

Analysis on Structural Response of Sharp Eagle WEC Under Extreme Sea States

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Abstract. To ensure structural safety of the Sharp Eagle wave energy converter under extreme sea states with the floaters locked, a safety assessment method combining time-domain analysis and static equilibrium equations was proposed to obtain constraint forces and conduct structural response analysis. Taking the "Nankun" as the research object, time-domain analysis was performed to obtain acceleration curves, and static equilibrium equations were solved for the forces on the floaters. Global static analysis and refined analysis of key components were carried out. The simulation results show that the utilization coefficient of the Sharp Eagle is 0.68, corresponding to a safety margin of 32%, indicating that the structure has a sufficient strength reserve and meets the design safety requirements. The proposed method achieves accurate load transfer from hydrodynamic response to structural stress, providing a theoretical basis and technical support for the structural safety assessment of Sharp Eagle wave energy converters under extreme sea states.

Keywords: Sharp Eagle wave energy converter; extreme sea states; time-domain analysis; structural safety assessment.

1. Introduction

Driven by climate change and energy shortages, marine renewable energy is key to low-carbon transition. Wave energy offers high density and long operating hours. However, the harsh marine environment—alternating loads, corrosion and extreme sea states—poses challenges. The reliability of moving parts limits large-scale commercialization.

The Sharp Eagle WEC is an oscillating float type with a semi-submersible structure. Real-sea tests confirm its reliability and efficiency. Globally, similar technologies have advanced; domestically, GIEC has developed 10–100 kW prototypes. The Sharp Eagle structure is the core moving component, converting swing to rotation, buffering loads, and ensuring transmission. Its load capacity and fatigue resistance directly affect efficiency and maintenance costs, making it key for structural design.

On wave energy capture mechanisms and device design, researchers have combined numerical simulation, tank tests and real-sea validation to clarify how configuration, load damping, wave-facing mode and mooring affect capture efficiency. Domestically, Zhang et al. [1] established a multi-float coupled model showing that motion amplitude differences between the absorber and carrier are key to efficient capture. Sheng et al. [2] completed the 100 kW "Wanshan" device, marking China's leap from prototype to real-sea operation. Chen et al. [3,4] addressed rotational collision between the absorber and limit beam, identified limitations of rubber buffers, and proposed an accumulator-based impact absorption scheme for extreme-sea safety.

Internationally, no research exists specifically on the Sharp Eagle structure. Relevant studies focus on its prototype—oscillating float WECs. The Duck WEC established the hinged float principle. Point-absorber theory was developed by Norway's Norwegian Buoy and USA's OPT PowerBuoy [5,6]. The UK's Pelamis validated multi-body hinge feasibility [7], and the Oyster series verified oscillating-body-driven hydraulic PTO systems. For hydrodynamics, potential flow

theory and Morrison's equation clarified wave load calculations. For nonlinear hydrodynamics of multi-body hinged devices, methods like Lagrange multiplier, pseudospectral and moving frame have been developed [8–13]. Research has progressed from linear static analysis to fully coupled time-domain simulations [14]. In structural reliability, Ambühl et al. [15] identified wave-load-induced fatigue as the dominant failure mode and established S-N curve prediction methods, while Kolios et al. [16] developed a fatigue-limit-state reliability framework. Hydraulic PTO is recognized as the highest-failure-rate subsystem, with standardized methods based on the OREDA database. Research has shifted to integrated life-cycle optimization covering hydrodynamics, structures, economics and environment, with full-life-cycle assessments conducted for various floating WECs [17–20]. Nevertheless, no study addresses the ultimate strength, fatigue life or hydrodynamic-structural coupling of the Sharp Eagle structure—the core innovation of this study.

Although existing research has laid a solid foundation for Sharp Eagle development, significant technical gaps remain in full-process systematic verification of its eagle-beak structure under complex marine conditions, hindering multi-scenario and large-scale application. Three core bottlenecks exist. First, insufficient model accuracy under extreme seas: fixed material parameters fail to map typhoon conditions to constitutive behavior, causing deviations from actual responses. Second, unclear influence of design parameters: single-condition verification on specific prototypes does not systematically explore how eagle-head geometry and draft ballast affect load distribution and stress concentration, thus unable to support serial designs. Third, missing verification of dynamic characteristics and stiffness matching: most studies focus on static behavior, with insufficient verification of natural frequency and resonance risk under alternating loads, and no matching criteria between stiffness and natural frequency have been established.

This paper systematically verifies the structural safety of the "Nankun" Sharp Eagle WEC under extreme sea conditions. Using measured sea state data, the full-condition load spectrum is constructed and impact loads clarified. A refined FE model verifies structural strength and locates stress concentration weak areas, followed by dynamic response verification. This full-process method supports structural design, reliability improvement, and commercialization of wave energy equipment.

2. Mathematical Model

2.1 Hydrodynamic Calculation

For the "Nankun" Sharp Eagle Wave Energy Converter, the platform model and coordinate system are shown in Fig.1(a). Assuming the fluid is ideal, the linear potential flow theory is applied, and the constitutive equation of the velocity potential is expanded as follows.

The total velocity potential can be decomposed as:

$$\phi(x, y, z, t) = \phi_r + \phi_I + \phi_d \quad (1)$$

where ϕ_r is the radiation potential; ϕ_I is the incident potential; ϕ_d is the diffraction potential.

The incident potential is:

$$\phi_I(x, y, z) = -\frac{igA_m}{\omega} \frac{\cosh[k(z+h)]}{\cosh(kh)} e^{ik(x \cos \beta + y \sin \beta)} \quad (2)$$

where: A_m is the wave amplitude; ω is the wave circular frequency; k is the wave number; h is the water depth; β is the angle between the wave propagation direction and the x-axis.

For the radiation potential and diffraction potential, the boundary conditions are as follows:

Body surface condition:

$$\left\{ \begin{array}{l} \frac{\partial \phi_r}{\partial n} = V_n \quad (\text{radiation potential}), \quad \frac{\partial \phi_d}{\partial n} = -\frac{\partial \phi_l}{\partial n} \quad (\text{diffraction potential}) \quad (\text{body surface}) \\ \frac{\partial \phi}{\partial z} - \frac{\omega^2}{g} \phi = 0 \quad (z = 0) \quad (\text{free surface}) \\ \frac{\partial \phi}{\partial z} = 0 \quad (z = -h) \quad (\text{seabed}) \\ \lim_{r \rightarrow \infty} \sqrt{r} \left(\frac{\partial \phi}{\partial r} - ik\phi \right) = 0 \quad (\text{far field}) \end{array} \right. \quad (3)$$

The velocity potential can be solved by the Boundary Element Method (BEM). The wave excitation force can be obtained from the incident velocity potential and diffraction velocity potential, and the added mass and added damping can be obtained from the radiation velocity potential.

$$\left\{ \begin{array}{l} F_{wj} = \iint_S j \rho \omega (\phi_l + \phi_d) n_j ds \quad (\text{Wave excitation force}) \\ m_j = \iint_S \rho \operatorname{Re}(\phi_r) n_j ds \quad (\text{Added mass}) \\ c_j = \iint_S \rho \omega \operatorname{Im}(\phi_r) n_j ds \quad (\text{Added damping}) \end{array} \right. \quad (4)$$

2.2 Structural Response Calculation

As shown in Fig. 1(b), under extreme sea conditions the platform enters the self-protection state, where the Sharp Eagle is locked onto the semi-submersible platform by hydraulic cylinder and mechanical limit, and the entire system is treated as a single floating body. Given nonlinear factors in actual sea conditions (eg. viscous damping, mooring restoring force, wind or current nonlinearities), frequency-domain analysis is inadequate. Therefore, the indirect time-domain method proposed by Cummins is adopted to establish the motion equation of the floating body. According to Newton's second law:

$$[M + \Delta M] \cdot \ddot{x}(t) + \int_0^t K(t - \tau) \dot{x}(\tau) d\tau + Cx(t) = F_{ex,j}(t) + F_{wind,j}(t) + F_{current,j}(t) + F_{T,j}(t) \quad (5)$$

where $j=1,2,\dots,6$ represents the six spatial degrees of freedom of the floating body; M is the mass matrix of the floating body; ΔM is the infinite frequency added mass matrix; $\ddot{x}(t)$ is the acceleration vector of the floating body; where $F_{ex,j}(t)$ is the wave excitation force; $K(t-\tau)$ is the hydrodynamic delay function matrix; C is the hydrostatic restoring force matrix;

$F_{wind,j}(t) = \frac{1}{2} \rho_a C_h C_s V_w^2(t) A_w \cdot n_j$; $F_{current,j}(t) = \frac{1}{2} \rho_w C_D V_c^2(t) A_c \cdot n_j$; where ρ_a and ρ_w are the air and seawater densities respectively; C_h , C_s are the height and shape coefficient of the above-water structure; C_D are the drag coefficient of the underwater structure; $v_w(t)$ and $v_c(t)$ are the relative velocities of wind and current speed with respect to the structural motion respectively; A_w and A_c are the windward projected areas of the above-water and underwater structures respectively; n_j is the directional derivative in the j direction.

$F_{T,j}(t)$ is the mooring force, calculated using the lumped mass method: the mooring line is divided into n segments with lumped mass nodes, and the force balance at node i gives $M_i a_i = F_{Ti} - F_{Ti-1} + F_{Di} + F_{Ai} - G_i$, where $F_{Ai} = \rho_w C_M V (-a_i)$ with F_{Ai} and F_{Di} are the fluid inertial force and drag force at node i ; C_M is the added mass coefficient; V is the displaced volume.

Under extreme sea conditions, the Sharp Eagle is rigidly locked to the platform and moves synchronously. Its dynamic behavior is dominated by platform acceleration, with the resultant external force equal to mass times acceleration. The constraint forces from the hinge, self-locking device, support and hydraulic cylinder balance this inertial effect. The force analysis and static equilibrium equations are shown in Fig. 1(b). Force balance equation:

$$F_{Aj} + F_{Bj} + F_{Cj} + F_{Dj} + F_{Ej} + G_j = m \ddot{x}_j(t) \quad (6)$$

where F_{Aj} and F_{Bj} are the constraint forces at point A and point B respectively; F_{Ej} is the force applied by the hydraulic cylinder; F_{Cj} and F_{Dj} are the support forces at points C and D respectively; G_j is the gravity of the Sharp Eagle floater; α is the angle between the hydraulic cylinder and the

horizontal plane; θ is the angle between the Sharp Eagle floater and the x-axis of the platform coordinate system. Moment balance equation:

$$r_i \times (F_{A,j} + F_{B,j} + F_{C,j} + F_{D,j} + F_{E,j}) = 0 \quad (7)$$

where $r_i = [x_i, y_i, z_i]^T$ ($i=A, B, C, D, E$) is the spatial coordinate value of each force point relative to the center of mass of the Sharp Eagle.

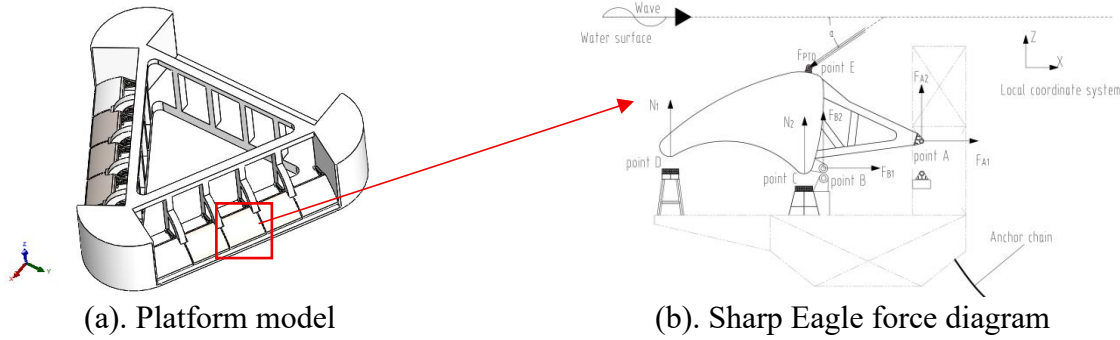


Fig. 1 Force analysis diagram of Sharp Eagle wave energy converter

The hinge, self-locking and support forces are solved from the force and moment balance equations, establishing a complete load transmission path from hydrodynamic response to structural load for subsequent strength verification.

3. Simulation Analysis

3.1 Device introduction

The "Nankun" platform, the world's first megawatt-class floating wave energy device, adopts a column-stabilized steel main hull with equilateral triangle layout (side length 80 m, height 27 m, displacement 15,000 t), providing good stability and anti-wave capability in water depths of 30–100 m. The platform consists of fan-shaped columns, buoys, Sharp Eagle floats and guide columns. The three column bases are connected by buoys, and the top is connected by a truss structure serving as the upper deck. Five Sharp Eagle floats are hinged on each side of the platform facing the wave direction to absorb wave energy, with photovoltaic panels on the truss top as supplementary power. The main parameters of the platform are shown in Table 1.

Table 1. Main parameters of the "Nankun" platform

Parameter	Value	Parameter	Value
Total length/m	80.0	Height (Main Deck)/m	4.0
Total width/m	88.0	Height (top deck)/m	27.0
Operating draft/m	13.5	Survival draft/m	16.5
Mass/t	6000	Displacement/t	15000

3.2 Hydrodynamic Analysis

Based on potential flow theory, ANSYS AQWA is used for frequency-domain hydrodynamic analysis. Considering platform symmetry, 6 wave directions from 0° to 180° are uniformly selected, with wave periods of 2–32 s. Under extreme sea conditions, the Sharp Eagle is locked on the platform, so relative motion is ignored. To highlight the key control conditions and focus on the typical scenario of the eagle-head structure loading, two typical conditions are selected for analysis: the wave incident direction directly facing the Sharp Eagle (120°) and directly facing the column (180°). Other directions are omitted. The corresponding RAOs are shown in Fig. 2.

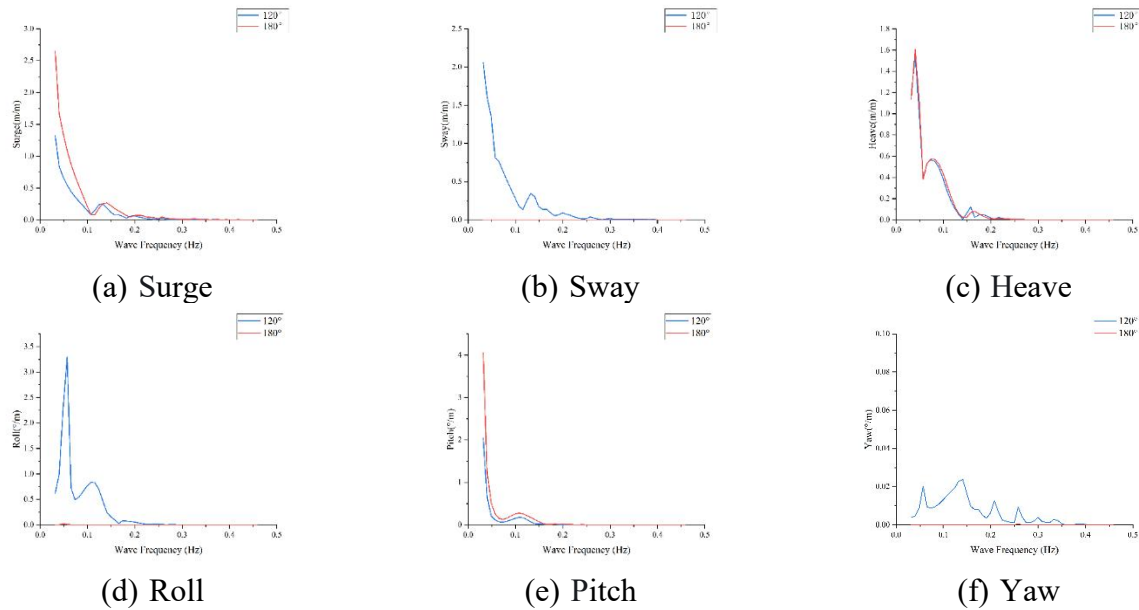


Fig. 2 RAOs of the platform motion response

For surge and pitch, the 180° direction yields significantly higher RAO amplitudes than the 120° direction, indicating that wave incidence on the column promotes longitudinal translation and pitch rotation. For sway, roll and yaw, the opposite holds: the 120° direction gives larger RAO peaks, meaning wave incidence on the Sharp Eagle induces stronger lateral translation and coupled roll-yaw rotations. Heave responses are nearly identical and insensitive to both directions.

For both directions, the six-DOF RAO peaks are concentrated at 0.032–0.10 Hz with rapid decay above 0.10 Hz, indicating low-frequency dominated motion. The 120° direction, with higher lateral (sway) and rotational (roll, yaw) RAO amplitudes, yields larger translational and angular accelerations overall, while the 180° direction only excels in surge and pitch (longitudinal motion). Consequently, the 120° direction induces stronger coupled motion and greater inertial loads on the Sharp Eagle, whereas the 180° direction has a weaker inertial effect.

3.3 Time-Domain Analysis

Based on the extreme waves and their corresponding wind and current conditions, the 50-year return period combined environmental sea conditions in the South China Sea are selected. The water depth is 40 m, and the wind speed refers to the 1-minute average wind speed at a height of 10 m above sea level. The specific environmental parameters are shown in Table 2. The JONSWAP spectrum is adopted for the wave spectrum.

Table 2. Environmental parameters

Environment	Parameters	Value
Wave	Significant wave height /m	7.59
	Peak spectral period /s	11.39
	Peak enhancement factor	1.0-3.3
Current	Surface current velocity /(m/s)	1.20
	Mid-layer current velocity /(m/s)	1.14
	Bottom current velocity /(m/s)	0.68
Wind	1min wind speed /(m/s)	58.08

Based on the above analysis, only the 120° co-directional combination of wind, wave and current is considered in the time-domain analysis (simulation duration 3600 s). The resulting platform accelerations are shown in Fig. 3. The surge, sway and heave accelerations range from −0.608 to 0.604 m/s², −0.925 to 0.895 m/s², and −0.760 to 1.001 m/s², respectively, with sway exhibiting

slightly larger amplitude than surge. These accelerations are then used to solve the constraint forces at the force-bearing points of the Sharp Eagle floater for subsequent structural response analysis.

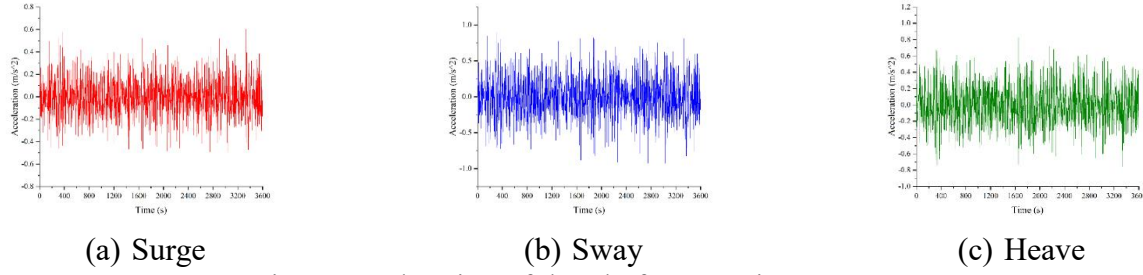


Fig. 3 Acceleration of the platform motion response

4. Structural Response

From time-domain analysis, the acceleration at the center of mass of the Sharp Eagle floater is obtained. Together with the position vectors of each force point relative to the center of mass, the time-history curves of constraint forces are calculated. The maximum value at each force point is selected as load input for static strength assessment using ANSYS. The overall stress distribution of the Sharp Eagle floater exhibits significant local concentration. The maximum von-Mises stress is approximately 217.54 MPa, occurring at the connection between the locking shaft and the main structure. The locking shaft is the core load-bearing component under extreme sea states, transferring gravity, inertial and PTO forces to the supporting structure. Stresses in the truss and non-load-bearing hinge areas are very low. The global analysis identifies the locking shaft and hinges as high-stress regions. Local stress analysis is then performed on these weak links using the maximum constraint force as input, with results shown in Fig. 4.

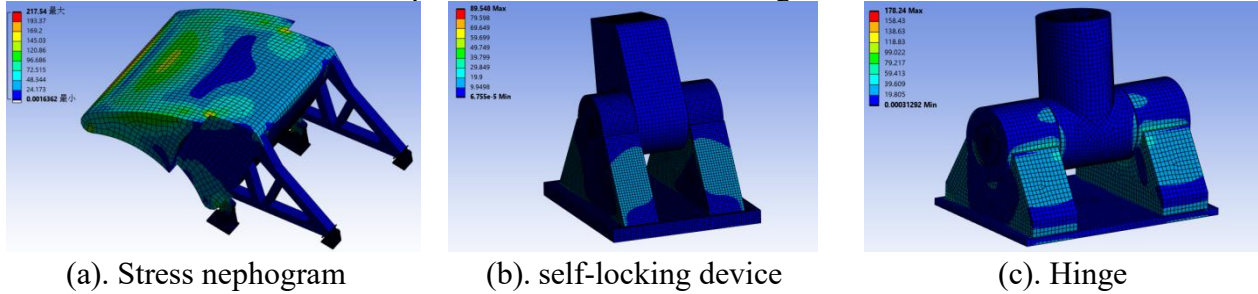


Fig. 4 Stress of Sharp Eagle WEC and key parts

The allowable stress $[\sigma]$ for the main structural components is determined according to the yield failure criterion as: $[\sigma] = \sigma_s / S$, where σ_s is the material yield strength, 355 MPa (AH36); S is the safety factor, 1.11 (combined working condition). To quantitatively evaluate the strength utilization of the eagle-head structure and other key load-bearing components, the utilization coefficient (UC) is introduced as a core assessment indicator. The UC is defined as the ratio of the maximum Von Mises stress obtained from finite element analysis to the allowable stress of the material: $UC =$

$$S \cdot \sigma_{vm} / \sigma_s.$$

where σ_{vm} is the max Von Mises stress (MPa). According to the strength acceptance criterion, $UC \leq 1.0$ indicates safety, otherwise failure risk. The safety margin $= (1 - UC) \times 100\%$. The UC values of the Sharp Eagle and key components section are calculated using the maximum Von Mises stresses obtained from finite element analysis under load cases. The maximum UC value obtained from the calculations is 0.68, corresponding to a safety margin of 32%. The maximum stress of the Sharp Eagle structure is far lower than the allowable stress of marine engineering structural steel, and the overall strength reserve is sufficient, meeting the structural safety requirements under extreme sea conditions.

Summary

This paper systematically evaluates the structural safety of the "Nankun" Sharp Eagle WEC under extreme sea states with the eagle-beak locked. The main conclusions are:

(1) Among all wave directions, the 120° incident direction (directly facing the Sharp Eagle) induces the most severe platform motion, particularly in sway, roll, and yaw. The corresponding time-domain accelerations are significantly higher than those under other wave directions, making it the most unfavorable loading condition for the eagle-beak structure.

(2) Under the extreme 120° wave condition, the maximum von Mises stress is 217.54 MPa at the locking shaft connection, with a utilization coefficient of 0.68 and a safety margin of 32%. This confirms sufficient strength reserve and design safety compliance. The proposed analysis framework provides an effective engineering tool for safety assessment, supporting the reliability design and commercialization of floating wave energy devices under harsh marine conditions.

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