A New Concept of Jackup Combined Semisubmersible Multifunction Platform

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Abstract. In order to overcome the shortcomings of the existing semisubmersible platforms, based on care investigation into various factors affecting the quality of floating platforms, a new concept of jackup combined semisubmersible multifunction platform named JCSM was developed. The JCSM integrates the advantages of the jackup platform and the semisubmersible platform. Also, the comprehensive performance of the JCSM is improved by optimizing the details of the topological structure. Therefore, the JCSM is well-suited for either wet tree or dry tree developments in harsh environments. Meanwhile, it possesses a variety of attractive functions covering drilling, early production, workover, oil and gas treatment, oil storage and unloading, and etc. Thus, a JCSM can be used throughout the entire life cycle of deepwater oil and gas field development, which can greatly help reduce the capex and opex and obtain higher economic benefit. The JCSM is an innovative alternative to the conventional semisubmersibles and a new choice provided for the development of offshore oil and gas fields in the future. The advantages of the JCSM was elaborated and analysed from mechanics perspective in the paper. This study will provide reference for the development of creative floating platforms.

1. Introduction

With the declining of oil and gas resources on land and offshore regions, deepwater oil and gas exploitation has become one of the focuses of international competition in energy fields. In general, the deepwater floating structures available mainly include SPARs, TLPs and Semis. Compared with other floating systems, Semis have many attractive traits, such as good stability, high wind/wave resistance ability, spacious deck, large payload capacity, adaptable to a wide range of water depths, etc., and thus are the most widely used and promising floating platforms for deepwater and even ultra-deepwater applications worldwide 0. However, the conventional semis have some shortcomings 0, including low stability margin due to relatively high center of gravity; inefficient utilization owing to deficient functions; shortage of oil storage capacity; too large heave motion to serve as the host of the dry-tree well system; and so on.

To mitigate the weaknesses of the conventional semis, many new concepts have emerged in recent years 0. Typical versions include the truss semisubmersible platform (Truss Semi) and the extensible draft semisubmersible platform (ESEMI) presented by US FloaTEC company, the expandable semisubmersible platform (EDP) proposed by France Technip company, the FourStar Semi by the United States SBM Atlantia company, and the semisubmersible platform with free suspended solid ballast tanks (FHS Semi) by Mansour and Huang 0. The main design goal of those new-type semis was to reduce the platform's heave motion. Unfortunately, although they have indeed improved the heave performance, meanwhile a series of new challenges followed with them, such as vortex-induced

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vibration caused by using long columns, difficulties in installment and towage also due to long columns, and unsatisfactory pitch/roll motion performance caused by deep draft design, sharply rising costs because of deep draft configuration, and etc. On the other hand, the new concepts and the matching techniques have been patented, forming the monopoly in deep water technology. By contrast, the types of the semis in China are seldom, and the research and application is still mainly concentrated on the drilling ones. Efforts on the other function of the semis are far from sufficient, which has been one of the bottlenecks of China's development of deepwater oil and gas fields. Thus, it is urgent to design the new-type semisubmersible platforms with own intellectual property rights and applicable in the harsh environment for the South China Sea in order to accelerate the development of deepwater oil and gas in China.

The uncertainty of the geological reservoir and the high costs of the conventional facilities determine the high risk of deepwater oil and gas field development. Especially under the current international situation that the oil price has been being long-term sluggish, how to maximize the platform utilization is the key measure to reduce the costs of the deepsea oil and gas exploration. Therefore, the multifunction platform has become the best choice for deepsea oil field development.

In consideration of the current situation, this paper proposed a new concept of the semisubmersible platform, which overcomes the shortcomings of the existing semis, adaptable to dry tree, wet tree and the combination of the both, also possessing multiple functions, such as drilling, early production, workover, oil and gas treatment, oil and gas storage as well. It will provide a new low-cost life-long solution for the future deepsea oil and gas field development.

2. Theoretical Basis

2.1. The Affecting Factors of Heave

Hydrodynamic response is one of the main indexes to evaluate a floating platform's behaviour. It is not only related to operation efficiency and economic benefit, but also directly affects platform safety. Generally, the heave motion of the conventional semi is large due to its natural heave period close to wave period, so it's difficult for the conventional semi to meet the movement requirements for dry tree with the top tension riser. Dry tree system is economical and practical, easy to operate and maintain. The amplitude of heave determines whether or not the dry tree system can be accommodated on a floating platform. Therefore, it's the most concerned topic to reduce the heave through careful studying the parameters affecting the platform's heave.

Ignoring the coupling effect between the heave and the motions in other directions, the heave motion equation of the semisubmersible platform can be written as 0

$$(\mathrm{M}+\mathrm{A}_{33})\ddot{Z}+(\mathrm{C}+\mathrm{B}_{33})\dot{Z}+\rho g\,\mathrm{A}_{\mathrm{w}}\,Z=\mathrm{F}_3(t) \tag{1}$$

where M is the platform mass, A_{33} is the heave additional mass, Z is the heave amplitude, C is viscous damping coefficient, B_{33} the heave damping, A_{w} the waterplane area, and F_3 the vertical excitation force on the platform.

Assuming that the free surface raise at the center of the platform is $\varsigma=\varsigma_\alpha \sin\omega t$. k is a small number and z_{m} is the height of the geometric center of the lower floating body from the waterplane. The heave amplitude is derived as follows:

$$Z=\frac{\varsigma\cos\left(\mathrm{k}B_{\mathrm{f}}/2\right)}{\exp(kz_{\mathrm{m}})}\left[1-\frac{kz_{\mathrm{m}}}{(\omega/\omega_n)^2-1}\right] \tag{2}$$

where B_{f} is the width of the lower floating body and ω_n is the natural heave frequency.

From equations (2), it can be seen that the heave response of the platform is proportional to the wave height, and the heave amplitude decreases with the increase of z_{m} or B_{f}.

The formula for the natural heave period of the platform is

$$T_{n3}=2\pi\left(\frac{\mathrm{M}+\mathrm{A}_{33}}{\rho g\,\mathrm{A}_{\mathrm{w}}}\right)^{1/2} \tag{3}$$

As shown in equation (3), the main factors affecting the natural heave period of the platform is the waterplane area and the heave additional mass when the mass of the platform is settled. The smaller the waterplane area is, the larger the natural heave period of the platform is; while the greater the heave additional mass is, the larger the natural heave period is. In addition, increasing the mass of the platform also can increase the natural heave period, which can achieve by enlarging the platform scale or adding the clump weight.

In summary, the heave motion of the platform within the range of wave frequencies can effectively reduce by increasing the damping and the natural heave period to keep it away from the wave energy range, and reducing the heave excitation force, and so on. Moreover, under a given marine environmental condition, the main affecting factors of the heave response are the draft of the platform, the width of the lower floating body, waterplane area and the heave additional mass of the platform. The new platform concept will be carefully designed from all the details of the topology to improve the heave performance.

2.2. The Affecting Factors of Roll and Pitch

Pitch and roll are important indicators of the operating performance of a floating platform. The swing amplitude will affect the working status of the production facilities, the processing quality of the crude oil and the comfort of the crew's living environment.

Due to the symmetrical structure of the floaing body in the horizontal plane, Just need study the case of the roll motion here. According to the theory of hydrostatic mechanics 0, there are

$$T_{n5} = 2\pi \left(\frac{I_x}{\nabla h} \right)^{1/2} \tag{4}$$

$$r = \frac{I_x}{\nabla} \tag{5}$$

$$h = z_{\mathrm{B}} + r - z_{\mathrm{G}} \tag{6}$$

$$\mu_\theta = \frac{N_\theta}{\left(I_x \nabla h \right)^{1/2}} \tag{7}$$

$$\theta = \frac{\alpha_0}{\left[(1 - \Lambda_\theta^2) + 4\mu_\theta^2 \Lambda_\theta^2 \right]^{1/2}} \tag{8}$$

$$I_x = \frac{\nabla}{12} (B^2 + 4z_G^2) \tag{9}$$

where T_{n5} is the natural roll period of the floating body, ∇ is the displacement, h is the initial stability height, $I_x = I_{55} + \mathrm{A}_{55}$ is the total inertia moment, herein I_{55} and A_{55} are the roll inertia and the roll additional mass respectively. According to the engineering experience of the semisubmersible platform based on the potential flow theory, the roll additional mass A_{55} is about 1/3 of the total inertia moment. r is the initial stability radius, z_{B} is the vertical coordinates of the buoyancy center, z_{G} is the vertical coordinates of the gravity center, μ_θ is the dimensionless damping coefficient, N_θ is the damping coefficient, θ is the roll angle, and B is the width of the floating body.

It can be seen from equation (4) that when the displacement is given, the increase of roll natural period can be achieved by reducing the initial stability height or increasing the roll moment of inertia.

As shown in equations (4) ~ (6), when the displacement is given, a smaller full-loaded waterplane area can make I_x reduce rapidly, accordingly make r decrease. Moving the buoyant center down simultaneously, h value will be smaller, so the larger T_{n5} value will achieve. Moreover, as seen from equations (7) and (8), reducing h will cause μ_θ to increase and the roll/pitch amplitude to decrease. On the other hand, the trouble with the decreasing waterplane area leading to the larger heave can be settled by setting some devices to increase the viscosity damping. From the equations (4) ~ (9), it also can be seen that increasing the width B of the floating body can induce I_x and T_{n5} to increase while

μ_θ to decrease, and then the roll/pitch amplitude of the floating body increases. Therefore, it is necessary to consider various factors in an integrated manner when carrying out the optimal design.

In summary, using the smaller waterplane scheme and the larger width is the effective measures to overall improve the roll performance of the floating body. In addition, using the inclined side edges is also helpful to increase the diffraction damping, thereby reducing the heave excitation force and the heave motion of the platform 0.

2.3. The Affecting Factors of Stability

Harsh and complex deepsea environments put forward higher requirement for the safety and weatherliness of the semisubmersible platform, so the reserve stability of the platform needs to be improved. As can be seen from Section 2.2, there are many measures to increase the stability of a floating body. For example, the increase of the width of the floating body can lead to the increase of the transverse waterplane moment of inertia of the floating body and the static moments of the wedges above and under the waterplane, and then the metacentric height and the arm of static stability will be larger, so the stability of the floating body is increased. The stability of the floating body can also be effectively enhanced by reducing the gravity center or modestly increasing the moulded depth of the floating body. In addition, the flaring-type design of the profile above the waterline can increase the righting moment when the inclination is large, so it can also enhance the stability of the floating body.

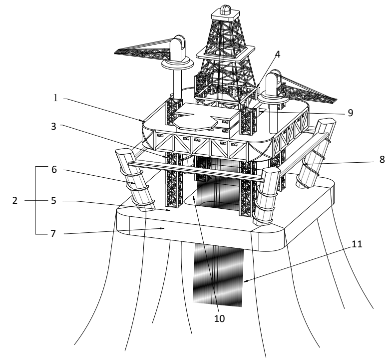
The initial stability is an important factor determining the swaying frequency of a floating body. The swaying period of the floating body with small initial stability is long and the swaying is gentle; otherwise, the swaying period of the floating body with large initial stability is short and the floating body will violently sway under wind and storm. As known from the analysis above, reducing the initial stability can improve the motion performance; however, reducing the stability height is contradictory with the stability requirement. Therefore, various factors must be comprehensive measured and wholly considered throughout the design process. The rational procedure is using collaborative optimization principle 0 to obtain the ideal stability under the premise of ensuring excellent motion performance of the floating body through adjusting the design parameters effecting performance of the platform, making both the stability and hydrodynamic performance be well satisfied.

3. JCSM Platform Concept

3.1. The Sketching of New Platform

Based on the detailed analysis of the shortcomings of the existing semis and the factors affecting the platform performance, combining the advantages of the jackup platform and the semi platform, the new concept of jackup combined semisubmersible multifunction platform (JCSM for short) has been put forward, which has been submitted to China’s State Patent Office for examination as a patent application (Patent application number: 2017102910467). An example for the technical solution of the new concept platform is illustrated by Figure 1. As shown in Figure 1, the main body of the JCSM is composed of a box deck, a lower floating body and at least three jackup legs. Thereinto, the lower floating body is made up of at least three outward-tilting columns from its bottom and an annular pontoon connecting the lower portions of the columns. The jackup legs connect the box deck and the lower floating body and support the topsides. The deck can be raised or lowered along the jackup legs to the required height through lifting device which is driven by electric hydraulic, electric gear rack or electromagnetic lift technology. Figure 2 shows the elevation view of the platform with the oil and gas production module on the deck. The platform is positioned using the mooring system, dynamic positioning system or the combination of the both according to the environmental condition and water depth of the working sea area.

Taking full advantage of the length adjustability of the jackup legs and great ballast capacity of the lower floating body, the gravity center of the JCSM can be changed according to the working conditions and the marine environment in order to improve the stability and hydrodynamic performance, particularly to reduce the heave amplitude so as to meet the requirements for dry tree oil production. Huge internal space of the annular pontoon can be divided into storage tanks, ballast tanks, pump tanks and others for production. The design of the jackup leg makes the sizes of the topside module and the lower floating body not affected by column spacing, and convenient to adjust the distance between the deck and the lower floating body, so quayside integration and overall towage can be conveniently implemented.



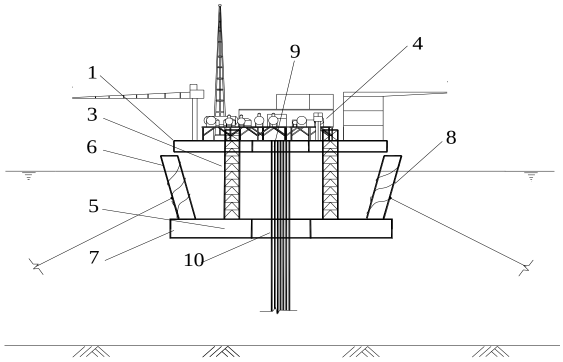


Figure 1. Conceptual diagram of JCSM. **Figure 2.** The elevation view of JCSM with production facilities on the deck.

(1 box deck; 2 lower floating body; 3 jackup leg; 4 drilling rig and oil & gas processing module; 5 annular pontoon; 6 outward-tilting column; 7 out-extending part of pontoon; 8 spiral side plate; 9 moon pool; 10 central well; 11 oil and gas production riser / drilling riser)

3.2. Components of the Platform

3.2.1. Box deck. The box deck is equipped with skid-mounted modular units, including oil and gas treatment system, dry and/or wet oil wellhead, drilling equipment, living quarter, power modular, mooring system, moon pool, and etc. The box deck has a 1-2-meter-high double bottom and 2-storey decks with height of 3-4 meters each. The double bottom enhances the global structural strength of the topside. Laying pipelines inside the double bottom contributes to the unified planning and layout for the pipelines. Also, the space inside the double deck can arrange production and drilling equipment, and more topside area will be saved for laying out increasing functional facilities in the future.

3.2.2. Lower floating body. The lower floating body includes the annular pontoon and the columns, two parts providing buoyancy and stability together. At the center of the annular pontoon is a cylindrical or prismatic central well. The interior space of the annular pontoon is divided into ballast tanks, oil storage tanks, production compartments, drilling equipment compartments and pump compartments. Among them, some of the ballast tanks are permanently fixed ballast with weights to ensure that the floating center is higher than the gravity center of the platform. At the top of the annular pontoon are at least three symmetrically arranged columns inclined outwardly along the vertical axis of the geometric center of the annular pontoon. The cross section of the columns is round, fillet square or the other fillet polygon. The outer inclined columns are each arranged near the outer side of the annular pontoon. The lateral side of each column sets up a spiral plate, and the internal space of each column is divided into several watertight compartments. The central well of the annular pontoon is aligned with the moon pool of the box deck in the vertical direction to facilitate the oil & gas rig and the production & drilling risers passing through. The jackup legs together with the central well protect the risers from collisions and provide lateral support for the risers.

3.2.3. Jackup leg. The JCSM uses the truss-framed jackup legs to connect the box deck and the annular pontoon and support the topsides, thus, the lower floating body is not directly connected with the box deck. Therefore, the length of the jackup legs between the box deck and the annular pontoon, the number of the jackup legs, the cross-section dimension and the location can be adjusted according to the configuration of the jackup legs, the weight of the upper module and installation requirements of the platform. Similarly, the deck size is not limited by the leg spacing and can be defined according to the area requirements of the deck. The size of the annular pontoon, the spacing and size of the columns can also be optimized to ensure favorable motion and stability performance.

3.3. Advantages of JCSM

3.3.1. Easy to Optimize. The deck of the JCSM is directly supported by the jackup legs and without direct contact with the lower floating body, so the deck design will not be limited by the column size. Therefore, the designer can independently define the size and shape of the deck to make the facilities on it meet the operational process requirements better, and then improve the operation efficiency of the platform, the safety and reliability of the topside facility as well. The topsides hardly interact at all with the lower floating body, so the column spacing, waterplane area and displacement can also be optimized in a wide range, thereby improving the global performance of the platform.

3.3.2. Strong adaptability to environment. The pontoon is designed as a box-shaped structure with fillet edges to reduce the wave drag force. Some of the ballast tanks in the pontoon are permanently fixed ballast filled with the iron ore or other heavy objects to significantly reduce the gravity center of the platform and then ensure the floating center is above the gravity center at any time. The others are water ballast tanks, which can dynamically adjust the draft to maintain the platform a deep draft state during the service to reduce the heave exciting force. The combination of the two types of ballasts achieves unconditioned stability of the JCSM in the marine environment. Furthermore, the weights with a heavier dense increase the heave natural period and improve the heave motion of the platform. The powerful ballast system allows the platform to have a larger adjusting range of drafts to better suit the marine environmental conditions and different operating modes in different marine areas. Besides, the deck can move up and down along the jackup legs to a reasonable distance between the deck and the pontoon through the lifting device. Combined with adjustment of the ballast volume, the optimization of the gravity center, displacement, inertia moment and waterplane area of the JCSM is achieved, so that it can be better adapted to the operating conditions in different sea areas.

3.3.3. Good self-maintaining capability. Variable load is an important indicator measuring performance of a deepwater semisubmersible drilling platform. Large variable load can reduce the frequency of transport supplies and operating costs to ensure continuous operation and improve economic efficiency. The annular pontoon extends outside from the bottom of the columns and forms the out-extending part of the annular pontoon, which increases the variable load, displacement and oil storage capacity, reduces the gravity center of the platform, and makes the annular pontoon double as a heave plate as well. The out-extending part of the annular pontoon increases the ratio of variable load to platform weight, allowing the platform to meet the requirements for the self-sustaining capability, and then adapting to deep or ultra-deep water, all-weather and long period working.

3.3.4. Excellent structural stiffness and strength. The annular pontoon not only serve as the support structure to provide sufficient buoyancy for the platform, increase loading capacity and then enhance self-sustaining ability of the platform, but also make the substructure become an integral frame structure to transfer the environmental load acting on the columns to the global structure, thereby effectively resisting the environmental impact on the platform and then enhancing the strength of the platform, so the JCSM has a good hull safety and anti-storm capacity. At the same time, the annular pontoon structure can also effectively transmit interaction between the columns caused by the wave and the imbalance load of the platform. Therefore, the JCSM has excellent global structural stiffness and strength and effectively decrease the fatigue stress of the connected joints, reduce the welding and building difficulty, and improve the fatigue life of the platform structure. Obviously, navigation resistance of the annular pontoon is significantly larger than that of the double lower shells, so the platform need be placed on a large barge to tow.

3.3.5. Adapted to dry tree system. The out-extending part of the pontoon not only enlarge the compartment volume, increase the payload, lower the gravity center and improve stability of the platform, but also function as a heave plate to increase the added mass and the added damping, thereby increasing natural roll/pitch period and natural heave period and then improving hydrodynamic performance of the platform. Thus, the JCSM is allowed to use the dry oil production systems. In addition, through optimization design of the internal compartments, the displacement can be separated into several parts to allocate reasonable positions, and then the platform can obtain more added mass than the conventional semis with the same displacement.

3.3.6. Tilt columns with obvious advantages. Large stability margin is key to enhancing anti-storm ability and safety of a floating platform. The outward-tilting columns make the column spacing larger at the waterline, so the inertia moment of the platform at the waterplane is larger and then the initial stability height and righting moment are larger, which effectively reduce pitch/roll motions as well as the mooring line tensions.

Moreover, the columns can be designed as a smaller size as they do not bear the topside load, which makes the waterplane area of the columns smaller. Wave diffraction effect on the columns is significantly reduced because the column diameter is very small compared with the wavelength, and then effectively reducing the surface wave load acting on the platform. At the same time, coupling hydrodynamic response is also reduced between the columns as well between the column and the jackup leg. And the natural heave period further increases the motion performance of the platform is improved. The tilt sides of the columns also help to increase the radiation damping, thereby increasing the natural heave period and reducing the vertical motion of the platform. The tilt column has a better structural strength than the conventional vertical column, and can better resist the bending moment caused by the waves and the gravity of the platform, so that the global structure strength increases. In addition, the tilt design of the column together with the spiral side plate can effectively reduce vortex-induced response of the platform caused by the current.

Furthermore, in the process of optimization design, according to the principle of external forces suppressed each other 0, the tilt angle of the column can be adjusted to make the column spacing more reasonable so as to offset some of the external forces such as the gravity, buoyancy, wind, wave force, inertial forces and others acting on the platform, thereby further reducing the motion of the platform. If the spacing of the columns is designed as half of a wavelength, the forces acting on the columns and the lower floating body are equal and opposite each other and then the motion of the platform is reduced. When the crest is located in the canter line of the platform, the left and right column together with the lower floating body will suffer from the force outwards which are equal and opposite; otherwise, when the trough is located in the center line of the platform, the left and right column together with the lower floating body will suffer from the force inwards which also balance each other. If the spacing of the columns equals to a wavelength, when the crest is located on the left and right columns, the upward buoyancy of the columns can be offset a portion so as to reduce the motion of the platform; and vice versa.

3.3.7. Truss-framed jackup legs with obvious advantages. Relative to conventional columns, the truss-framed jackup legs are transparent to waves and wind, save steel as well, facilitate the current through in serious sea flow and reduce drag force; thereby reduce the mooring line tension and the platform motion. Moreover, they can also reduce the wave climbing up the leg and effectively increase airgap of the platform.

3.3.8. Easy to install and transport. The JCSM has smaller draft but larger displacement than other semis with the same amount of steel, so it is fully capable of quayside integration. This effectively reduces the difficulty of installation and minimizes installation risk. The JCSM can also achieve significantly simple offshore transportation without large floating crane. As shown in Figure 3, while towing or shifting operations, the ballast water in the pontoon is discharged and the deck is lowered along the jackup legs to near the pontoon in order to minimize the gravity center of the platform, reduce the windward area, improve towing stability, reduce towing drag, and then avoid the risk of installation at sea. After arriving at the specified working site, the deck is raised to the designed height along the jackup legs, and then the risers are installed for operation. At this point, the stability is plentiful because the floating center is above the gravity center. In sum, quayside integration and overall towing of the JCSM greatly reduce offshore working hour, cost and risk.

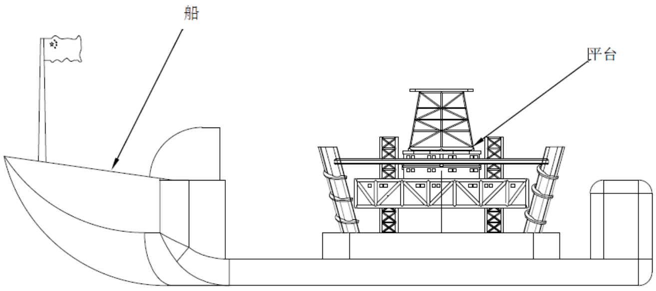


Figure 3. JCSM in the course of towage.

3.3.9. Modular design and construction. The JCSM has symmetrical configuration and simple structure, so it is suitable for modular design and construction to reduce cost and shorten construction time. In addition, the structure of each module is highly similar, which further reduces the difficulty of design and construction, and thus the serialization of design and construction of the JCSM can be easily achieved.

4. Conclusion

In this paper, a new concept of jackup combined semisubmersible multifunction platform named JCSM was developed. The JCSM overcomes the disadvantages of the available semis and possesses a lot of advantages: large stability margin, superior hydrodynamic characteristics, adaptable to the dry tree well system, large variable load, heavy oil storage capacity, simple structure, excellent global structure strength and stiffness, easy to construct and install, and high operation efficiency as well. Meanwhile, the JCSM has multiple functions with drilling, workover, oil production, and can be used throughout the life process of deepwater oil and gas field development. The JCSM with satisfactory comprehensive performance and high utilization can greatly reduce the overall development cost of the oil field, thereby obtaining the higher value of the investment.

The JCSM fully expands the application of the semis. It is invented as a low-cost solution for the oil production in deep water, which can meet the requirements for complicated deepwater environment. With the continuous exploitation of deepwater oil and gas fields in China, the JCSM will have a good application prospect. In the follow-up study, in order to verify the applicability of this novel platform in the South China Sea, it is necessary to carry out a series of studies on its key technologies such as stability, hydrodynamic, mooring system design by numerical calculation and model testing, and etc.

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