body rocking motion, wave damping force and the speed of the rocking motion is proportional to the opposite direction, the proportionality coefficient is called wave damping coefficient, so it can be derived.

$$\mathrm{F_{r2}} = -\mathrm{c_2 v_1} \tag{3}$$

The hydrostatic recovery force is the force that causes the floating body to return to the equilibrium position when the floating body is in a vertical swinging motion in seawater, i.e., the difference between buoyancy and gravity [10].

$$\mathrm{F_b} = -\mathrm{k_2 x_1} \tag{4}$$

According to the force analysis it is known that

$$\mathrm{F_{PTO}} = -\mathrm{k_1}(\mathrm{x_1} - \mathrm{x_2}) - \mathrm{c_1}(\mathrm{v_1} - \mathrm{v_2}) \tag{5}$$

in equation (4)

$$\mathrm{k_2} = \rho \mathrm{gA} \tag{6}$$

$$A = \pi R^2 \tag{7}$$

The force analysis of the oscillator shows that it is subjected to the gravitational force G_2, the reaction force of the spring and the damper - F_{PTO}. Where

$$G_2 = m_2 g \tag{8}$$

$$-\mathrm{F_{PTO}} = \mathrm{k_1}(\mathrm{x_1} - \mathrm{x_2}) + \mathrm{c_1}(\mathrm{v_1} - \mathrm{v_2}) \tag{9}$$

Therefore, according to Newton's second law, the differential equation for the case of float and oscillator pendulum can be established as follows.

$$(\mathrm{m_1} + \mathrm{m_a})\,\mathrm{a_1} + \mathrm{c_2 v_1} + \mathrm{c_1}(\mathrm{v_1} - \mathrm{v_2}) + \mathrm{k_2 x_1} + \mathrm{k_1}(\mathrm{x_1} - \mathrm{x_2}) = \mathrm{f}\cos\omega\mathrm{t} \tag{10}$$

$$\mathrm{m_2 a_2} + \mathrm{c_1}(\mathrm{v_2} - \mathrm{v_1}) + \mathrm{k_1}(\mathrm{x_2} - \mathrm{x_1}) = -\mathrm{m_2 g} \tag{11}$$

2.2.3 Analysis of longitudinal rocking motion

For the longitudinal rocking motion, a polar coordinate system is used for the analysis, with the angular direction shown in Figure 3 as the positive direction, and a non-inertial reference system is used for the analysis of the oscillator, with the rotation axis as the origin, and the coordinate system is established as follows.

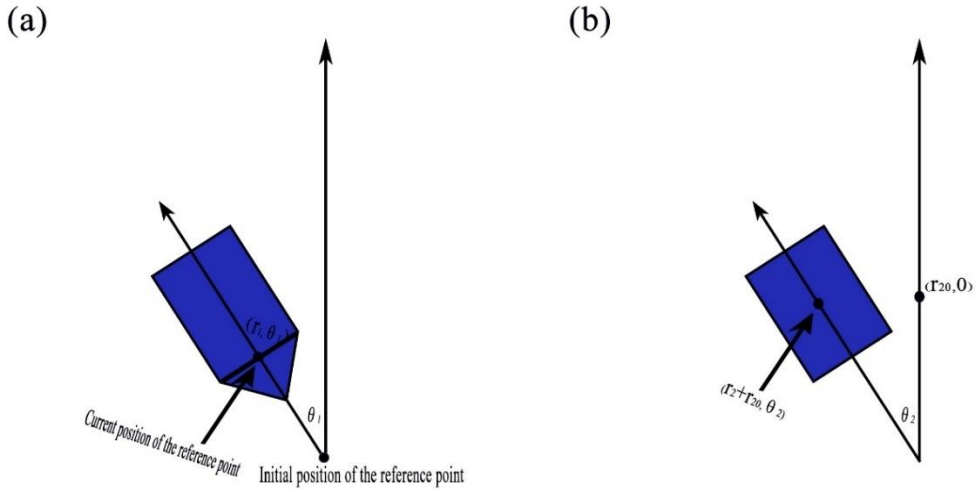


Figure 3. Float polar coordinate system (a) and oscillator polar coordinate system (b)

The float coordinate system takes the initial position of the reference point as the origin directly, r_1 is the pendulum displacement and θ is the longitudinal rocking angle, while the oscillator coordinate system takes the rotating axis as the origin, the pendulum displacement r_2 is actually the diameter length in the coordinates minus the distance of the reference point from the rotating axis at the equilibrium position, due to the regular shape of the oscillator, the reference point here is chosen as its center of mass.

The wave excitation moment on the float is

$$\mathrm{L_W} = \mathrm{L}\cos\,\omega\,\mathrm{t} \tag{12}$$

The additional moment of inertia is related to the angular acceleration and the additional rotational moment of inertia.

$$L_{r_1} = -I_a\ddot{\theta}_1 \tag{13}$$

The Hinpo damping moment is related to the angular velocity.

$$L_{r_2} = -c_{22}\dot{\theta}_1 \tag{14}$$

The hydrostatic recovery moment is related to the angular displacement.

$$L_b = -k_{22}\theta_1 \tag{15}$$

The rotational damper torque is related to the relative angular velocity.

$$L_{n_2} = -c_3\dot{\theta}_2 \tag{16}$$

The torsional spring moment is related to the relative angular displacement.

$$L_{n_1} = -k_3\theta_2 \tag{17}$$

The inertial forces on the oscillator are the translational inertial force, the centrifugal force, and the Coriolis force, of which the centrifugal force does not produce a moment on the oscillator, so consider the other two forces, and the moment produced by the translational inertial force.

$$L_p = -m_2\ddot{r}_1(r_2+r_{20})\sin\theta_2 \tag{18}$$

The Coriolis force produces a moment of

$$L_c = 2m_2(r_2+r_{20})\dot{r}_2\dot{\theta}_2 \tag{19}$$

Gravitational moments need to be considered at this point

$$L_G = -m_2 g(r_2+r_{20})\sin(\theta_1+\theta_2) \tag{20}$$

The following differential equation is easily obtained.

$$(I_1+I_a)\ddot{\theta}_1 + c_{22}\dot{\theta}_1 + k_{2_2}\theta_1 - k_3\theta_2 - c_1\dot{r}_2 = L\cos\omega t \tag{21}$$

$$I_2\ddot{\theta}_2 + c_3\dot{\theta}_2 + k_3\theta_2 + m_2 g(r_2+r_{20})\sin(\theta_1+\theta_2) = -m_2\ddot{r}_1\left(r_2+r_{2_0}\right)\sin\theta_2 + 2m_2\left(r_2+r_{2_0}\right)\dot{r}_2\dot{\theta}_2 \tag{22}$$

2.2.4 Analysis of device output power

The power of the damper is the output power, divided into linear dampers and torsional dampers, according to the form of force and moment, the power can be organized as a function of the relative displacement of the process of dip swing and the relative angular displacement of the process of longitudinal rocking.

$$P = \frac{1}{T}\left[\int_0^T c_1{\dot{r}_2}^2 dt + \int_0^T c_3{\dot{\theta}_2}^2 dt\right] \tag{23}$$

Where $\dot{r}_2$ denotes the pendulum displacement in the non-inertial system and $\dot{\theta}_2$ denotes the angular displacement during the longitudinal rocking motion in the non-inertial system.

2.2.5 Simulated annealing algorithm

The simulated annealing algorithm is a classical optimization algorithm that simulates the annealing process so that the solution can move within a certain range of domains, so that it can avoid the drawbacks of traditional algorithms that tend to fall into local optima. Also the probability of accepting and generating new solutions decreases as the temperature decreases, allowing the results to converge [11].

The steps of the single-objective optimization model solving algorithm based on simulated annealing established in this paper are as follows.

Step1: Constant assignment and data preprocessing

Perform data preprocessing, calculate the bottom area, side area and volume of the cylindrical part and conical part of the float, generate time t, and input the expression of the objective function, i.e., the expression of the average output power.

Step2: Initialization parameters and initial solution

Initialize the parameters, set the number of external cycles to 200 and the number of internal cycles to 20, initialize the initial temperature and temperature update factor, set the initial temperature to 10000, and set the temperature update factor to 0.95.

Step3: Generate new solutions and calculate new values

In case 1, let the new solution of the damping factor be equal to the product of the current solution of the damping factor + temperature and random weights in the range of [-1,1].

Step4: Determine whether to update the solution and update the temperature cycle to find the best

If the new solution of the average output power is greater than the current solution, the damping coefficient (scale factor and exponential power) is updated; if the new solution is not greater than the current power, the new solution is received according to the metropolis criterion. After that, the temperature is updated into the loop and then back to Step.3. and set a smaller step to find the maximum average output power and the best damping coefficient at the best temperature.

The flow chart of the simulated annealing algorithm in this question is shown in Figure 4 below.

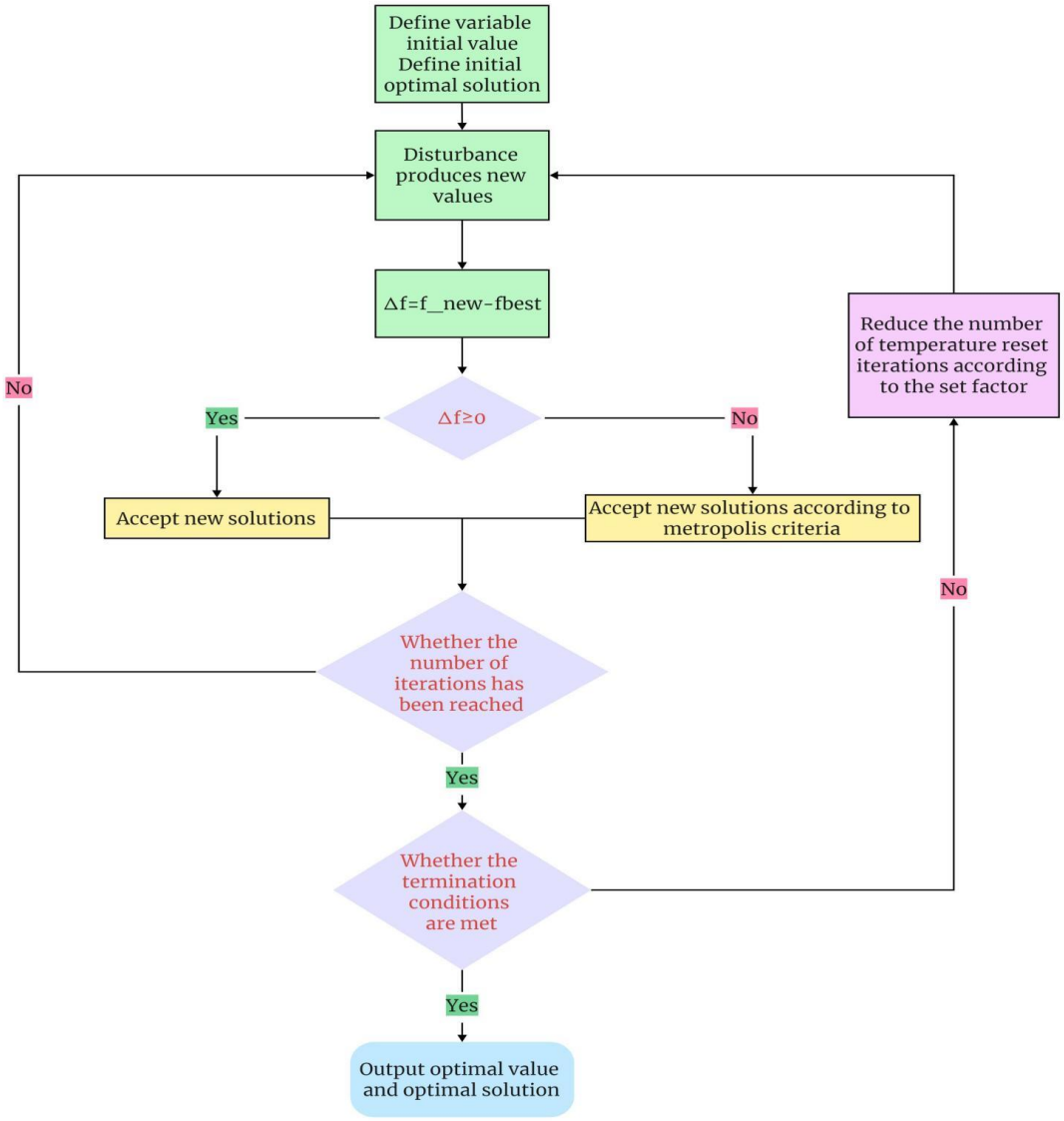


Figure 4. Flow chart of simulated annealing algorithm

3. Results

3.1. Visualization of optimization results

The maximum average output power and damping coefficients obtained based on the traversal search of the simulated annealing algorithm are shown in Table 1 below.

Table 1. Optimization results

Maximum output power P(W)	Optimal damping factor c_1 (N·s/m)	Optimal damping factor c_3 (N·s/m)
457.1656	38651.1260	99399.5449

The output power iteration diagram is shown in Fig. 5. From the diagram, it can be seen that after 200 iterations, the value of the output power has been basically stabilized and reached the optimal value.

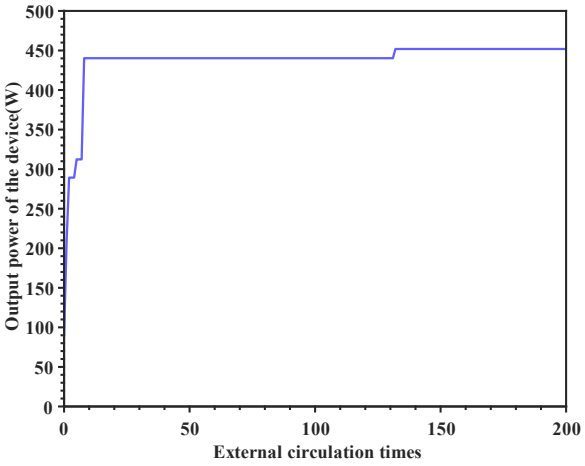


Figure 5. Output power iteration diagram

3.2. Analysis and testing of experimental results

The analysis of the results shows that the optimal damping coefficient of the linear damper is located in the smaller position of the interval, while the optimal damping coefficient of the rotary damper is close to the maximum value of the interval, which shows that the influence of the rotary damper on the output power of the device is greater than that of the linear damper, and the influence of the linear damper on the output power in the process of vertical swing and longitudinal rocking is non-linear.

To test the results, 10,000 points were selected to make a three-dimensional scatter plot of the output power versus the damping coefficients of the linear and rotary dampers as shown in Figure 6.

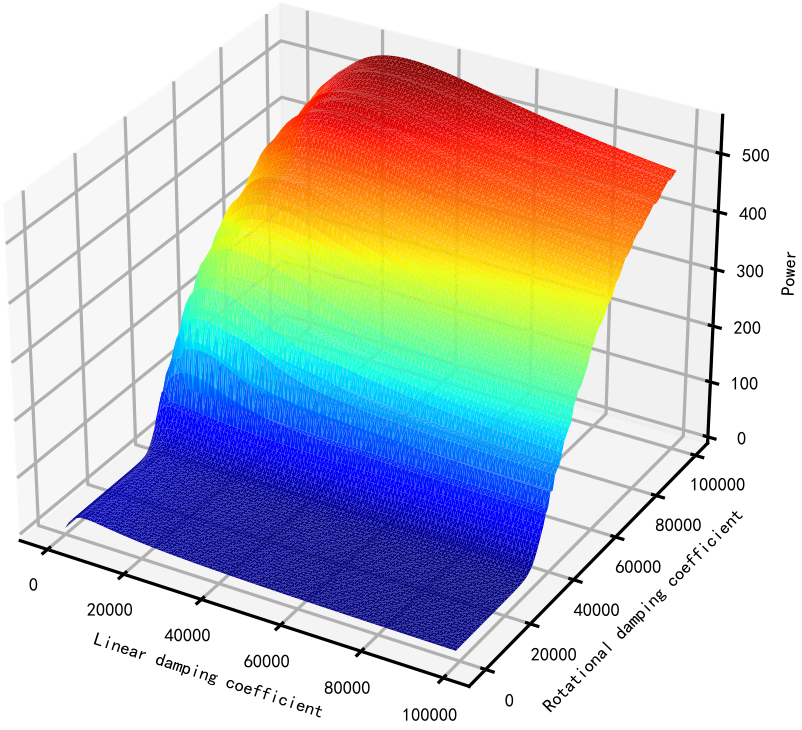


Figure 6. Results test

The above validated relationship diagram shows that for the wave energy device with only vertical oscillation and longitudinal rocking motion, the output power of the PTO system increases with the increase of the damping coefficient of the rotating damper in a certain range, increases with the

increase of the damping coefficient of the linear damper at [0,38651], and decreases with the increase of the damping coefficient of the linear damper at [38651,100000].

4. Conclusions

The main work of this paper is to analyze the working mechanism of the float-vibrator type wave energy device, give the differential equations of float and vibrator motion as constraints, use the simulated annealing algorithm to find the output power of the device, and find out the device configuration when the output power is optimal, which can make some suggestions on the design of the wave energy device to make the collection better for better utilization of wave energy.

References

[1] Khojasteh, D., Mousavi, S. M., Glamore, W., & Iglesias, G. (2018). Wave energy status in Asia. Ocean Engineering, 169, 344-358.

[2] Pecher, A., & Kofoed, J. P. (2017). Handbook of ocean wave energy. Springer Nature.

[3] Shoaib, M., Siddiqui, I., Rehman, S., Khan, S., & Alhems, L. M. (2019). Assessment of wind energy potential using wind energy conversion system. Journal of cleaner production, 216, 346-360.

[4] Solar Fuels and Solar Chemicals Industry

[5] Sergent, P., Baudry, V., Bonviller, A. D., Michard, B., & Dugor, J. (2020). Numerical assessment of onshore wave energy in france: wave energy, conversion and cost. Journal of Marine Science and Engineering, 8(11), 947.

[6] Zhu, Y., Yang, Z., Jiao, C., Ma, M., & Zhong, X. (2022). A multi-modal energy harvesting device for multi-directional and low-frequency wave energy. Frontiers in Materials, 310.

[7] Zhao, L. C., Zou, H. X., Xie, X., Guo, D. H., Gao, Q. H., Wu, Z. Y., ... & Zhang, W. M. (2023). Mechanical intelligent wave energy harvesting and self-powered marine environment monitoring. Nano Energy, 108222.

[8] Zhang, D., Li, W., & Lin, Y. (2009). Wave energy in China: Current status and perspectives. Renewable energy, 34(10), 2089-2092.

[9] Huang Xiuxiu. Power Control of Oscillating Float Wave Power Generation System.Chinese Master's Theses Full-text Database, 2019. DOI: 10.27151/d.cnki.ghnlu.2019.001731.

[10] YANG Peng;GU Xue-kang;PENG Zheng-liang;WU Dong-wei;ZHANG Kai. Study on nonlinear springing and whipping of a 6750 TEU container ship. Journal of Ship Mechanics,2020,24(02):221-235.

[11] LU Yu-ting;LIN Yu-you;PENG Qiao-zi;WANG Ying-zhe;School of Mathematical Science,Beijing Normal University. A Review of Improvement and Research on Parameters of Simulated Annealing Algorithm. College Mathematics,2015,31(06):96-103.