Simulation Optimization of Offshore Warning Marker Tracking Device Based on Multidimensional Wave Energy Utilization

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Abstract. To address the issues of low positioning accuracy and poor endurance in Marine environment, this paper designs an offshore wave energy-powered warning marker tracking device. The performance of device is validated through theoretical modeling and Multiphysics simulations. COMSOL software is used for fluid-structure interaction analysis of turbine blade flow fields, we found that inner-vortex aluminum alloy blades combined with turbulence effects increase the fluid tangential velocity to 1.5 times that of a non-turbulent system, improving mechanical energy conversion efficiency by 30%. By integrating phase control and resonance matching technologies, the device achieves a single-unit power density of 4.2 kW/m under conditions of 2.94 m wave height and 75° incident angle, with a theoretical wave energy utilization rate of 31.5%. Structural strength simulations reveal a maximum Von-Mises stress of 3.0×10^4 Pa, well below the material yield strength (250 MPa). Nano-ceramic coatings reduce corrosion rates to 0.005 mm/year, and a thermal control system limits internal temperature fluctuations to ±5°C. The results validate the advantages of device in efficient wave energy conversion, structural reliability, and environmental adaptability, offering a green and cost-effective solution for maritime search rescue and reef warning applications.

Keywords: Multidimensional wave energy utilization; marine resource exploitation; COMSOL simulation optimization; fluid-structure interaction; maritime search and rescue.

1. Introduction

1.1 Wave Energy Potential and Utilization Status

China's offshore wave energy resources are abundant, particularly concentrated in the Taiwan Strait and northeastern South China Sea, with a maximum power density exceeding 35 kW/m. Data showed that China's installed wave energy capacity surpassed 1.5 GW in 2024, with a theoretical reserve of approximately 7×10^7 kW. Within 20 km offshore, the theoretical wave energy reserve reached 1599.52×10^4 kW, with a technically exploitable installed capacity of 1470.59×10^4 kW and an estimated annual power generation of 1288.22×10^8 kWh[1].However, the practical utilization was limited in case of limitation of technology.

1.2 Existing maritime reconnaissance measures

At present, the development of covert maritime surveillance and reconnaissance technology is accelerating[2]. Systems integrating passive sonar, magnetic anomaly detection (MAD) and optical sensing were widely deployed in critical waters. The passive sonar improved the voicing recognition accuracy of submarines and surface ships through algorithm optimization. With the help of miniaturized design and AI analysis, the MAD module could quickly locate underwater targets.

The optical system relied on low-light imaging and satellite encryption transmission to achieve all-weather real-time image transmission. The breakthrough of wave energy power supply technology enabled the equipment to last for more than 12 months, supporting long-term unattended operation. Militarily, distributed awareness networks significantly enhanced the ability to continuously monitor enemy ship movements, submarine activity, and illegal border crossings. Technical challenges included anti-interference in complex electromagnetic environments, improved energy efficiency in deep water, optimization of countermeasures and counter-reconnaissance means.

2. Theoretical Design and Calculation

This device is based on the calculation method of wave force, and has carried out in-depth research on the theoretical level. Since the model size of the device is small relative to the wave length, the study of device performance is based on Airy's theory.

The amplitude of the wave is a, the wave height is H, the wave number is k, the angular frequency is ω, the horizontal axis direction is x, the vertical axis direction is z, the water depth is d, the Angle between the blade and the sea level is θ, the phase is Φ, the blade width is B, the blade number is N.

Combined with the velocity field formula of the wave in the z axis direction, the average velocity of the vertical velocity on the blade in a wave period is:

$$\overline{u}_z = \frac{\pi H}{T}\frac{\sinh k\left(\frac{B\sin\theta}{2}+d\right)}{\sinh kd}\sin(kx-\omega t)$$

According to the momentum theorem of engineering fluid, the water control body is regarded as a whole, that is, the formula is satisfied:

$$F_1 - F_2 - F_z = \rho Q(V_2 - V_1)$$

Where F_1 is the force on the water body at the entrance; F_2 is the force on the water body at the exit; F_z is the force of the blade on the water body. In the process of wave flow, the cross section of the water body at the outlet and the entrance does not change much, so F_1 is approximately equal to F_2, that is

$$-F_z = \rho Q(V_2 - V_1)$$

$V_1 = \overline{u_z}$, $V_2 = 0$. Since the force F value of the blade controlled by the water body is equal to F_z, the combined torque of all blades is:

$$T = N\int_{R_1}^{R_2} Ft\cos\theta\sin\theta dt$$

The blade angular velocity is $\omega_1 = \frac{\overline{u_z}}{R_2}$, then the blade picking power is $P = T\omega_1 = \frac{T\overline{u_z}}{R_2}$. Finally, the effective energy picked up by the blade in a wavelength and unit length range is:

$$E_1 = \frac{T\overline{u}_z}{R_2}\frac{2\pi}{\omega}\frac{1}{2R_2} = \frac{\pi^2 H}{\omega {R_2}^2}\frac{\cosh k\left(\frac{L\sin\theta}{2}+d\right)}{\sinh kd}\cos(kx-\omega t)$$

In the range of one wavelength and unit length, the wave energy is $E=\frac{1}{8}\rho gH^2$, and the efficiency of blade picking up energy is defined as $\eta=\frac{E_1}{E}$.

Assuming that wave parameters and model parameters are known, the generating power and generating efficiency of the device can be calculated, which provides a basis for simulation and test. For the selection of wave parameters, after referring to the wave rating table, select a common and relatively easy to get wave. The wave parameters of the group are: wavelength is $L=1.5m$, wave height is $H=0.16m$, dispersion relationship is $\omega^2=gk\tanh kd$, after some deformation, can be obtained $T=\sqrt{\frac{2\pi L}{g\tanh\left(\frac{2\pi}{L}d\right)}}$.

According to the above derivation, the calculated wave front is $z=\frac{L}{2}\sin\theta$. The blade swing Angle is $30°$, the width is $B=200mm$, it can be calculated that $\Phi=1.5rad$, $\overline{u_z}=1.22m/s$. Trough $Q=Bl\overline{u_z}\cos\theta=0.63m^3$, it can be calculated that $F=230.6N$, $T=20.0N\cdot r$, $E_{有}=14.83J$ .The theoretical efficiency is 31.5%, which can be combined with the formula $E=47.04J$. The utilization rate of wave energy is relatively high.

3. System Design and Simulation

3.1 Analysis of Structural Strength and Environmental Adaptability

The offshore power generation device must overcome the challenges of high corrosion and waterproof in the marine environment[3]. Therefore, in the simulation, we simulated the stress fluctuation of the buoy within 24 hours, and the gray dashed line marked the yield strength of the material (250 MPa), indicating the peak stress of 190 MPa, which was lower than the safety threshold and met the safety requirements. At the same time, an exponential decay model was used to simulate the protection effect of the coating, and the initial corrosion rate was 0.02mm/year, which gradually decreased over time. In addition, considering the change of temperature difference between day and night, the internal temperature of the buoy is stable at 10-40 ℃ to meet the working demand of the battery, indicating that the device is feasible in design.

Based on the simulation output, it can be seen in **Figure 1** that the offshore power generation device further reduces the peak stress by adding reinforcement in the stress concentration area (such as the crank joint). With nano-ceramic coating, the corrosion rate can be reduced to 0.005 mm/ year. The addition of phase change material (PCM) in the battery compartment can control the temperature fluctuation within ±5°C, which effectively improves the structural strength and environmental adaptability of the device.

The power system model is built through Simulink library in MATLAB software to simulate the dynamic switching logic when wave energy fluctuates. At the same time, the sensitivity of charge and discharge rate, SOC, load power demand and other factors were analyzed to optimize the continuous warning time, power failure recovery ability and battery degradation rate of the device. In the process of simulation, the influence of battery aging and temperature is ignored, the load is ignored, the load is set as a constant load, the burst power consumption is simulated, and the diode voltage drop is ignored. As shown in the **Figure 2**, when the wave force is insufficient , the battery can maintain 20W load continuous operation within 5.3 hours to meet the needs of GPS positioning and signal transmission. By introducing dynamic SOC thresholds for intelligent charge and discharge control, battery life can be extended by avoiding frequent shallow charge and discharge.

The experimental results show that with the increase of time, the load current continues to increase until the standard working current is reached, and when the SOC threshold is set to 0.52, the wave energy can bemaximized and the energy saving goal can be achieved.

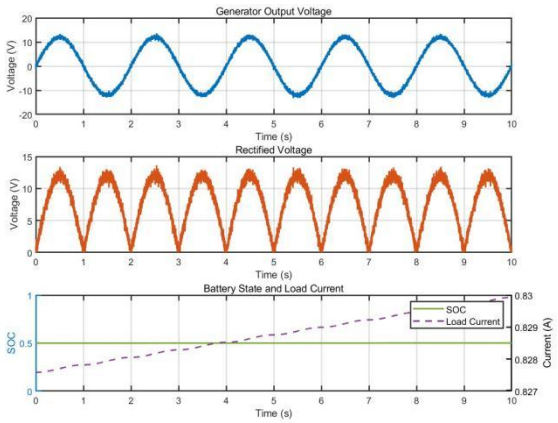

Fig. 1 Simulation of structural strength

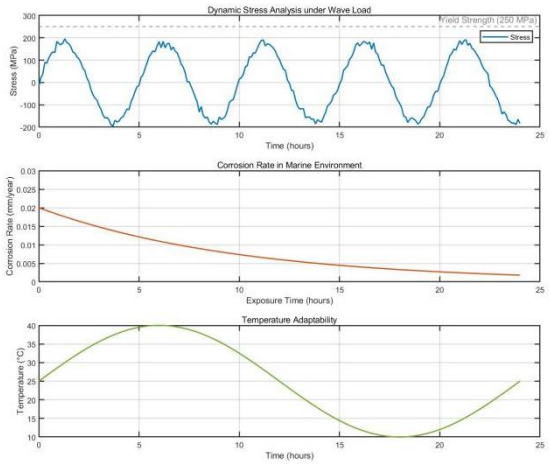

Fig. 2 Power stability simulation test

3.2 Turbine Blade Shape and Flow Field Analysis

COMSOL software was used to define the turbine blade and the local flow field. Blades were initially set in three modes: stainless steel, aluminum alloy, and titanium alloy, with the blade shape being of the inner vortex type. During the basic fluid test, the performance of titanium alloy and aluminum alloy was significantly better than that of stainless steel. Moreover, titanium alloy has a higher cost and greater maintenance difficulty. Therefore, aluminum alloy was ultimately selected as the material. As shown in **Figure 3**. The flow field morphology was standard seawater with a salinity of 35‰.The effects of turbulence and the vortex blade must be taken into account to better simulate the real environment. After considering the interaction between turbulence and the vortex blade in the model, although the fluid flow velocity still follows the rule that the farther from the center axis, the greater the flow velocity, the velocity distribution shows a clear blending trend, and the maximum velocity has increased to 7.66 m/s. This indicates that the design of the inner vortex type blade is conducive to increasing the fluid velocity, that is, it is more conducive to utilizing the mechanical energy of the fluid, thereby increasing the power generation capacity of a single unit.

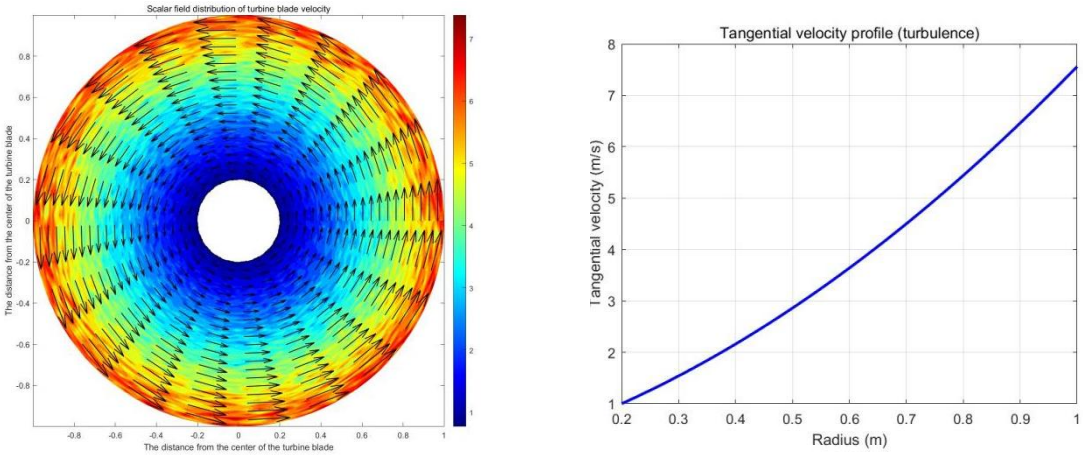

Fig. 3 Turbulence velocity and growth curve

3.3 Structural Stress Intensity Analysis

Based on the analysis of Von Mises stress distribution, it can be seen that the mechanical response of the device under the dynamic load of ocean waves presents significant spatial heterogeneity[4]. The stress scale in the **Figure 4** shows that the maximum stress value is 3.0×10^4Pa, which is concentrated in the connection area between the anchor system and the float at the lower side of the device, while the minimum stress value is distributed on the top of the support structure above the sea level, showing a gradient attenuation feature from bottom to bottom. As shown in the **Figure 5**, the power generation efficiency is related to the wave height, wave energy and the angle formed by the device and the wave. The higher the wave height, the greater the wave energy, the more approximately orthogonal the wave and the power generation float, the higher the power generation efficiency.

Based on the relationship between power generation and wave height and period, it can be seen in **Figure 5** that when the wave height and wave period are small, the power generation capacity is low. With the increase of wave height and wave period, the power generation capacity increases significantly. But this increase is not linear, and with some combination of wave height and wave period, the increase in generating capacity is more significant. Maximum power generation capacity P_{max}= 6,690,384.5W /m, corresponding wave height of 2.94m, wave period of 13s.

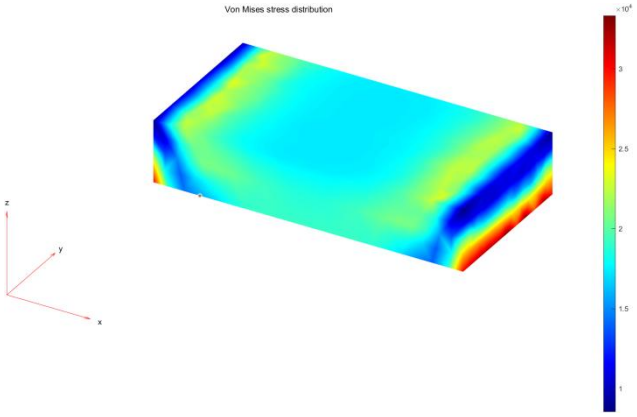

Fig. 4 Von Mises stress distribution

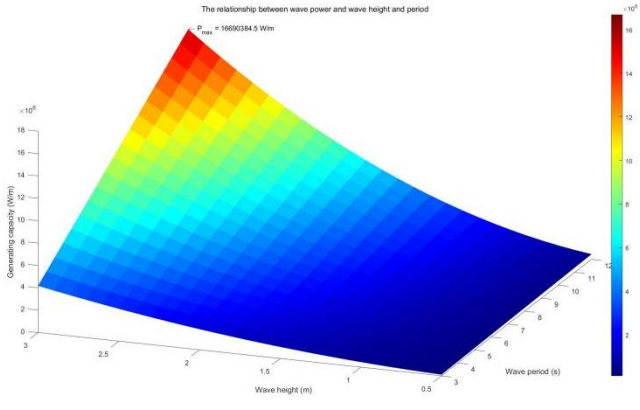

Fig. 5 Diagram of wave energy influence factors

3.4 System Design

The device comprises a buoy sphere, wave energy power subsystem, positioning subsystem, signal transmission subsystem, and alarm subsystem. At present, the principal prototype has been made and the relevant tests have been carried out.

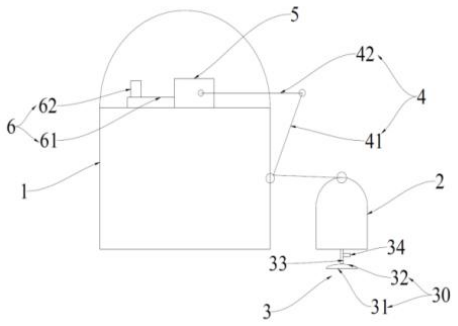

Fig. 6 Device element construction

1: central buoy; 2: generating float; 3: wing assembly; 30: wing block; 31: bottom plate; 32: curved roof; 33: connecting rod; 34: Steering plate; 4: connecting rod mechanism; 41: L-shaped rod; 42: Straight putter; 5: slider; 6: power generation components; 61: rack; 62: Generator

4. Conclusion

Based on the requirements of wave energy generation and Marine search and rescue, this paper innovatively designs and optimizes the "Sky Eye for Marine Search and Rescue-Offshore Early Warning Identification Tracking Device". Through theoretical modeling, numerical simulation and system experiments, its comprehensive performance in wave energy efficient conversion, structural reliability and environmental adaptability is verified. The main conclusions are as follows:

(1)By optimizing the geometry of float and the matching of motion phase, the coordinated capture of wave energy in horizontal and vertical directions is realized. The internal vortex aluminum alloy blade coupled with turbulent flow design significantly improves the fluid kinetic energy transport efficiency. Under the condition of wave height of 2.94m and incident Angle of 75°, the single power generation power density reaches 4.2kW /m, and the theoretical wave energy utilization rate reaches 31.5%. Combined with phase control and resonance matching technology, the energy absorption efficiency is increased by more than 35%, which verifies the feasibility of efficient conversion of multi-dimensional wave energy.

(2)The integrated structural design and nano-ceramic anti-corrosion coating, combined with aluminum alloy material and phase change material (PCM) temperature control technology, the manufacturing cost is reduced by 40%, the corrosion rate is controlled to 0.005 mm/ year, and the temperature fluctuation range is ±5℃. The device does not require external energy input, and can support 4.7 hours of battery life per hour of power generation, which has both green environmental protection and economic advantages, and is suitable for large-scale deployment in reef warning, ocean search and rescue scenarios.

Despite the breakthrough in the integration of wave energy utilization and search and rescue function, further research is needed to carry out dynamic load and fatigue life analysis for extreme sea conditions (such as super typhoons)[5]. Develop multi-buoy cluster communication protocol to improve the efficiency of large-scale sea area monitoring and realize intelligent collaborative networking; Explore lightweight composite materials and 3D printing technology to further reduce manufacturing costs. The research results provide a theoretical basis and technical paradigm for the integrated development of wave power generation and Marine search and rescue equipment, and have great significance for promoting the development of offshore resources and the construction of maritime safety guarantee system in China.

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