Verification of Hydrodynamic Characteristics of New Combined Structural Cage

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Abstract: *Due to the reliance of semi-submersible aquaculture cages on marine environments and issues such as excessive material usage and the single-purpose nature of closed cages, an innovative modular cage structure has been designed to address these weaknesses while playing to their strengths. This design results in a smaller spatial footprint within the marine area, allows for zone-specific cultivation, achieves 'multi-use from a single cage,' and enhances breeding efficiency and quality. The analysis of movement trends across three different operational conditions in the frequency domain shows that the cages are sensitive to high-frequency waves, but less likely to experience large motion amplitudes in this range. In simulated sea states, time domain analysis indicates that the cages maintain a dynamic equilibrium in new positions after repeated oscillations, meeting the stability design requirements for deep-sea aquaculture cages.*

Keywords: *cages; hydrodynamics; waves; aquaculture*

1. Introduction

Traditional net fishing has led to the gradual exhaustion of fishery resources, and the limited near-shore resources are severely polluted, which has caused cage aquaculture to gradually move from the nearshore to the deep and distant sea. Deepsea cage systems mainly include floating mobile steel frame cages [1-2], semi-submersible truss cages, and bottom-sitting pillar-frame structure cages, such as Havfarm 1, Dehai No.1, Ocean Farm 1[3-5], etc. all of which are open water aquaculture facilities. However, enclosed cages have problems such as high construction costs, massive use of materials, and singular use. If we combine open cages with enclosed cages and develop new types of structures like semi-open and semi-closed combined cages, we can integrate their advantages, achieve "multiple uses for one cage", and improve aquaculture efficiency and quality.

This paper designs a semi-open and semi-enclosed combined structural cage. The open aquaculture area is constructed using a steel truss structure, while the closed aquaculture area is built with a composite material plate structure. It utilizes a four-point mooring system and is equipped with a floating box at the bottom, providing lift capability. For this new combined cage, simulation analysis is conducted on the forces, motion characteristics, and stability under the combined effects of wind, waves, and currents. The results offer certain reference value for the design and analysis of new, large-scale, deep-sea cages.

2. Combined Cage Model

Compared to flat semi-submersible cages, the new combined structural cage occupies a smaller sea area, allows for higher aquaculture depth, and can cultivate a variety of species in separate zones. The cage is divided into closed and open areas for aquaculture, with the detailed structure shown in Figure 1. By adjusting the water load of the floating box, the draft depth of the cage is controlled. Three working conditions are designed: in the no-load condition, the cage is completely above the water surface for maintenance activities such as changing the netting and accessories; during normal aquaculture operations, the open area is submerged below the water level; and in the self-storage condition, the entire closed aquaculture area is submerged to effectively withstand extreme sea conditions.

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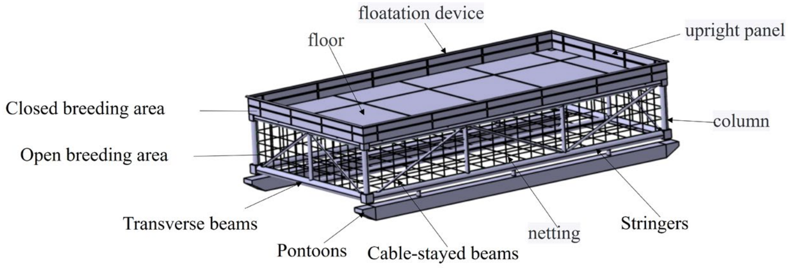


Figure 1: Model of the main frame of a new type of composite net cage

The new combined structural cage is designed based on deep-sea cage design criteria, featuring a square structural body. The total length of the cage is 83 meters, the total width is 43 meters, and the weight of the framework is approximately 1431 tons. It encloses an effective aquaculture volume of 38,500m^3, with a maximum design draught of 23 meters. It is designed for a service life of 20 years. Detailed design parameters are provided in Table 1.

Table 1: Cage frame and breeding parameters

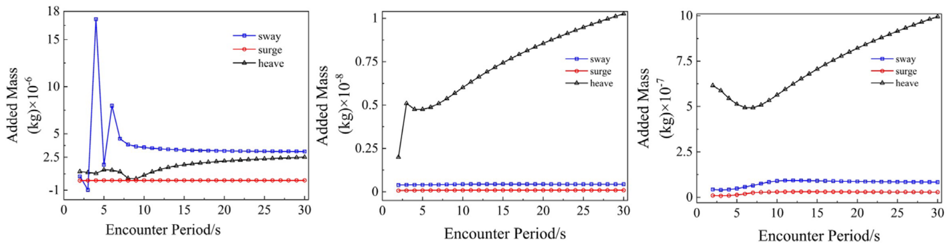
Structural Parameters	value	Performance Parameters	value
total length/m	83	aquaculture water bodies/m^3	38540.5
overall width/m	43	closed area volume/m^3	7138
type depth/m	21.37	open area water body/m^3	31402.5
weight of the cage main frame/t	1,431	main body displacement of the cage/m^3	2977.42
column radius/m	0.7	floating box displacement/m^3	1515
bottom column radius/m	0.9	no-load draft/m	2.71
upper column radius/m	0.6	draft of breeding conditions/m	19.5
reinforced column radius/m	0.5	draft under full load condition/m	23
cylinder thickness/mm	15		
closure plate thickness/mm	30		

3. Hydrodynamic simulation analysis

3.1 Frequency domain analysis

3.1.1 Additional Mass and Radiation Damping

Wave loads act on the surface of the cage, causing dynamic pressure[6], leading to forced harmonic motion, which gives the cage a certain acceleration. The force pushing the cage not only works to increase the kinetic energy of the cage itself but also increases the kinetic energy of the surrounding fluid. Therefore, the acceleration obtained by the cage is greater than the acceleration produced by the cage's own mass. The added mass that accounts for this increase is known as the added mass, which characterizes the inertia force of the cage, with the force being directly proportional to the acceleration of the cage. In the frequency domain analysis, the added mass under three working conditions of the simulation cage is compared, and Figure 2 records the changes in added mass under a wave period of 2-30 seconds for the cage.



(a) Unladen added mass *(b) Cultivation added mass* *(c) Full-load added mass*

Figure 2: Translational added mass at different immersion depths of the net cage

The added mass in the heave direction is minimal under three conditions and can be neglected due to the wave disturbance within the analyzed period. For the empty net cage swaying laterally, the added mass fluctuates dramatically within 3-6 seconds, reaching a peak of 17,162,840 kg at the 4th second. The

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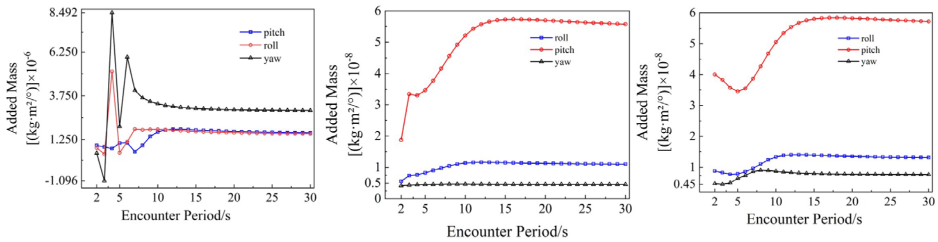
fluctuation diminishes after 7 seconds, and the structure's response to wave impact becomes steady. Although the volume of the surrounding water that the net cage can move laterally significantly decreases with increasing immersion depth, leading to the added mass for the cultivation and full-load conditions approaching zero. In contrast, for the empty-load condition, the added mass in the sway direction progressively increases under high-frequency wave cycles and levels with the lateral added mass. For the cultivation and full-load conditions which have greater immersion depths, the added mass in heave increases with the wave cycle period.

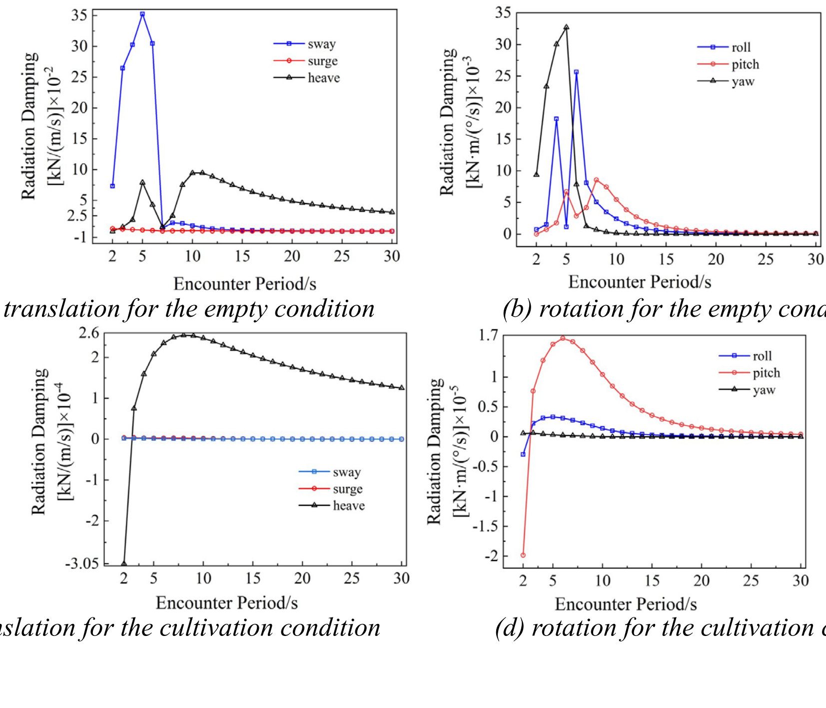


(a) Unladen added mass *(b) Cultivation added mass* *(c) Full-load added mass*

Figure 3: Rotational added mass at different immersion depths of the net cage

From Figure 3, it can be seen that the rotational added mass of the net cage varies more dramatically under wave disturbance, with the added mass in the rotational direction being much greater than that in the translational direction. For the cultivation and full-load conditions with greater immersion depth, the magnitude of rotation is relatively smaller. The added mass in pitch for the empty condition drops to its lowest at the 7th second, 5,625,551.39 kg·m²/°, then gradually rises and tends toward stability. Owing to the rectangular structure design, the added masses in pitch and roll directions are relatively stable with the added mass in roll for the empty condition peaking at the 4th second before quickly decreasing to level with the pitch added mass. In contrast, the added mass in pitch at the bow for the empty condition fluctuates continuously at the 3-6s, indicating a more noticeable hydrodynamic interaction effect in this direction. For the cultivation and full-load conditions, the bow pitch added mass decreases to its lowest at the 5th second and then increases with the wave period, reaching a maximum at the 16th second.

When the net cage moves in seawater, it inevitably causes the surrounding water to move, and the waves generated will carry away energy, which is the work performed by the motion of the net cage. This energy manifests as a resistance faced by the net cage, known as radiation damping. The resistance is directly proportional to the velocity[7]. Figure 4 illustrates the variation in radiation damping for six degrees of freedom at different immersion depths of the net cage.



(a) translation for the empty condition *(b) rotation for the empty condition*

(c) translation for the cultivation condition *(d) rotation for the cultivation condition*

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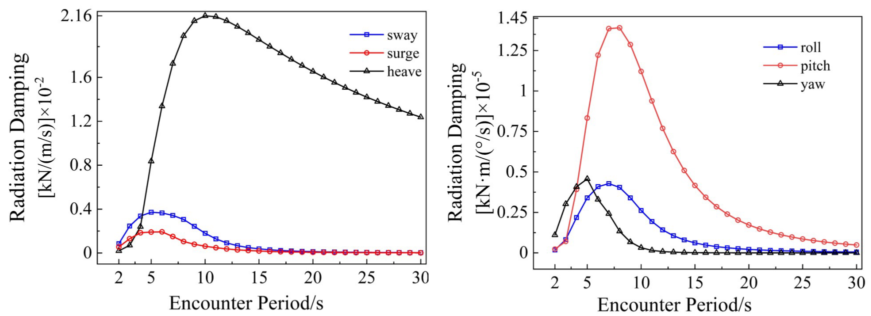


(e) translation for the full-load condition *(f) rotation for the full-load condition*

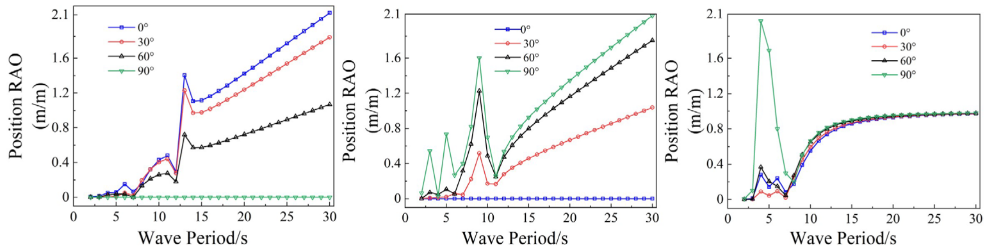
Figure 4: Radiation damping for six degrees of freedom at different immersion depths

The oscillation period is consistent with the added mass. The radiation damping in the sway direction for the empty condition undergoes a sudden change at the 5th second, reaching a maximum value of 3526.25 kN/(m/s). As the immersion depth increases, the radiation damping in the heave direction gradually increases, while the values in the sway and surge directions remain small. For the rotational damping, under aquaculture and full-load conditions, the values are larger in the roll direction, reducing the likelihood of excessive rotation. For the empty condition, there are several peaks between 2-6s, with the maximum radiation damping in the pitch direction being 32704.66 kN·m/(°/s) at the 5th second. In the roll direction for the empty condition, there are continuous sudden changes from 3s to 6s, with significant fluctuation amplitudes. Although the radiation damping in the longitudinal rolling direction for the empty condition undergoes three sudden changes, the numerical changes are relatively minor, and overall, it tends to stabilize over time.

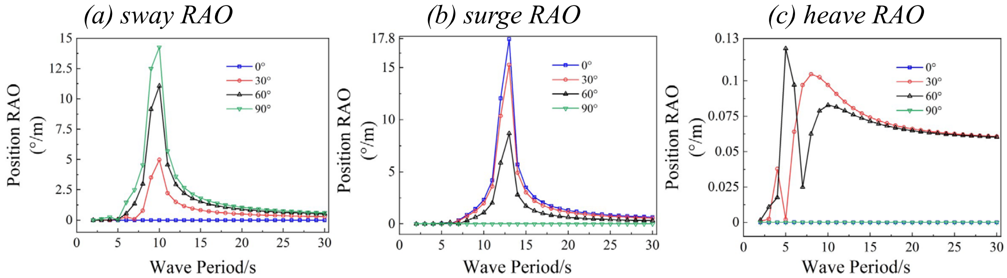
In a realistic marine environment, the distribution of wave periods is complex. An increase in added mass and radiation damping will lower the natural frequency of the platform. When the wave period ranges between 1-30 seconds, the energy possessed by the waves constitutes more than half of the total energy of the ocean waves. Approximately 10 seconds is the peak of energy. For empty conditions, it is advisable to avoid the wave peaks as much as possible to minimize impacts on the platform.

3.1.2 Response Amplitude Operator

The Response Amplitude Operator (RAO)[8] represents the motion amplitude of a floating structure under the action of unit wave force. When the cage is subjected to wave action, vibrations occur. Resonance response occurs when the frequency of the incident waves is close to the natural frequency of the cage, reflecting the ability of the floating structure to resist wave loads. As illustrated in Figure 5, for the empty condition, the combined structural cage RAO for 0-90° varies with the wave period.



(a) sway RAO *(b) surge RAO* *(c) heave RAO*



(d) roll RAO *(e) pitch RAO* *(f) yaw RAO*

Figure 5: RAO of Four Wave Incidence Angles under Empty Load Condition

Under the empty load condition, the translational RAO of the cage at various wave incidence angles increases gradually with the wave period. The swaying motion amplitude at 90° is the largest, whereas the heaving motion amplitude is completely opposite, with the maximum amplitude occurring at 0°. The

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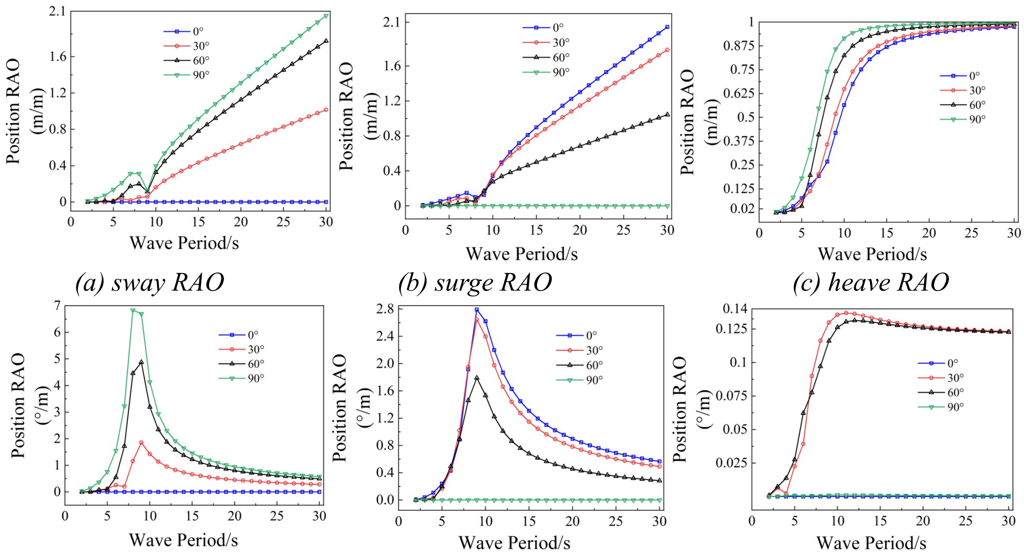
heaving motion amplitude experiences a sudden change at the 4th second, showing a single peak characteristic of 2.02m/m, and tends to stabilize after approaching 0.98m. When the wave period is between 5 to 15 seconds, the cage shakes violently, causing a sharp change in the amplitude of motion in the rotational direction. The roll angle at a 90° wave incidence is 14.27°, and the pitch angle at a 0° wave incidence is 17.74°. Under this condition, the restoring moment of the square cage is small, and it is advisable to avoid carrying out cleaning operations in the wave period range of 5 to 15 seconds.

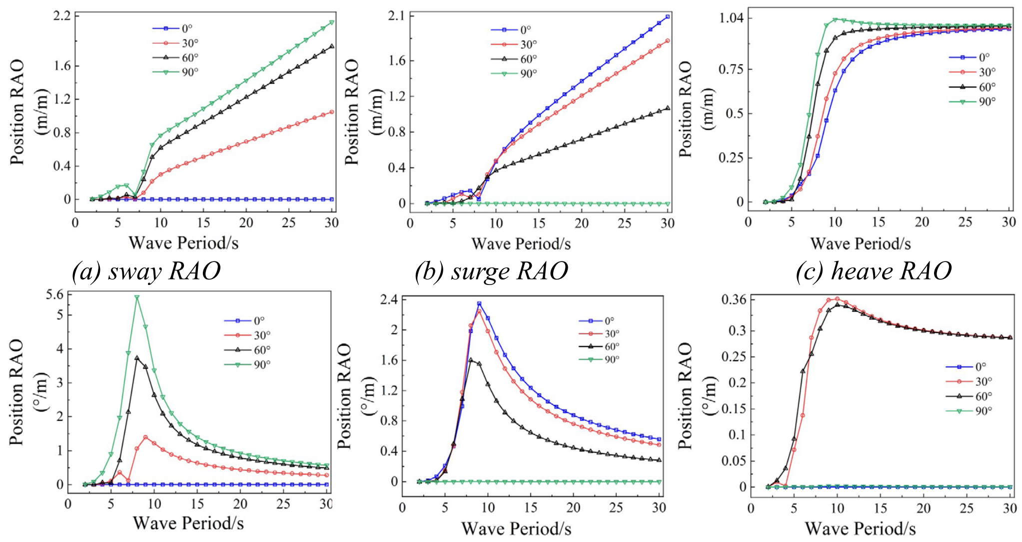


(a) sway RAO *(b) surge RAO* *(c) heave RAO*

(d) roll RAO *(e) pitch RAO* *(f) yaw RAO*

Figure 6: RAO of Four Wave Incidence Angles under Cultivation Condition

Figure 6 shows the changes in RAO from 0-90° of the combined structured cage under cultivation condition with varying wave periods. In this condition, the center of buoyancy of the cage is raised, and the amplitude of translational motion is basically consistent with that under empty load conditions. With a wave period of 5 to 15 seconds, the abrupt change in the motion amplitude of the cage is much smaller than that of the empty load condition, and there's no sudden peak change in the heaving motion amplitude. The abrupt peaks in the rotational motion amplitude are concentrated between 8-10 seconds, with the roll angle at a 90° wave incidence being 6.84°, and the pitch angle at a 0° wave incidence being 2.79°, which are significantly smaller than those under empty load conditions.



(a) sway RAO *(b) surge RAO* *(c) heave RAO*

(d) roll RAO *(e) pitch RAO* *(f) yaw RAO*

Figure 7: RAO of Four Wave Incidence Angles under Full Load Condition

Figure 7 illustrates the changes in RAO from 0-90° of the combined structural cage under full load conditions with varying wave periods. The trend of the surging motion is essentially consistent across all three operational conditions, gradually approaching zero as the angle decreases, with the 0° wave incidence angle consistent with the surge direction. The RAO in the pitch direction remains relatively

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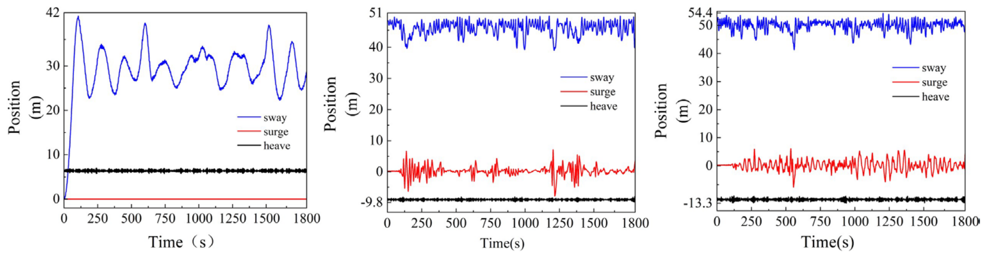
stable under wave incidence angles from 0° to 90°, generating small amplitudes of motion that can be neglected. After reaching a maximum roll motion amplitude at 8 seconds, it gradually decreases with the wave period, with the lowest motion amplitude occurring in low-frequency waves. The cage is more sensitive to high-frequency waves and less likely to produce significant motion in the low-frequency range. Under full load conditions, the amplitude of variation in each degree of freedom of the cage is small, indicating a strong ability to withstand extreme sea conditions.

3.2 Time-domain analysis

3.2.1 Structural Movement under Different Operational Conditions

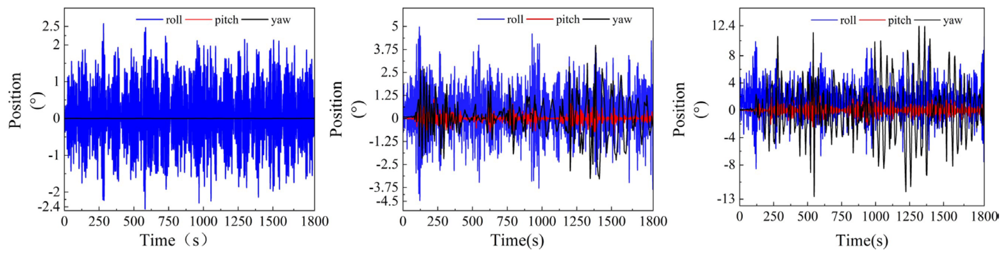
During frequency domain analysis, the cage exhibits the greatest movement amplitude at a 90° wave incidence angle. Time domain analysis is further utilized to investigate the cage's extreme positions. Wind, wave, and current loads are applied in the 90° direction, and when the cage tilts under the combined effects of these forces, it is dragged by the anchor chains and maintains dynamic stability at the new position. Once external forces cease, the cage can return to its original equilibrium position on its own. Time domain simulation is used to perform coupled calculations on the cage. Under typical sea conditions, the period generally lasts about 3 hours[9], but the simulation sea condition cycle is shortened to 1800 seconds with a step size of 0.2 seconds, and a total of 9001 analysis steps. Figure 8 shows the structural displacement at different draught depths.



(a) Unladen *(b) Cultivation* *(c) Full-load*

Figure 8: Structural Displacement of the Cage at Different Draught Depths

After applying environmental loads, the movement amplitude of the cage is significantly greater than the hydrostatic results under frequency domain analysis. At 105.8 seconds, the cage without load swung laterally a maximum displacement of 41.23 meters. Subsequently, the cage moved in the opposite direction under the dragging force of the anchor chains, causing the cage to reciprocate within a range of 18.63 meters. Under unloaded conditions, since the cage's draught is shallow, the superstructure accounts for 87.32%, which is significantly affected by wind load; however, the overall force experienced is relatively small, and excessive displacement of the cage can be controlled by tightening the anchor chains. As the draught of the cage deepens, the inertial movement of the cage increases, and the lateral swing distance becomes larger—with a maximum value of 54.39 meters under full load, a difference of 13.16 meters compared to the unloaded condition. The surge and heave displacements maintain dynamic equilibrium at the new position, with unloaded conditions showing an upward trend and full load and farming conditions showing a downward trend. The movement amplitudes are small and their impacts can be disregarded.



(a) Unladen *(b) Cultivation* *(c) Full-load*

Figure 9: Structural Rotation Angles of the Cage at Different Draught Depths

From Figure 9, we can observe the variations in structural rotation at different draught depths. Due to the gradual movement of the cage towards a new position under the effect of environmental loads, resulting in a stabilization, the time domain analysis indicates a smaller rotational amplitude of the cage compared with the conditions under frequency domain analysis. The cage can maintain stability even

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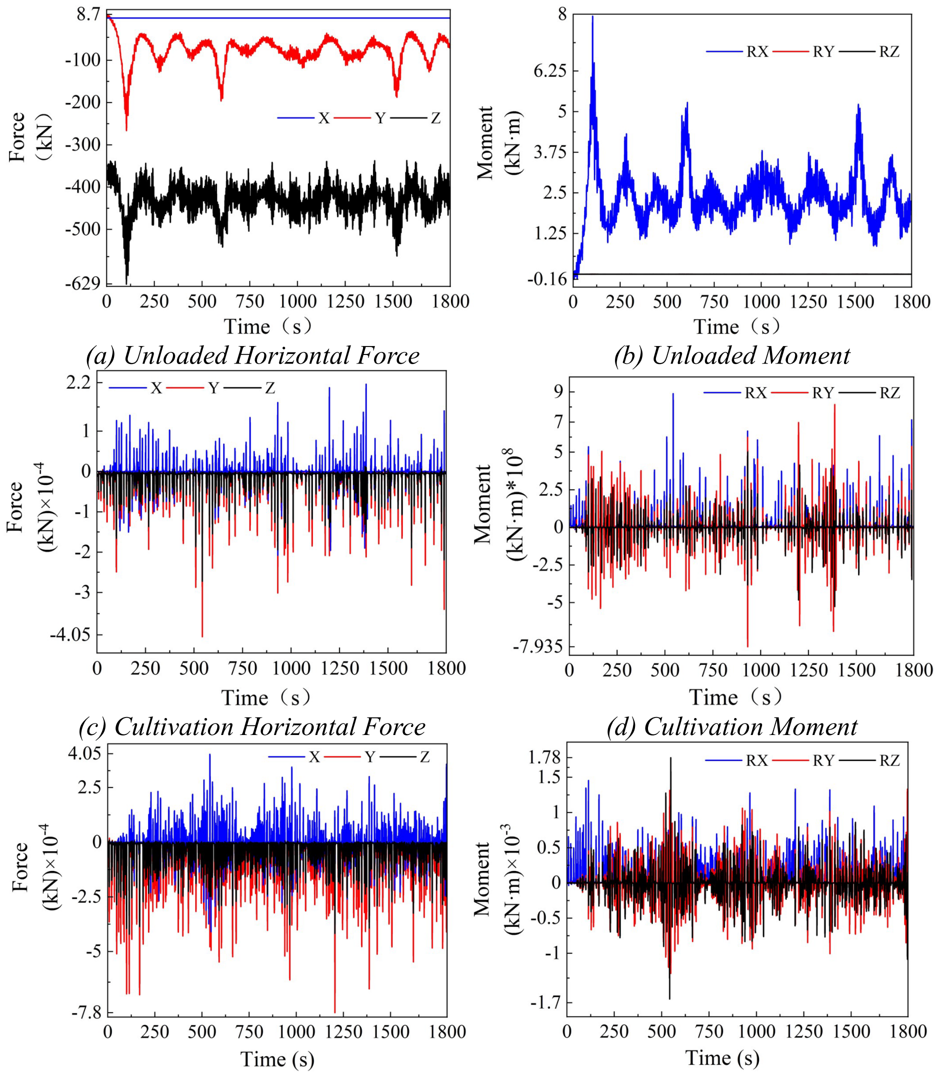
when the restoring moment is small. For the unloaded and farming conditions, the roll is significantly greater than pitch and yaw. Under unloaded conditions, the maximum roll angle is 2.58°, and for farming conditions, it is 4.97°; these belong to small-angle rotations and are relatively stable in terms of displacement. However, under full load conditions, due to the severe environmental loads, a sudden change occurs in the bow's yaw angle, with a maximum angle of 12.31°. At this point, the drainage outlets of the enclosed farming area are opened to connect with seawater, and the anchor chains are tightened to reduce the bow's yaw of the cage.

3.2.2 Structural Forces under Different Operating Conditions

Several factors can affect the magnitude of the structural forces when cages move in the water, causing forces to be exerted on the surfaces of the structure. The figure 10 below illustrates the forces acting on the structure at different draught depths.



(a) Unloaded Horizontal Force *(b) Unloaded Moment*

(c) Cultivation Horizontal Force *(d) Cultivation Moment*

(e) Full-load Horizontal Force *(f) Full-load Moment*

Figure 10: Time Domain Analysis of Structural Forces at Different Draught Depths

The main directions of force on the aquaculture cage are along the X-axis and about the RX axis. As the cage undergoes sway motions, tch does not deform the cage structure. The combined loads of wind, current, and waves generate signifhe drag force it experiences gradually increases. Under fully loaded conditions, the force peaks at 40,270.46 kN at 541.8 seconds. After reaching this peak, the cage initiates a turning motion which momentarily reduces the structural forces[10]. The secondary peaks in force correlate with the movement trend of the cage. In the Y direction, the cage withstands a maximum force of 77,931.26 kN at 1204.80 seconds, whiicant moments, with the pitch moment of force reaching a maximum of 1,780,499.46 kN·m at 547.8 seconds. The maximum restoring moment in this direction is 4,923,500.71 kN·m, indicating that capsizing will not occur. Environmental loads experienced under unloaded and operational aquaculture conditions are smaller, and the overall structural moments are less

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than those under fully loaded conditions.

4. Conclusion

In response to the dependence of submersible net cage aquaculture on marine environments, and the issues of high construction costs, excessive material usage, and limited utility of traditional enclosed net cages, a new type of modular net cage structure has been proposed. This structure is designed to integrate strengths and address weaknesses, achieving 'multi-purpose use for one cage' to enhance aquaculture efficiency and quality. The total aquaculture water body encompasses 38,540.5 m³, and the utilization of floating boxes enables the net cage to function in three different working conditions, thereby reducing the area occupied on the sea surface.

Frequency domain analysis was carried out on the motion trends of the net cage under three different operating conditions. The net cage is found to be sensitive to high-frequency waves. However, significant motion amplitudes are not easily generated in the high-frequency regions. Under calm water conditions, a restoring moment is present to ensure the stability of the net cage. Time domain analysis over a period of 1800 seconds simulates sea conditions, and under the action of co-directional combined loads, the net cage eventually achieves dynamic equilibrium at a new position through repeated vibrations. Even in dynamic water conditions, the structure of the net cage endures the forces, and the restoring moment still ensures that the net cage does not overturn. The new modular net cage structure is able to effectively meet the design requirements for deep-sea net cages.

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