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Finite Element Analysis of Overall Structural Strength of Multifunctional Offshore Platform

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Abstract

In this paper, the concept of underwater oil storage is introduced into the jack-up production and storage platform, and a concept of mobile assembled underwater oil storage platform is proposed. It becomes a multi-functional platform of marginal oil field integrating drilling, production, storage and transport, which is suitable for the marginal oil field with a depth of about 200 meters, so as to solve the problems of limited oil storage and high cost of traditional jack-up production and storage device. Aiming at the new movable assembly type offshore platform, the strength analysis of its whole structure is carried out by using the finite element software ANSYS, and the problems of working condition type and load calculation are explained accordingly.

Keywords

Multi-functional platform; Production and storage of oil; Environmental load; Finite element analysis

Introduction

With the rapid development of China's economy and technology, the demand for petroleum energy has also increased rapidly. The exploration and development of marine oil and gas resources has received high attention. To increase the output of marine oil and gas resources, the development of marine oil and gas has become a strategic focus of China's sustainable energy development [1]. In recent years, the development speed of this field has increased significantly.

Currently, CNOOC, Sinopec Group, and CNPC are the three major oil and gas exploration and development companies in China. During their exploration and development in most of China's sea areas and some overseas blocks, they have discovered numerous marginal fault-block oil fields with enormous crude oil reserves. Compared to conventional oil fields, marginal oil fields are characterized by small scale, small reserves, scattered distribution, and wide range. They also have short production periods, diverse reservoir lithologies, and high development risks. Due to constraints such as uncertainties in economic evaluation, environmental conditions, and equipment technology levels, many marginal fault-block oil and gas fields have not been effectively developed. Therefore, there is an urgent need to research corresponding technical solutions and new platforms suitable for marginal fault-block oil and gas fields.

For offshore oil and gas development, a combination of methods is typically employed, including fixed jacket platforms, compliant towers (CTs), FPSOs, and subsea production facilities, as shown in Figures 1-4. However, for oil extraction projects located in waters no deeper than 300 meters and requiring support from various types of equipment, fixed drilling platforms and satellite systems are the optimal choice. While this approach offers abundant development resources, it also comes with high costs. Compliant tower platforms are relatively expensive, non-reusable,

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and rarely used globally, often replaced by floating installations within their suitable water depth range. Furthermore, the high initial investment costs of commonly used FPSOs and subsea production facilities make them difficult to economically justify for developing some marginal oil fields. In China, the development of marginal fault-block oil fields mainly relies on mobile oil production platforms. The maximum working water depth of traditional jack-up production platforms is only 168 meters, and there are only a few of these in the world. Most jack-up drilling platforms are suitable for water depths of up to 120 meters. For offshore marginal oil fields with water depths of 200 meters, there is currently a lack of effective development methods and models. As a result, most marginal fault-block oil fields have not been effectively developed. Therefore, there is an urgent need to develop a new type of multi-functional development equipment suitable for the development of marginal fault-block oil fields with water depths of 200 meters.

1. Finite Element Model of a Mobile, Modular Underwater Oil Storage Platform

1.1 Platform Introduction

The mobile, modular subsea oil storage platform is a new type of offshore platform equipment. It consists of a jack-up production platform, subsea oil storage support devices, cylindrical legs, a lifting system, and living quarters. After being towed to the designated operating area, the subsea oil storage and support devices are anchored to the seabed using self-sinking technology. They then connect and are secured to the jack-up production platform via pile-shoe support boxes, forming a unified whole. This creates a multi-functional platform for marginal oilfields, integrating drilling, production, storage, and transportation.

The side view of the platform is shown in Figure 5.

The environmental factors under normal operation and storm self- sufficiency conditions of the target platform are shown in Table 1.

1.2 Platform Main Dimensions and Structural Parameters

The upper part of the platform is a four-legged self-elevating production platform, and the lower part is an underwater oil storage pad support device. The main dimensions of the platform are shown in Table 2.

1.3 Finite Element Model

Based on the basic structure of the platform, an overall finite element model was established. The finite element software ANSYS was used to determine the element type based on the actual stress state of the structure and the specific size of the structural components [2]. For the main parts of the platform (such as the outer protective plate, various compartments , the outer side of the ballast water tank , the fixed pile frame , and the pile shoe bearing box), the Shell181 shell element was used for modeling ; while for some smaller components, such as ordinary beams and longitudinal ribs on the deck , the Beam188 element was used for modeling; the pile legs above the water surface and the pile legs inside the pile shoe bearing box were modeled using the PIPE16 element ; the pile legs and support trusses in deep water were modeled using the PIPE59 element . In order to improve the accuracy of the calculation, the mesh was made as rectangular as possible. The structural materials of the multifunctional marine platform are all DH 36 and EH36 grade steel with a yield strength of 355MPa, a safety factor of 1.25, and an allowable stress of 284MPa. The finite element model diagram is shown in Figure 6.

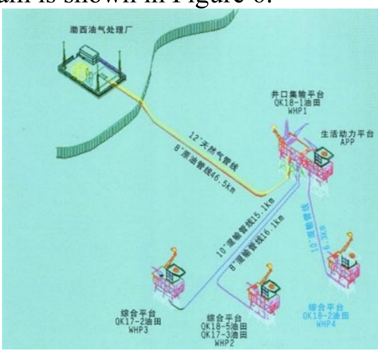


Figure 1. Based on a fixed guide frame platform.

Figure 2. Based on the compliant tower (CT).

Figure 3 Based on FPSO.

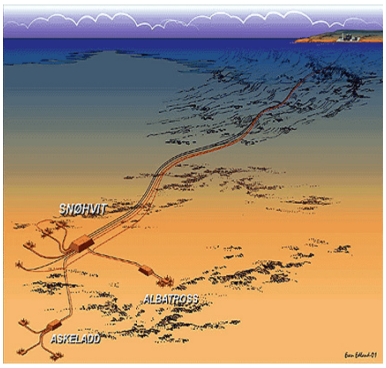


Figure 4. Development using underwater production facilities.

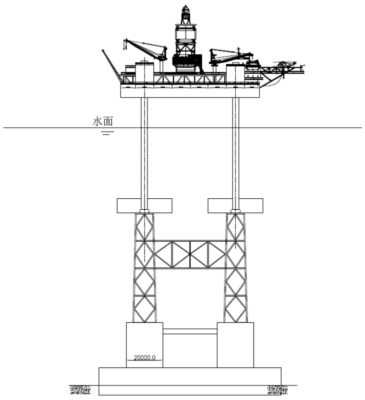


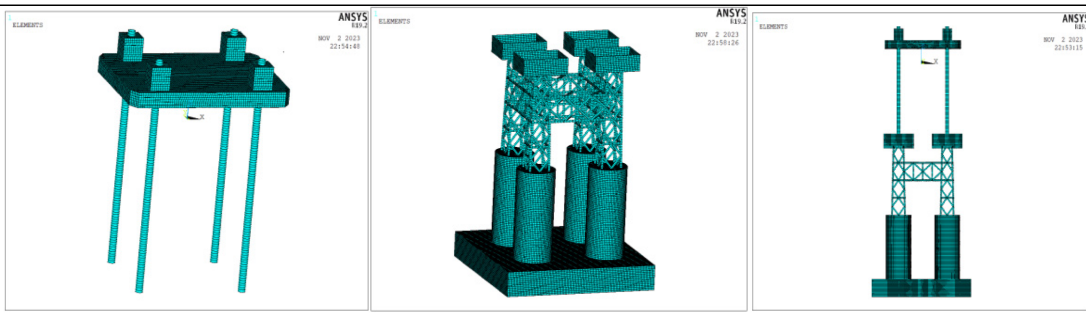
Figure 5. Platform side view.

Table 1. Environmental parameters under normal operating and storm self- sustaining conditions

Operating conditions	water depth	Water surface velocity	Mid-layer flow velocity	Bottom flow rate	maximum wave height	cycle	wind speed
Normal operation	200 m	1.08 m /s	0.78 m /s	0.56 m /s	23 m	14.8s	36 m /s
Storm self-sustaining	200 m	1.08 m /s	0.78 m /s	0.56 m /s	29 m	16.6s	51.5 m /s

Table 2. Platform Main Scale

name	Parameter value
Platform main body length	76m
Platform main body width	54m
Platform main body deep	6.5m
Pile fixing frame	9×8.5×10m
Number of pile legs	4
Pile leg diameter	3.5m
Pile leg length	100m
Lateral spacing of pile legs	40.5m
Longitudinal spacing of pile legs	49m
Pile shoe bearing box	30×20×10m
Lower cylindrical water storage tank	φ25×55m
Oil storage pad	100×100×15m



(a) Upper self-elevating production platform (b) Subsea oil storage support device (c) Multifunctional marine platform

Figure 6. Finite element model of the platform structure.

2. Platform Load

The loads that the platform bears during operation mainly include fixed loads, variable loads and environmental loads [3]. The application methods of various loads are as follows: the liquid tank load is applied in the form of a surface load in the corresponding area, the weight of the equipment and the weight of the superstructure are applied according to the calculation and applied to the corresponding positions. The load of the cantilever beam structure is the support reaction force derived from the weight of the cantilever beam and then added to the deck area.

Generally, the following coordinate system is used to describe environmental loads during platform calculations. The origin of the coordinate system is located at the stern end of the platform's centerline, with the positive x-axis pointing towards the bow and the positive y-axis pointing towards the port side of the ship. The environmental load angle refers to its incident angle with the positive x-axis. Figure 7 shows the coordinate system used when modeling the platform. In this analysis, we considered the directions of environmental loads at 0°, 30°, 60°, 90°, 120°, 150°, and 180°.

In the calculation of wave loads on marine engineering structures, the method for calculating wave loads is usually determined according to the size of the marine engineering structure [4]. This paper studies the strength of the platform under normal operation and storm self-sustaining conditions. The pile legs are subjected to wave loads. The pile legs are small-sized components. The Morrison formula is used to calculate the wave loads on the pile legs.

For the main body side and fixed pile frame of the mobile modular underwater oil storage platform, the wind load will be directly applied to the actual surface position. For high-rise building parts such as residential areas and living facilities, the model does not fully construct them. The wind load of these structures is mainly applied by applying corresponding horizontal forces at the corresponding positions on the deck surface and converting the moment at the actual height into a moment on the deck surface [5].

The underwater support truss and the pile legs in the water were constructed using the PIPE59 element. The Stokes fifth- order wave theory method was used to realize the automatic calculation of the influence of wave and current forces. This element is a tubular structure in ANSYS specifically used to simulate the submerged tubular structure subjected to wave and current forces [6]. During the operation, actual parameters such as outer diameter, wall thickness, CD, and CM need to be input and set. The software will perform calculations according to the selected wave theory and automatically apply wave forces at the corresponding node positions.

3. Overall Structural Strength Calculation and Analysis

3.1 Static Analysis

Static analysis refers to the analysis of a structure's response under a given static load, without considering the effects of damping and inertial forces. For deep-water jack-up platforms, static analysis primarily considers the platform's own weight and the maximum environmental load conditions. Based on the calculation results from the ANSYS program, the following table shows the maximum wave force and maximum phase angle obtained under different incident angles during operation and self-storage conditions.

of the data in Table 3 reveals that the platform exhibits its most dangerous state when the external load reaches 90°, regardless of whether it is in operation or self- sustaining condition. Detailed calculation results are shown in Table 4. Under normal operating conditions, the maximum stress value is 121.738 MPa; under self-sustaining conditions, the maximum stress is 137.557 MPa. In both conditions, the maximum stress occurs at the connection between the pile legs and the upper platform body. This area includes the lifting system and other components. This area bears the weight of the platform itself and the vertical loads from various equipment, and resists horizontal loads generated by environmental factors such as wind, waves, and currents. Figures 8-13 show the stress distribution under operating and self-sustaining conditions.

3.2 Modal Analysis

Modal analysis is a method for studying the dynamic characteristics of structures. A mode refers to the inherent vibration characteristics of a mechanical structure. Each mode has a specific natural frequency, damping ratio, and mode shape. Modal analysis is also the starting point for transient dynamic analysis. Modal analyses performed by ANSYS software are all linear analyses. This paper uses the Block Lanczos method to extract the first six vibration characteristics of the platform. The frequencies of the first six modes of the platform are shown in Table 5. The calculated mode shapes of the first six modes of the multifunctional platform are shown in Figure 12. As can be seen from Figure 14, modes 1-4 are dominated by vibrations along the X and Y directions, while modes 5-6 are dominated by rotations around the Z- axis with relatively small offsets.

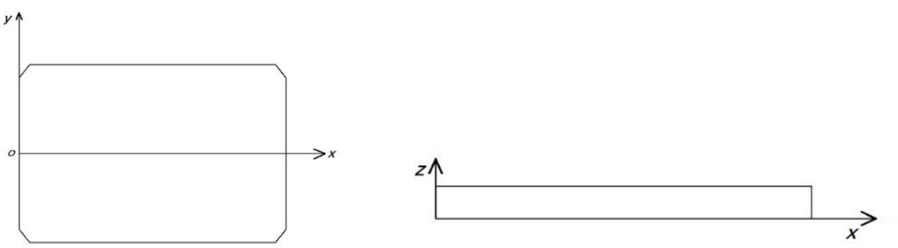


Figure 7. Calculation coordinate system.

Table 3. Maximum wave current force and phase angle under different working conditions

Operating conditions	Operating conditions							Self-storage condition						
wave height	23m							29m						
cycle	14.8s							16.6s						
Angle of incidence (degrees)	0	30	60	90	120	150	180	0	30	60	90	120	150	180
Maximum phase angle/degree	78	75	76	76	77	78	81	62	61	61	61	62	63	64
Maximum wave force/KN	6671	6699	6766	6799	6766	6698	6671	8194	8231	8300	8332	8300	8231	8194

Table 4. Calculation Results

Operating conditions	External load direction	Maximum overall stress of the platform (MPa)	(MPa) on the upper platform-leg pile	Platform/Leg - Allowable Structural Stress (MPa)
Normal operation	90°	121.738	121.738	284
Storm self-sustaining	90°	137.557	137.557	284

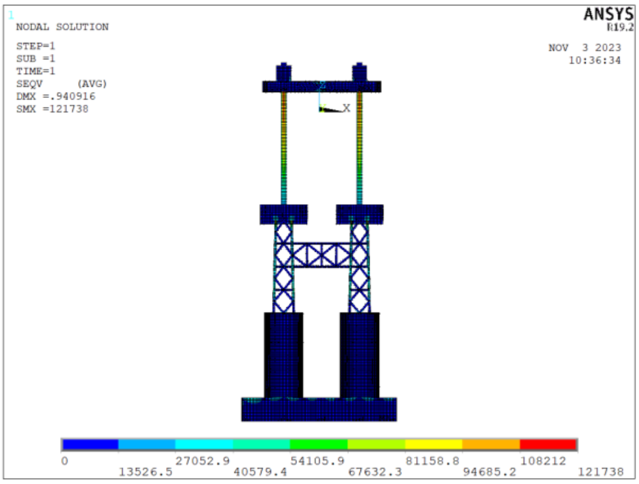


Figure 8. Overall stress distribution of the platform (working at 90°).

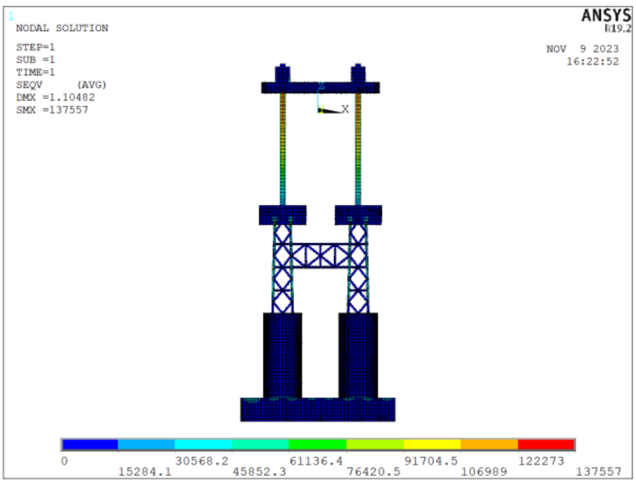


Figure 9. Overall stress distribution of the platform (self-storage 90°).

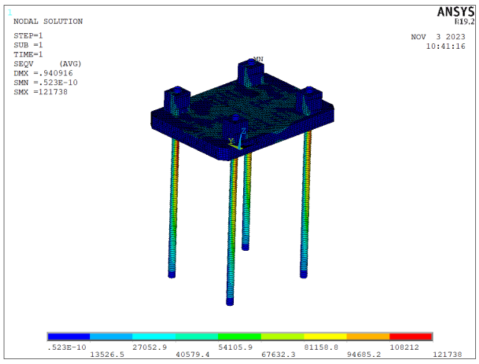


Figure 10. Stress distribution on the upper platform (working angle 90°).

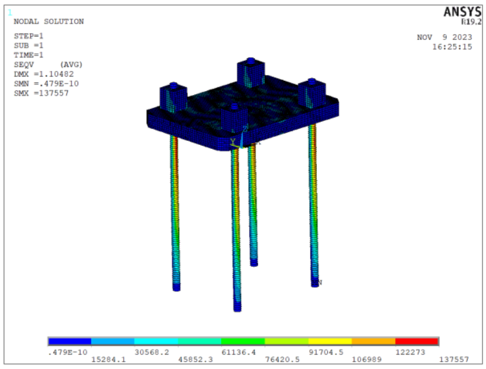


Figure 11. Stress distribution on the upper platform (self-storage 90°).

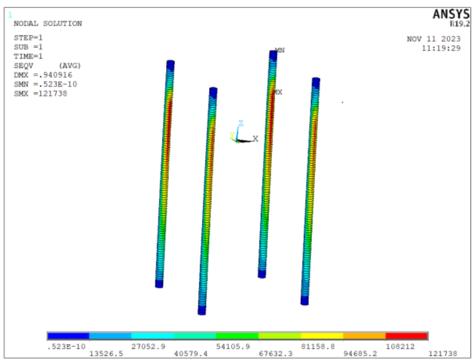


Figure 12. Stress distribution of pile leg (working angle 90°).

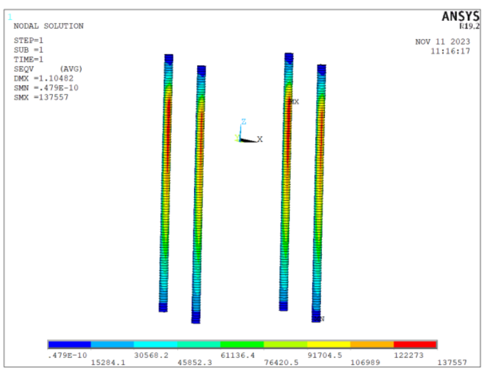
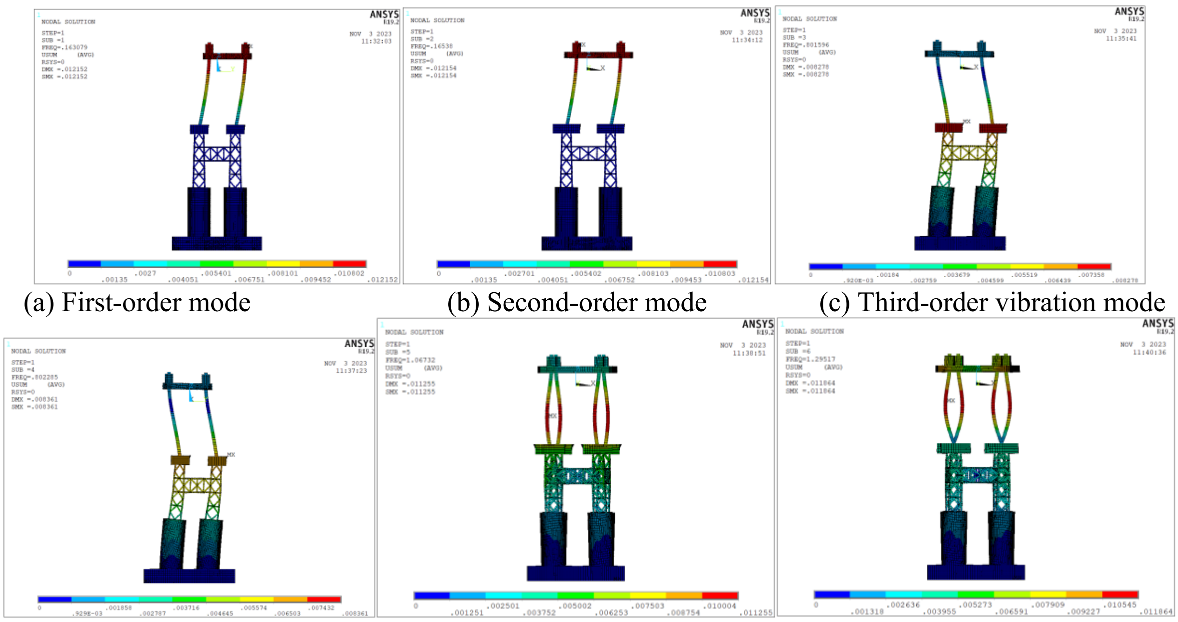


Figure 13. Stress distribution of pile leg (self-saved 90°).

Table 5. Calculation Results

Frequency order	Frequency value (Hz)
1	0.16308
2	0.16538
3	0.80160
4	0.80228
5	1.0673
6	1.2952



(a) First-order mode (b) Second-order mode (c) Third-order vibration mode

(d) Fourth-order vibration mode (e) Fifth mode (f) Sixth-order vibration mode

Figure 14. Displacement diagrams of the first 6 modal analyses of the platform structure.

3.3 Dynamic Response Analysis

Transient structural analysis is a method used to analyze the dynamic response of a structure under loads that vary over time. It is used to determine the displacement, strain, and stress of a structure under arbitrary combinations of steady-state, transient, and harmonic loads. To obtain the true velocity and acceleration response of a platform, a comprehensive evaluation using dynamic time -history analysis is required; this section uses transient structural analysis. Rayleigh damping is a common factor in the dynamic analysis of marine structures; that is, we define the damping matrix as...

$$[C] = \alpha[M] + \beta[K]$$

In the formula, $\alpha$and $\beta$are the mass damping coefficient and stiffness damping coefficient, respectively. The damping coefficient $\alpha$and βmagnitude are related to the modal damping ratio and natural frequency [7], and can be determined by calculating the first two natural frequencies of the platform structure.

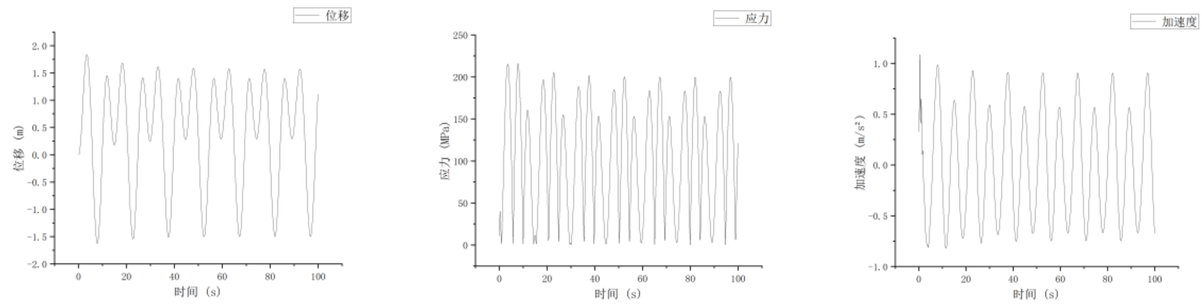
$$\alpha = \frac{2\omega_1\omega_2(\xi_1\omega_2 - \xi_2\omega_1)}{\omega_2^2 - \omega_1^2}$$

$$\beta = \frac{2(\xi_2\omega_2 - \xi_1\omega_1)}{\omega_2^2 - \omega_1^2}$$

In the formula, ω1 and ω2 are the natural frequencies of the first two sections of the platform structure, which are obtained through modal analysis of the platform structure. ξ1 and ξ2 represent the corresponding damping ratios, which are usually selected between 2% and 5%.

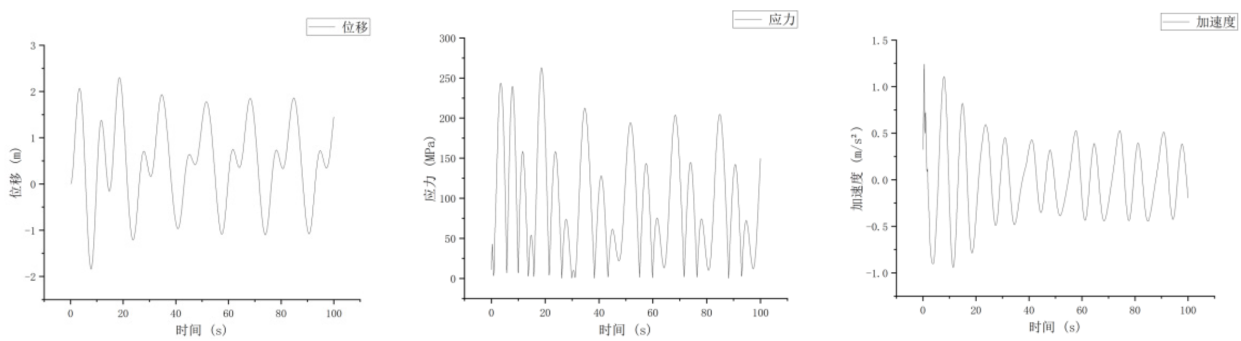
The dynamic response of the structure was analyzed using the ANSYS transient analysis method. A period of 100s was used, with a time interval of 0.1s. Taking a wave angle of 90 ° as an example, the analysis was conducted under normal operating conditions and storm self-sustaining conditions, focusing on the points of maximum overall displacement and stress. The resulting structural response is shown in Figures 15-16.

the multi-functional platform structure shown in Figures 15-16, the maximum displacement of the platform under load during normal operation is 1.58 m, the maximum stress is 200.32 MPa, and the maximum acceleration is 0.907342 m/s². Under storm self-sustaining conditions, the maximum displacement of the platform under load is 1.86 m, the maximum stress is 212.51 MPa, and the maximum acceleration is 0.526944 m/ s².



(a) Dynamic analysis of time-displacement (b) Dynamic analysis of time-stress (c) Dynamic analysis of time-acceleration

Figure 15. Platform dynamic response analysis under normal operating conditions.



(a) Dynamic analysis of time-displacement (b) Dynamic analysis of time-stress (c) Dynamic analysis of time-acceleration

Figure 16. Platform dynamic response analysis under storm self-sustaining conditions.

4. Conclusion

Based on the specifications, a study was conducted on the overall structural strength assessment method for multi-functional offshore platforms, and the following conclusions were drawn:

(1) Based on the CAD structural drawings of the platform, a finite element model of the multifunctional offshore platform was constructed using the finite element software ANSYS, and environmental loads of wind, waves and ocean currents were applied to it. The overall structural strength of the multifunctional offshore platform under normal operation and storm self-sustaining conditions was analyzed using static analysis, modal analysis and instantaneous dynamic dynamic analysis.

(2) In order to ensure that the calculation results are consistent with the actual situation, this paper studies how to calculate environmental loads, including wind, waves, currents, etc., to ensure that the effect of environmental loads is consistent with the actual situation.

(3) The yield strength of the overall finite element model of the mobile assembled underwater oil storage platform was verified and met all the required strength standards.

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