Design and analysis of energy supplement system of waterfowl-type unmanned vessel platform

Zifan Fang, Junpeng Hong1, Lin Qin, Jin Liu, Zhiheng Xie and Zheyu Xie
College of Mechanical and Power, China Three Gorges University, Yichang, China

1 E-mail: 1228560008@qq.com

Abstract. For the marine unmanned vessel platform’s long-distance navigation, a waterfowl-type unmanned vessel platform energy supplement system consisting of a wave energy collecting mechanism and a hydraulic conversion system was presented. A four-link acquisition mechanism and an energy conversion system are designed. The wave force on the float and the vertical wave force on the unmanned vessel platform were calculated by Matlab software. Based on the energy flow conversion process, the Adams and AMESim co-simulation model of the system was established. The energy conversion efficiency of the system under different sea conditions was calculated. The research shows that it can realize the continuous energy supplement and provides a reference solution for solving the problem of continuous energy supply in marine unmanned vessel platforms.

1. Introduction
The unmanned vessel platform has greatly assisted people in marine development, resource exploration, and energy supply [1]. The waterfowl-type unmanned vessel platform is a kind of mobile engineering equipment with certain carrying functions in the marine environment. It is small, mobile, long endurance and so on. Because the marine environment is more complicated, the unmanned vessel needs a larger energy source to provide its power demand. Usually, this part of the energy is supplied by the battery. During long-time navigation, the source shortage problem is difficult to avoid, so the small unmanned vessel platform under long-distance navigation needs to be equipped with an energy supplement system suitable for its working environment [2].

McKinney and DeLaurier [3] proposed a new concept of energy harvesting based on the submerged-floating-pitch-floating-wing mode for the first time. The flapping wing generates ups and downs and pitches under the action of the flow field, and the flow energy flow is converted into mechanical energy to realize energy harvesting. Mohammad-Reza Alam [4] proposed a “wave-energy conversion carpet” with viscoelasticity based on the wave resistance effect along the muddy coast. The energy absorption rate reached 6.5 kW per square meter by adjusting its system elasticity and damping coefficient in real time. Rico H. Hansen and M.M. Kramer [5] studied the feedback control theory of wave energy acquisition system by using the characteristics of virtual elastic components, and conducted a sea trial on the array multi-float acquisition method. And its energy conversion efficiency reached 70%. Deng Jian and Dai Bin [6] conducted a numerical simulation study on the two-degree-of-freedom passive current energy harvesting system, and the highest collection efficiency was close to 20%. Sheng Songwei [7] designed a combination of hydraulic and direct drive eagle wave power generation device, which optimizes the parameter configuration in the system through model test and improves the energy conversion efficiency. They are all just qualitative analysis of the energy...
conversion device. They do not have an analysis of conversion efficiencies at different wave levels. This paper creatively proposes an analysis of the conversion efficiency under different wave levels.

At present, the navigation power and detection power of the marine unmanned platform are mainly provided by the battery. When the battery is low, the unmanned platform cannot replenish the electric energy by itself, and it needs to be returned to rely on the maintenance of the staff. To this end, the wave energy utilization technology applied to the unmanned boat platform is studied, and a wave energy supplement system of the waterbird-type unmanned vessel platform is proposed to realizes the wave energy acquisition, conversion, stability.

2. Energy supplementary system for waterflow-type unmanned vessel platform

2.1. Supplement principle

This energy supplement system is mounted on the waterfowl-type unmanned vessel platform. The energy supplement principle is a subsubsection, Figure 1 explains the relationship between energy harvesting and conversion system parameters:

2.2. Wave energy collection mechanism

The waterfowl's wing structure will gain lift to collect energy in the moving flow field [8]. The movement of the flapping floating in the sea is similar to the movement of the waterfowl's wings in the air. The linkage mechanism that the flapping wing floats up and down in the seawater is used to simulate the movement of the waterfowl's wings. As part of the wave energy harvesting mechanism, the four-bar linkage mechanism has the function of transmitting the motion of the object and the wave force. Figure 2 is the working principle diagram of the wave energy collection mechanism.

2.3. Random energy hydraulic drive system

When the hydraulic energy conversion system is working, the signal source 9 is the speed signal and the displacement signal of the hydraulic cylinder piston rod 1. It realizes a reciprocating linear motion of the float. According to the layout characteristics of the mechanical structure, the system needs to set
two sets of hydraulic energy conversion devices. The two groups of hydraulic cylinders receive the same force load. The flow and pressure of the hydraulic oil are basically the same. After the combination of the hydraulic pipes, the stability of the overflow valve 5 is utilized. The pressure characteristic sets the upper limit of the hydraulic line pressure. The hydraulic oil exceeding the rated pressure will flow from the overflow valve to the tank to prevent the system from being overloaded. Combined with the buffering of the accumulator 6 to achieve the function of peaking and filling the valley, the throttle valve 7 is arranged at the same time to stabilize the flow rate of the hydraulic pipeline, and the hydraulic energy is converted into relatively stable mechanical energy by the conversion of the hydraulic motor 8. Figure 3 shows the hydraulic energy conversion system scheme.

![Figure 3. Hydraulic energy conversion system.](image)

1- hydraulic cylinder, 2- check valve, 3- fuel tank, 4- check valve, 5- relief valve, 6- accumulator, 7- speed governor, 8- hydraulic motor, 9- signal source

2.4. System overall plan
The wave energy collecting mechanism is hinged to the inner cavity of the unmanned boat platform by two fulcrums. The floating body moves up and down under the action of sea water to drive the link mechanism to rotate around the fulcrum. The link mechanism pushes the piston rod of the hydraulic cylinder at the other end to move.

Figure 4 shows the three-dimensional model of waterfowl-type unmanned vessel platform and its energy supplement system:

![Figure 4. Three-dimensional model.](image)

3. Vibration model and wave force calculation of unmanned vessel platform float

3.1. Vibration model
The heave motion is analyzed. When the float makes a heave motion under the action of the wave power $F_{zz}$, a mathematical model of vibration can be established:

$$M_{zz} \ddot{Z} + 2N_{zz} \dot{Z} + C_{zz}Z = F_{zz}$$

(1)
Among them, $M_{zz} = \frac{D}{g} + \lambda_{zz}$, the inertia moment coefficient of the float heave motion, $2N_{zz}$ is the heave moment coefficient, $C_{zz} = \gamma S_w$ is the restoration torque coefficient for heave.

$$ (\frac{D}{g} + \lambda_{zz})\ddot{Z} + 2N_{zz}\dot{Z} + (\gamma S_w)Z = F_{zz} $$ (2)

Where: $D$ is the weight of the float; $g$ - gravitational acceleration; $\lambda_{zz}$ - additional moment of inertia caused by the additional mass of water; $\gamma$ - the gravity of the water; $S_w$ - the surface area of the float waterline.

3.2. Sea state analysis

Combined with the wave conditions in the Diaoyu Islands of the South China Sea [9], this paper analyzes the forces of objects in three common sea conditions. Table 1 shows the wave-related parameters of the sea level 2, 3, and 4.

### Table 1. Wave related parameters of multi-level sea conditions.

| Sea level | Wave height (H/m) | Cycle (T/s) | Wave Length (λ/m) | Wave Number (k) | Water depth (h/m) | Seawater density ρ/(g.cm⁻³) |
|-----------|------------------|-------------|-------------------|-----------------|------------------|-----------------------------|
| Level 2   | 0.3              | 2.4         | 6.1               | 1.03            | 1.0              | 1000                        |
| Level 3   | 0.884            | 3.9         | 15.85             | 0.40            | 20               |                              |
| Level 4   | 2.1              | 5.4         | 30.18             | 0.21            |                  |                              |

3.3. Wave force analysis model

Using the Matlab software, the wave force calculation model of the float and the hull is established. The wave forces of the float and the hull at different times are calculated under different sea conditions. The bottom of the hull is close to a semi-circular shape which can be simplified when calculating the wave force, and the hull is considered as a horizontal cylindrical object for calculation. With the Froude-Krylov hypothesis [10], the wave excitation force on the float can be calculated, and the vertical wave force on the horizontal cylinder float is:

$$ F_V = C_V \int p_z dS $$

$$ = 2C_V \int_{\frac{L}{2}}^{\frac{L}{2}} \frac{d(t) - R}{R} p R \sin \theta d\theta dx $$

$$ = C_V \frac{2 \rho g H R A}{k \cos k d} \frac{k L}{2} \cos \alpha t $$

In the formula, $P_z$ is the component of the wave pressure of the incident wave at any point on the surface of the floating body in the vertical direction; $C_V$ is the vertical diffraction coefficient; $S$ is the contact area of the floating body and seawater.

$$ A = \int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} \sin \frac{d(t) - R}{R} \cosh k (d + R \sin \theta) \sin \theta d\theta $$ (4)

The float structure is simplified to a horizontal cylindrical float with a length $L = 2$ m and a radius $R = 0.5$ m. The floating body and hull force equations are established in Matlab. For the convenience of calculation, the hull is equivalent to a horizontal cylinder for calculation, and the relative motion between the hull and the float is not considered.

Calculate the combined wave force of concentrated mass $m1$, the concentrated mass $m2$, and the float $m3$ under the sea conditions of 2nd, 3rd, and 4th grades. $F(t)$ is the sum of the wave buoyancy and the vertical force of the object. The result is shown under Figures 5-7.
4. Energy supplement system simulation research

4.1. Virtual prototype model
The dynamic simulation model of the waterfowl-type unmanned vessel platform and its energy supplement system was established by using Adams multi-body dynamics analysis software, as shown in Figure 8.

Define the quality parameters of each part, in which the float mass is 200 kg and the hull mass is 3000 kg. The quality of the connecting rod and each connecting piece has little influence on the system dynamics, and the influence can be neglected. Since the heave and pitch motion of the ship are considered, we simplify the front and rear ends of the ship into concentrated masses \( m_1 \) and \( m_2 \), set the concentrated mass \( m_3 \) at the centroid of the float. Then we respectively establish tension and
pressure at $m_3$, the mass points $m_1$ and $m_2$ of the hull. The spring damper unit is set with its corresponding stiffness coefficient and damping coefficient. The detailed data of the detailed stiffness coefficient and damping coefficient of the Adams model are shown in Table 2.

Table 2. Adams model dynamics parameters.

| Concentrated quality | Quality (kg) | Stiffness coefficient (N·mm⁻¹) | Damping coefficient (N·(m·s⁻¹)-1) | External incentive |
|----------------------|-------------|---------------------------------|----------------------------------|-------------------|
| m1                   | 1500        | 89                              | 240                              | SFORCE_CHAU1      |
| m2                   | 1500        | 89                              | 240                              | SFORCE_CHAUN2     |
| m3                   | 200         | 10.93                           | 7.4                              | SFORCE_BO         |

The Matlab calculation results are input into the Adams wave acquisition system dynamics model. In the Adams software, the movement and force of the float, the connecting rod structure and the hull are obtained. The speed and displacement parameters of the connecting rod structure and the hull rod connecting the hydraulic cylinder are extracted. The Adams/Controls interface plug-in is used to export Adams data. The two output parameters are input to the AMESim hydraulic conversion system model as input parameters of the AMESim software [11]. The hydraulic circuit characteristics are used to realize the energy commutation, consolidation and stabilization process. The hydraulic motor output speed and torque parameters, and the thrust of the hydraulic cylinder piston rod will feedback to the Adams model which has an impact on the movement of the energy harvesting mechanism [12-14]. Figure 9 shows the co-simulation model of the energy supplement system for the waterfowl-type unmanned vessel platform. Table 3 shows the setting parameters of the AMESim model.

Figure 9. Co-simulation model of energy supplement system.

Table 3. AMESim related parameter settings.

| Hydraulic cylinder stroke | Piston rod initial position | Hydraulic cylinder inner diameter | Piston rod diameter |
|---------------------------|-----------------------------|----------------------------------|--------------------|
| 800 mm                    | 400 mm                      | 30 mm                            | 20 mm              |
| Accumulator volume        | Speed control valve opening diameter | Hydraulic Motor displacement | Hydraulic motor rated speed |
| 10 L                      | 5 mm                        | 163 mL/r                         | 600 r/min          |
| Relief valve pressure     | Accumulator pressure        | Moment of inertia                | Rotational friction coefficient |
| 2.5 MPa                   | 1.6 MPa                     | 0.1 kg·m²                       | 0.01 r/min         |
| Speed gain                | Displacement gain           | 0.001                            | 0.001              |
4.2. System performance analysis under multi-level sea conditions

In order to simulate the movement of the energy supplement system of the waterfowl mobile platform in the actual ocean wave, combined with the common wave level in the South China Sea, the response of the system under the sea conditions of Level 2, Level 3 and Level 4 can be more convenient by using the virtual prototype technology to establish a waterflow mobile platform energy supplement system simulation model. The co-simulation adopts Discrete simulation model, and the simulation calculation mode is Interactive operation mode. The advantage is that it can observe the motion of the mechanism in real time during co-simulation, and it is convenient to monitor the simulation calculation. In order to minimize the error of the Adams software and AMESim co-simulation, the simulation step and end time should be set to the same as the time step of the wave excitation force in the Adams model. The simulation termination time is set to 30s, and the simulation step length is set to 0.1s. Figure 10 shows the piston rod displacement of the hydraulic cylinder under multi-level sea conditions, and Figure 11 shows the hydraulic cylinder feedback force under multi-level sea conditions.

Figure 10. Hydraulic cylinder piston rod displacement under multi-level sea conditions.

Figure 11. Hydraulic cylinder feedback force under multi-level sea conditions.

In Class 2 sea conditions, the hydraulic cylinder piston rod displacement is between 400 mm and 450 mm. The hydraulic cylinder feedback force is large in the first cycle which is to 800 N, and then reciprocates between 400 N and -200 N. In Class 3 sea conditions, the hydraulic cylinder piston rod displacement is between 300 mm and 560 mm. The hydraulic cylinder feedback force varies between -600N and 1300N.In the 4th sea state, the hydraulic cylinder piston rod displacement is between 120mm and 650mm. The hydraulic cylinder feedback force varies between -1000N and 1750N.
4.3. System output analysis and calculation of conversion efficiency

4.3.1. System Output Analysis. With the Adams/Machinery Motor module, the torque and speed of the motor can be output according to the key parameters of the input motor, which can simulate the driving effect of the motor more realistically.

In Class 2 sea conditions, the generator torque is stable at 1.7 Nm. The generator speed is 152 r/min. The average induced electromotive force is 4V, and the average generator output power is 26 W.

In Class 3 sea conditions, the generator torque is stable at 4.7 Nm. The generator speed is 410 r/min. The average induced electromotive force is 11 V, and the average generator output power is 210 W.

4.3.2. Calculation of system energy conversion efficiency. The energy conversion efficiency $\eta$ of the system is the ratio of the power output power $P_o$ to the wave energy acquisition power $P_i$ of the system. It reflects the internal working efficiency of the system and is the working condition of the system under different sea conditions. The energy conversion efficiency $\eta$ can be calculated by the following formula:

$$\eta = \frac{P_o}{P_i} \times 100\%$$

Figure 12 shows the system generator speed, Figure 13 shows the system generator torque, Figure 14 shows the system generator induced electromotive force, and Figure 15 shows the system generator output power.

In the 4th sea state, the generator torque is stable at 7 Nm. The hydraulic motor is stable after 5s and varies periodically from 580 r/min to 610 r/min. The generator speed is 600 r/min. The average induced electromotive force is 16 V, and the average generator output power is 400 W.

The output power $P_o$ of the generator can be obtained from the simulation results of the Adams generator model. After the co-simulation model results are processed, the acquisition power $P_i$ of the wave float can be calculated. When the wave collecting mechanism works, the kinetic energy and potential energy of the wave energy are converted into the kinetic energy and potential energy of the wave float. When the wave float reaches the highest point of displacement, its kinetic energy will be converted into potential energy. Therefore, by solving the maximum potential energy of the wave float in a cycle under a specific sea condition, the work done by the wave on the float in one cycle can be
solved. In the case where the wave period is known, the acquisition power $P_i$ of the wave float can be obtained. The maximum potential energy $E_p$ of the float in one cycle (regardless of the relative displacement between the float and the hull) can be expressed as:

$$E_p = mg(h_{\text{max}} - h_0)$$  \hspace{1cm} (6)

Where $h_{\text{max}}$ is the maximum displacement of the float in a single cycle, $h_0$ is the minimum displacement of the float in a single cycle.

The time at which the float acquires the maximum potential energy $E_p$ is half a cycle, so the acquisition power of the float can be expressed as:

$$P_i = \frac{2mg(h_{\text{max}} - h_0)}{T}$$  \hspace{1cm} (7)

After obtaining the change of the float displacement under different sea conditions, the maximum potential energy obtained by the float in half cycle can be solved, and the energy harvesting power of the float is calculated, and the power generation efficiency of the energy supplement system is obtained. After calculation, the power generation efficiency under multi-level sea conditions is shown in Table 4.

It can be seen from Table 4 that in the 2nd sea state, the generator output power $P_o$ is 26 W, the float collector power $P_i$ is 204.17 W, and the system power generation efficiency is 12.73%; in the 3 sea state, the generator output power $P_o$ is 210 W. The floating collector power $P_i$ is 500.55 W, and the system power generation efficiency is 41.95%. In the 4 sea state, the generator output power $P_o$ is 400 W, the float collector power $P_i$ is 1104 W, and the system power generation efficiency is 36.23%.

### Table 4. System energy conversion efficiency.

| Sea level | Output power $P_o$/W | Float displacement difference [h_{\text{max}}-h_0]/m | Float acquisition power $P_i$/W | Conversion efficiency $\eta$/% |
|-----------|-----------------------|-----------------------------------------------|--------------------------------|-----------------------------|
| 2         | 26                    | 0.125                                         | 204.17                         | 12.73%                      |
| 3         | 210                   | 0.498                                         | 500.55                         | 41.95%                      |
| 4         | 400                   | 1.522                                         | 1104.00                        | 36.23%                      |

From the above results, it can be analyzed that in the case of sea level 2, the wave contains less energy and the float collection power is lower, while the energy conversion efficiency of the system is lower, only 12.73%. When the wave level is 3, The system energy conversion efficiency has been greatly increased to 41.95%. When the wave level becomes 4, the system energy conversion efficiency has decreased slightly to 36.23%.

This indicates that the energy conversion efficiency of the waterfowl-type unmanned vessel platform energy supplement system is low in low sea conditions, while the energy conversion efficiency of the system is higher in medium sea conditions [15-16].

### 5. Conclusions

In order to solve the long-distance power supply problem of the waterfowl-type unmanned vessel platform, the paper proposes a waterflow-type unmanned vessel platform energy supplement system, which consists of two parts that are the wave energy acquisition system and the random energy conversion system. The article uses the combination of numerical calculation and simulation test to carry out wave energy acquisition mechanism and energy conversion mechanism design, dynamics modeling and analysis, system dynamic performance analysis, simulation test and other issues, which is the promotion and application of wave energy generation technology.

The navigation power and detection power of the current marine unmanned platform are mainly provided by batteries. They cannot meet the navigation requirements when the power is not enough. In contrast, we have designed a sustainable, stable energy conversion device. Through simulation analysis, it can achieve the purpose of continuously and stably conveying energy for navigation.
Acknowledgements
The work was supported by the National Science Foundation of China under Grant No. 51875314 and by Research Fund for Excellent Dissertation of China Three Gorges University.

References
[1] Liu Ming 2019 New progress in marine science and technology since the 13th Five-Year Plan[N]. China Ocean News, July
[2] Xiao Xi, Bai Nianzong and Kang Qing 2014 A Review of the Development of Wave Power System and the Research on Direct-Drive Wave Power System[J]. Transactions of China Electrotechnical Society 29 No. 3 pp 1-11
[3] Mckinney William and J Delaurier 1981 The wingail: an oscillating wing windmill[J]. Journal of Energy 5 No. 2 pp 109-115
[4] Mohammad-Reza Alam 2012 A flexible seafloor carpet for high-performance wave energy extraction[C]. ASME 31st Int Conf on Ocean Offshore and Arctic Engineering America: American Society of Mechanical Engineers pp 839-846
[5] Hansen Rico H and M M Kramer 2013 Discrete Displacement Hydraulic Power Take-Off System for the Wavestar Wave Energy Converter[J]. Energies 6 No. 8 pp 4001-4044
[6] Deng Jian, Dai Bin and Shao Xueming 2013 Hydrodynamic mechanism of fully passive energy harvester from ocean current[J]. Journal of Zhejiang University(Engineering Science) 47 No. 10 pp 1784-1789
[7] Sheng Songwei, Zhang Yaqun and Wang Kunming 2015 Experiment research on the power generation system of the Sharp Eagle wave energy converter[J]. Renewable Energy Resources 33 No. 9 pp 1422-1426
[8] Xie Yonghui, Jiang Wei, Lu Kun and Zhang Di 2016 Review on Research of Flapping Foil for Power Generation From Flow Energy[J]. Proceedings of the CSEE 36 No. 20 pp 5564-5574+5733
[9] Zheng Chongwei, You Xiaobao and Chen Xiaobin 2014 Feasibility analysis on the wind energy and wave energy resources exploitation in Fishing Islands and Scarborough Shoal[J]. Marine Forecast 31 No. 1 pp 49-57
[10] Fang Zifan, Ma Zhenhao and Gao Shu 2015 Development of multi segment float type mechanical wave energy power generation device[J]. Acta Energiae Solaris Sinica 36 No. 10 pp 2518-2523
[11] Gao Hong, Liang Ruizhi and Tsukiji Tetsuhiro 2019 Research on dynamic characteristics and energy conversion of wave energy conversion hydraulic system[J]. Hydraulic and pneumatic No. 6 pp 1-4
[12] Dean C Kamopp, Donald L Margolis and Ronald C Rosenberg 2006 System Dynamics: Modeling and Simulation of Electromechanical Systems: Fourth Edition[M]. National Defense Industry Press
[13] Xiao Daizong 2007 Simulation technique of AMESim and its application in design and performance analysis of hydraulic component[J]. Ship Science and Technology pp 142-145 (S1)
[14] Zhu Dequan 2012 Study on optimization design method for mechanical-electrical-hydraulic integrated system based on collaborative simulation[D]. University of Science and Technology of China
[15] Wei Wei and Wang Tuichen 2019 Application of oscillating water column wave energy generation technology in navigation mark[J]. Pearl River Water Transport No. 11 pp 92-93
[16] Liu Xuan and Liu Denghua 2019 Design and Research of Large Ocean Semi-submersible Power Generation Platform[J]. Technology and Innovation No. 11 pp 15-17