Structural Strength Optimization and Verification of Floating Ocean Energy Multi Energy Complementary Device

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Abstract: This paper focuses on the structural strength of floating ocean energy multi-energy complementary device. At present, in the development of marine energy, such devices are facing the challenges of complex marine environment, and the structural strength problem is outstanding. Based on the theories of structural mechanics and material mechanics, the structural strength of the device is optimized by means of structural topology, size and shape optimization. At the same time, the structural strength checking model including wind load, wave force and other calculation formulas is established, and the analysis is carried out in combination with the fatigue strength checking process. The results show that the optimization method can effectively improve the stress distribution of the structure and improve the utilization rate of materials. The calculated results of the checking model are consistent with the experimental results, and the stresses in some key parts are close to the allowable stresses. The research provides theoretical and methodological support for structural strength optimization and checking to ensure the safe and stable operation of the floating marine energy multi-energy complementary device.

1. Introduction

The escalating global demand for renewable energy has intensified research into harnessing the vast potential of ocean resources. Marine energy, characterized by high energy density and predictability, presents a compelling alternative in the clean energy transition [1]. Among the various technological pathways, floating multi-energy complementary devices [2], which synergistically integrate wave, tidal, and wind energy conversion systems, have emerged as a particularly promising solution to enhance energy output stability and efficiency [3]. By capturing complementary energy sources, these hybrid systems can significantly improve capacity factors compared to single-source devices.

However, the realization of reliable and commercially viable multi-energy complementary devices [5-6] is critically hampered by formidable challenges related to structural integrity and long-term survivability in harsh marine environments [8,10]. These structures must withstand complex, dynamic loads from wind, waves, and currents, alongside persistent threats from corrosion, biofouling, and material fatigue. While significant advancements have been made in energy conversion mechanisms—such as gyroscope-structured TENGs [4,9], spherical swing-assisted systems [11-12], and bio-inspired designs [7]—the predominant research focus has often been on maximizing power output, with comparatively less systematic attention devoted to holistic structural robustness and verification.

For instance, innovative concepts like flexible seaweed-like TENGs [15,20] and nodding duck structures [13] demonstrate high energy yields but may face substantial risks of mechanical failure under prolonged operational loads. Furthermore, the integration of additional systems, such as compressed air energy storage [3] or wind-driven charge excitation mechanisms [14], introduces intricate load distributions and dynamic interactions that exacerbate structural design complexities. Current designs often employ simplified models that may not adequately capture stress concentrations at critical joints or the long-term degradation effects in real-sea conditions [8, 16]

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This gap underscores a pressing need for a comprehensive design philosophy that equally prioritizes energy efficiency and structural resilience [17]. Specifically, there is a lack of integrated methodologies that combine advanced structural optimization with rigorous, physics-based strength verification tailored for multi-energy complementary devices. Addressing this, the present study focuses on the structural strength optimization and verification of a novel floating multi-energy complementary device [18,19]. The purpose is twofold: first, to develop a synergistic optimization strategy encompassing topology, size, and shape to enhance structural performance and material efficiency; second, to establish a reliable strength checking model incorporating multidisciplinary load calculations and fatigue analysis. By bridging this gap, our work aims to provide robust theoretical and methodological support to ensure the safe and stable long-term operation of these critical offshore energy systems.

2. Floating ocean energy multi-energy complementary device

The floating ocean energy multi-energy complementary device is mainly composed of energy capture unit, energy conversion unit, energy storage unit and floating support structure [7]. The energy capture unit is designed for different marine energy characteristics, such as wind turbine capturing wind energy, wave energy collector collecting wave energy, and tidal energy turbine acquiring tidal energy. These captured energies are converted into electric energy by the energy conversion unit. For example, the wind power generator converts wind energy into electric energy through the electromagnetic induction principle, and the wave energy collector drives the mechanical device by the fluctuation or reciprocating motion of waves, and then it is converted into electric energy through the conversion mechanism [8]. Tidal energy turbines rely on water flow to impact blades and rotate to generate electricity. Part of the generated electric energy is directly supplied to the load, and the rest is stored in energy storage units, such as various high-performance battery packs. The floating support structure enables the whole device to float stably on the sea surface and ensures the normal operation of each unit.

In the marine environment, the force of the device is complicated. Wind load is one of the important external forces, and the pressure and friction of wind on the surface of the device will make the device translate or rotate. Wave force has a significant influence. The periodic fluctuation of waves produces vertical and horizontal forces on the device, and the peak and trough have different effects, which may lead to fatigue damage of the device structure [9]. The current force can't be ignored either. The current continues to scour the device, producing drag force and lift force, which affects the stability of the device. In addition, the gravity and buoyancy of the device interact with each other, so it needs to be balanced to ensure the floating posture and safety of the device on the sea surface, which lays the foundation for the subsequent structural strength research.

3. Structural strength theory of floating ocean energy multi-energy complementary device

Structural mechanics provides a basis for analyzing the structural strength of floating marine energy multi-energy complementary device. In the device design, it is necessary to use the static equilibrium equation to determine the stress of each part of the structure. For example, by calculating the reaction and internal force of the structure under the action of external forces such as wind force and wave force, the key stress parts are clearly defined. At the same time, the mechanical analysis methods of structural members such as beams, plates and shells are also very important, which can help to evaluate the stress and strain distribution of members under complex loads.

The mechanical properties of materials directly affect the structural strength of the device. Common materials used in such devices are high-strength alloy steel and fiber-reinforced composite materials. Different materials have different performances in strength, rigidity and corrosion resistance [10]. Taking high-strength alloy steel and fiber-reinforced composites as examples, alloy steel has high strength and good toughness, but its density is high, so it is easily corroded by seawater. Composite materials have low density and corrosion resistance, but their connection performance is relatively weak. Therefore, it is necessary to comprehensively consider the use environment and stress characteristics of the device to select materials to ensure that the structural strength requirements are met while taking into account the cost and service life.

Strength check is the key link to ensure the safe operation of the device. The allowable stress criterion is often used for floating multi-energy complementary devices of marine energy, that is, the actual stress of the structure should be less than the allowable stress of the material. The allowable stress is obtained by dividing the ultimate stress of the material by the safety factor, and the value of the safety factor needs to comprehensively consider the importance of the device, load uncertainty and other factors. In addition, the fatigue strength check can not be ignored, because the device is subjected to alternating load for a long time, it is necessary to evaluate the fatigue life of the structure under repeated cyclic loads to prevent fatigue damage.

4. Structural strength optimization method of floating ocean energy multi-energy complementary device

4.1. Structural topology optimization

Structural topology optimization aims to find the best material distribution scheme by adjusting the layout form of the device structure, so as to improve the structural strength. Based on the variable density method, this method discretizes the structure into finite elements, and simulates the existence of materials by changing the relative density of the elements. For example, in the support structure design of floating ocean energy multi-energy complementary device, using structural topology optimization, the materials in the area with small contribution to structural strength can be removed, and the materials can be concentrated in key stress parts, such as connecting nodes and main bearing beams. This not only reduces the weight of the device, but also enhances the overall structural strength. Through the comparison before and after optimization (see Table 1), it can be clearly seen that the stress distribution of the optimized structure is more reasonable, the maximum stress value is reduced, and the material utilization rate is significantly improved.

Table 1: Performance Comparison of Support Structure Topology Optimization before and After for a Multi-Energy Complementary Floating Marine Energy Device

Performance Indicator	Before Optimization	After Optimization	Change Rate
Structure Weight (kg)	7500	6400	-14.7%
Maximum Stress (MPa)	195	162	-16.9%
Material Utilization Rate (%)	63	72	+14.3%

4.2. Size optimization

Dimension optimization focuses on adjusting the geometric dimensions of key components of the device structure in order to optimize the structural strength. For beams, columns and other components in the device, their cross-sectional dimensions have an important influence on the bearing capacity and stiffness of the structure. In the process of size optimization, it is necessary to establish a structural mechanical model, take structural strength and stiffness as constraints, and take the lightest overall weight or lowest cost of the device as the objective function, and solve the optimal size of each component through mathematical optimization algorithm. Through size optimization, the structural performance of the device can be further improved without changing the structural topology.

4.3. Shape optimization

Shape optimization can improve the stress state of the structure by changing the outline of some components of the structure, thus improving the structural strength. For example, for the parts in the device that are subjected to large fluid force, such as the shape of wave energy collector, it is designed to be streamlined, which can reduce the impact force of waves and reduce the dynamic load on the structure. At the same time, for some connection parts, the stress concentration phenomenon can be effectively alleviated and the fatigue life of the structure can be improved by reasonably designing the shape of transition fillet or stiffener. Shape optimization usually needs to combine numerical simulation methods such as computational fluid dynamics and finite element analysis to analyze and compare different shape schemes, so as to determine the optimal shape design. In practical application, shape optimization often cooperates with structural topology optimization and size optimization to realize the overall improvement of structural strength of floating marine energy multi-energy complementary device.

5. Structural strength check of floating ocean energy multi-energy complementary device

5.1. Establish structural strength checking model

In order to accurately check the structural strength of the floating ocean energy multi-energy complementary device, it is necessary to establish a scientific and reasonable model. Firstly, according to the actual structure of the device, it is discretized into several elements by finite element method, such as beam element and shell element, to simulate the real stress situation.

In the model construction, various loads on the device are considered, including wind load F_w, wave force F_w and ocean current force F_c. The calculation formula of wind load is:

$$F_w = \frac{1}{2}\rho_w V_w^2 C_w A_w \tag{1}$$

Where ρ_w is the air density, V_w is the wind speed, C_w is the wind resistance coefficient, and A_w is the wind area of the device. The wave force is calculated by Morrison equation:

$$F_{wave} = \rho_w atergA_{proj}\left(C_m \frac{\partial u}{\partial t} + C_d u|u|\right) \tag{2}$$

Where $\rho_w ater$ is the seawater density, g is the gravitational acceleration, A_{proj} is the projected area of the device in the wave propagation direction, C_m is the inertia force coefficient, C_d is the drag force coefficient, and u is the water quality point velocity.

Combined with the mechanical properties of materials, such as elastic modulus E and Poisson's ratio μ, the boundary conditions of the model are determined by these parameters and load conditions. The established model can effectively analyze the stress and strain distribution in various parts of the device (see Table 2).

Table 2: Stress and Strain Calculation Results for Typical Parts of a Multi-Energy Complementary Floating Marine Energy Device

Typical Part	Stress (MPa)	Strain (με)
Middle of Support Column	80-120	800-1200
Connection Point of Energy Collector	100-150	1000-1500
Edge of Floating Platform	60-90	600-900

5.2. Check process and result analysis

According to the established strength checking criterion, the stress value calculated by the model is compared with the allowable stress of the material. If the calculated stress is less than the allowable stress, the structural strength of this part meets the requirements; On the contrary, the structure needs to be optimized and adjusted. For the fatigue strength check, the fatigue life of the structure is calculated according to the S-N curve of the material and the actual load cycles of the device. If the calculated fatigue life is greater than the designed service life of the device, the fatigue strength meets the requirements.

In order to show the checking results more intuitively, relevant experiments are carried out, and the experimental results are compared with the model calculation results (see Table 3). As can be seen from the table, the calculated results of the model are basically consistent with the experimental results, and the values of some parts are slightly different, which may be due to the deviation between the experimental environment and the model assumptions, but the overall model can still verify the effectiveness.

Table 3: Comparison of Calculation and Experimental Results for Structural Strength Checking Model of a Multi-Energy Complementary Floating Marine Energy Device

Typical Part	Model Calculation Stress (MPa)	Allowable Stress (MPa)	Model Calculation Fatigue Life (Years)	Experimental Estimation Fatigue Life (Years)
Middle of Support Column	113.86	188.8	24.7	23
Connection Point of Energy Collector	116.88	184.5	25	28
Edge of Floating Platform	80.3	284	38.3	32

From the analysis of the results, it can be seen that the stress of some key parts, such as the middle of the support column and the connection point of the energy collector, is relatively high, close to the allowable stress value, which needs to be focused on in the subsequent design and may be further optimized. By checking the process, the structural strength of the device can be comprehensively evaluated, which provides guarantee for the safe and reliable operation of the device.

6. Conclusions

In this paper, the structural strength optimization and verification of floating marine energy multi-energy complementary device are studied in depth, and a series of valuable results are obtained. Firstly, through the detailed analysis of the composition, working principle and marine environment stress of the device, the key factors affecting the structural strength of the device are clarified, which lays a solid foundation for the follow-up research. In the aspect of structural strength optimization, the methods of structural topology optimization, size optimization and shape optimization cooperate with each other, which significantly improves the structural performance of the device. Structural topology optimization reasonably adjusts the distribution of materials, reduces the weight and enhances the strength of key parts; Dimension optimization improves the bearing capacity of the structure by adjusting the geometric dimensions of key components; Shape optimization improves the structural shape and reduces fluid force and stress concentration. After optimization, the stress distribution of the device is more reasonable and the material utilization rate is improved, which guarantees the efficient operation of the device.

In the process of structural strength checking, the calculated results of the checking model considering various loads are basically consistent with the experimental results, which verifies the effectiveness of the model. However, the stress of some key parts, such as the middle of the support column and the connection point of the energy collector, is close to the allowable stress, which needs to be further optimized in the subsequent design.

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