

# Concept Design of a New Deep Draft Platform

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**Abstract:** The authors analyzed requirements for a new deepwater platform, from conceptual design to hydrodynamic analysis. The design incorporated Deep Draft Multi-Spar (DDMS) that allowed easy fabrication, reduced costs, and provided favorable motion performance. It also provided a dry tree system and other benefits. The conceptual design process included dimension estimation, general arrangements, weight estimation, weight distribution, stability analysis, *etc.* A high order boundary element method based on potential theory and the modified Morison equation was used to predict the hydrodynamic and viscous effects of this new concept platform. The response amplitude operators (RAOs) were acquired and compared with those of a typical Truss Spar. The response of the platform to the JONSWAP spectra of 3 different extreme ocean conditions was analyzed to evaluate the seakeeping ability of the new concept. The results revealed favorable motion performance due to all the degrees of freedom available.

**Keywords:** Spar; potential theory; Morison equation; deepwater platform; mooring line; heave plate

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## 1 Introduction

With the rapid development of deep-water oil industry, some types of deepwater platform are widely used around the world, e.g. SEMI, TLP and Spar platforms. Recently some new conceptual deepwater platforms are brought forward due to the keen competition of market. The new concepts pay more attention to the platform motion performance, dry tree system availability, various ocean conditions adaptability, low cost, low fabricative difficulty, the more design flexibility, *etc.* (Chedzoy and Lim, 2003; Cermelli *et al.*, 2004; Jatar and Dove, 2005).

The technologies of design and fabrication have been mature for the conventional SEMI platform. Therefore it is widely used for drilling and producing in deepwater region. The draft of SEMI is relatively shallow, the wave exciting force, especially the heave loading due to the large area from horizontal pontoons is generally high. Therefore the motion behavior is inferior compared with some other platform types, e.g. Spar and TLP. Another reason for the inferior SEMI's motion behavior is the natural periods are close to the wave frequency (W-F) range, and the resonance may cause large response under the extreme environment. TLP platform applies the tensioned tendons to connect the hull and the sea bed fundament in order to control the vertical, roll and pitch motions. The heave and pitch natural periods are much lower than the W-F range due to the huge stiffness provided by the tendon. The typical heave natural period of TLP is around 3 s.

One of the main advantages of the TLP compared with the Spar is larger topside operational area and more flexibility of design. However, the cost of TLP is sensitive to the water depth. With the increase of water depth, the total cost of TLP increases fleetly. Thereby up to now, the water depth record of TLP is 1 425 m while that of the Spar is 2 400 m.

Generally, the Spar is a preferable solution to deepwater oil and gas exploration due to the favorable motion performance (Agarwal and Jain, 2003). There have been 17 Spars existing in the world since the Neptune which is the first Classical Spar installed in the Gulf of Mexico (GOM). After 3 Classic Spar platforms, the 2nd generation Spar, i.e. the Truss Spar is favored by the oil company. The most different aspect between the Classic Spar and Truss Spar is the middle section. The Truss Spar discards the oil storage function and employs the space truss frame to replace the conventional middle section. Due to the decrease of steel use, the cost reduces obviously. In addition, some heave plates between hard and soft tanks are adopted to improve the hydrodynamic performance. The heave plates are used to attract added mass to shift the heave natural period higher than the wave period in order to minimize the response. Besides, due to the flow separation, the heave plates also excite the viscous damping to reduce the response amplitude. Heave plate has been proven to be an efficient device which is able to reduce the heave motion (Prislin *et al.*, 1998; Rho *et al.*, 2002; Srinivasan *et al.*, 2006). The 3rd generation Spar, i.e. cell Spar was first used in 2004, GOM. Cell Spar utilizes array columns of small dimension as the hard tank. The low fabricative difficulty, low cost and short construction period are the main advantages of the Cell Spar. There are many shipyards all over the world that can produce the small circular column. Therefore, the oil companies can choose the

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dock which is close to the installation site. However, the Cell Spar limits the topside weight and payload, and there is only one Cell Spar, i.e. Red Hawk which employs the wet tree system.

Through the comprehensive analysis and comparison between various types of platforms, a novel deep draft platform called Deep Draft Multi-Spar (DDMS) with easy fabrication, low cost, favorable motion performance and dry tree system available, *etc.* is proposed. In this paper, this new concept platform and the unique features are introduced firstly. Then, the conceptual design method is discussed and subsequently the detailed design steps, e.g. the main dimension estimation, stability analysis, mooring and riser configurations, *etc.* are exhibited and the structural parameters are confirmed and given. As we know that the seakeeping ability is the crucial issue for the floating platform. Thus, we emphasize the hydrodynamics and motion analysis for this novel concept, and the calculated methods, e.g. potential theory, Modified Morison Equation, catenary theory, *etc.* as well as the steps are illustrated distinctly. The wave exciting forces and the RAOs of DDMS platform are analyzed and specially compared with a typical Truss Spar. Finally, the extreme responses of DDMS platform under 3 different environment conditions are predicted through the traditional frequency domain approach.

## 2 Introduction of DDMS platform

Fig.1 shows the innovative DDMS platform concept. The hard tank of DDMS consists of four symmetrical spars with small diameter which are used to provide the buoyancy. One larger column locates at the center of the horizontal cross-section as a moonpool. The moonpool is able to make the top tension risers through it and protect the risers against the impact induced by wave and current. Especially, the buoyancy-can installed in the moonpool attaches the riser to provide the top tension which implies the increase of payload. Besides, the type of hydraulic-pressure riser can also be used here and the customers may decide whether to adopt the moonpool or not. The soft tank filled with high density liquid or metal locates at 40 m below the hard tank. There are four small circular columns to connect the hard tank and the ballast tank. The distance between the spars and soft tank should be adjusted to guarantee the adequate stability. This new concept makes the center of gravity (CG) below the center of buoyancy (CB). Therefore, The DDMS has good stability even under extreme condition. Though the draft of hard tank is very deep, even up to 146 m, we also consider employing heave plate to reduce the heave response more. In addition, another function for heave plate is to connect the five separate spars and provide the global lateral stiffness. Each heave plate is composed of four triangular sub-plates and spaced out with four horizontal beams. We also set the horizontal bracing and K-type beams at top of the spars to increase the lateral stiffness. The distance of the spars

depends on the topside dimensions requirement, oil and gas output, stability requirement, *etc.* The dimensions of spars and moonpool depend on the total displacement, buoyancy requirement, the riser configuration, *etc.* Therefore, the DDMS platform has good design flexibility to adapt to any requirement from customers. Similar to the Spar or SEMI platforms, DDMS employs mooring system to keep its position.

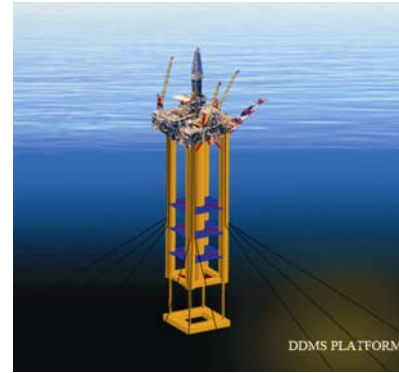


Fig.1 Sketch of DDMS Platform

## 3 Concept design of DDMS platform

The concept design of deep-water platform generally follows some principles. Firstly, buoyancy must balance the total weight including the platform structure, mooring system, risers system and any other vertical loading. Secondly, space available must equal or exceed the space required for the functions. Thirdly, the motion, station-keeping and stability must meet the minimum criteria (Chakrabarti, 2005). Based on the mentioned principles prior, the steps of conceptual design should include the functions and design requirement of platform, hull dimension estimation, weight estimation, topside arrangement, mooring, risers, loading, design computation and stability, *etc.*

The design of platform is an interactive work based on the integrated design steps (Almeida *et al.*, 2001; Schachter *et al.*, 2002; Grove *et al.*, 2003). When the initial design dimensions are established, the calculation of stability and hydrodynamic analysis can be done. If the calculated results don't meet the minimum requirement, the main dimensions, general arrangement or weight control have to be modified to meet the criteria. It should be noted that the checking calculations of stability and motion are two major focuses in the whole design process.

### 3.1 Main dimension estimation and general arrangement

In this section, we are going to confirm the main dimensions of DDMS platform. Firstly, the most important thing is to collect and understand the customer's requirements such as water depth, oil and gas output per day, payload, design working life, *etc.* Due to the conceptual design, we simply suppose that the design water depth, design reference period and payload requirement are 1 200 m, 100-y return period in GOM and 10 000 t respectively.

### 3.1.1 Hard tank

The main function of the four spars is providing sufficient buoyancy to counteract the vertical loading. Considering the total weight of DDMS, the total volume of the four spars is given. Generally considering the global performance and design experience of deep water platform, the four spars have the same shape and dimensions. The diameter of spars and the distance between them could be roughly estimated through consulting the existing TLP platforms at initial stage. The exact values may be acquired after the establishments of weight control and stability calculation. The length of moonpool equals to the other spars and the diameter depends on the riser quantity and configuration. Here, we arrange 9 slots for risers and make their buoyancy-cans go through the moonpool.

### 3.1.2 Pontoon

The four pontoons locate at the bottom of hard tank to connect the spars. The pontoons primarily provide the global stiffness of structure and meanwhile are considered as the variable ballasts in order to adjust the horizontal center of gravity. According to the experience of TLP platform design, the width and ratio of width and height of pontoon approximately equal to half of the spar diameter and 1.0 respectively. The length, width and height of pontoon in this case are 30 m×5 m×5 m.

### 3.1.3 Heave plate

Prislin *et al.* (1998) and Tao and Cai (2004) researched the hydrodynamic performance of heave plates via the scaled experiments and CFD numerical simulation, and some beneficial results and conclusions were released. In this case three heave plates are employed. Based on the former researcher's conclusions and recommendations, 0.7 m and 25 m for the thickness of heave plates and the vertical distance between the plates are adopted. The facade section and two cross-sections are shown in Figs.2 and 3.

### 3.1.4 Air gap

The air gap is an important parameter and primarily concerned with the wave slamming and green water. Besides, the sufficient air gap is able to avoid the flooding when DDMS inclines. As the conceptual design phase and according to Chou *et al.* (1983), the minimum operational air gap value can be simply estimated.

$$h_{ag} = 0.60H_w + 1.52 + 0.2\%W_D + H_{td} \quad (1)$$

where  $H_w$  and  $W_D$  denote the wave height and water depth. 1.52 m is accounted for a safety margin, and 2 m is considered for the tide height  $H_{td}$ . The calculated result in this case for air gap is 13.9 m, and finally 14.0 m for air gap is adopted.

### 3.1.5 Topside dimensions and arrangement

The design values of topside dimensions are 70m×70m×12m for length, width and height. The arrangement of DDMS

topside is similar to traditional TLP or SEMI platforms. The accommodations, helicopter deck and control room locate at the bow. Drilling tower locates at the center of deck, and the drilling quarters are defined at the portside near the drilling rig. The power supply such as turbo generators is defined at starboard. The astern side is located in the production plant. The cargo handing area and two cranes are located at the portside and starboard. It should be noted that the arrangement of the handing area must guarantee the safe operation. Fig.4 illustrates the topside arrangement of DDMS platform in this case.

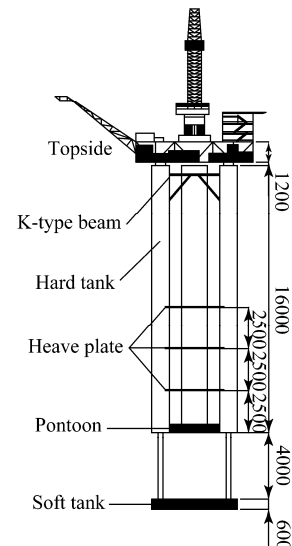


Fig.2 Sketch of facade section (unit: cm)

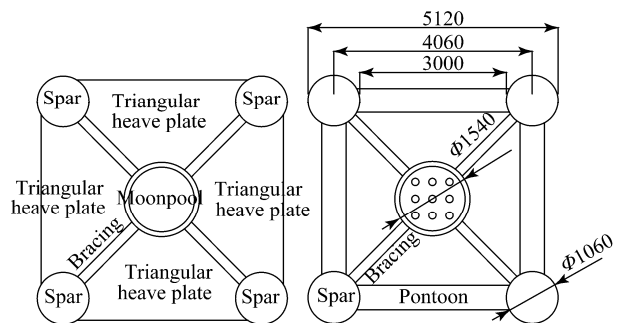


Fig.3 Sketch of cross-sections (unit: cm)

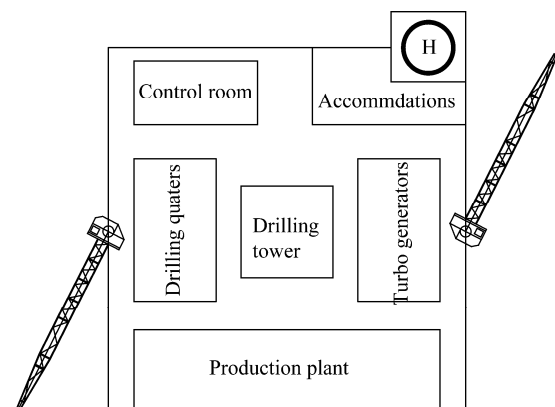


Fig.4 Topside arrangement

### 3.1.6 Weight estimation and distribution

The total weight of platform primarily comes from the topside structure, payload, weight of light ship, mooring, risers, ballasts, and so on. The weight distribution must be listed and prepared to determine the center of gravity. The general weight arrangement should keep the longitudinal and transverse centers of gravity (LCG, TCG) at the centerline. As the conceptual design, we suppose the LCG and TCG are located at the centerline already, and then all we need to do is to calculate the vertical center of gravity (VCG) by using some most important mass contributions (ignoring the weight of mooring and risers) of DDMS via an EXCEL spreadsheet. Table 1 represents the weight distribution, and  $H_{KG}$  is the distance between the keel and the center of gravity.

**Table 1 Weight distribution**

Items	Weight/t	$H_{KG}$ /m
Topside structure	7 730	210
Payload	10 000	210
Hard tank	21 570	126
Heave plate 1	1 000	121
Heave plate 2	1 000	96
Heave plate 3	1 000	71
Pontoons	750	48.5
Small columns	246.3	26
Soft tank and ballast	24 685.4	3
Total	67 982	97.89

**Table 2 Main dimensions and mass features**

Items	Value
Mass for surge/t	91 098
Mass for heave/t	67 982
Pitch radius of gyration/m	79.8
Distance of keel to $CG$ /m	97.89
Distance of keel to $CB$ /m	106.21
Diameter of spar/m	10.6
Length of spar/m	160
Diameter of moonpool/m	15.4
Distance between spars/m	40.6
Height of soft tank/m	6.0
Average draft/m	192.0

When the  $CG$  calculation is accomplished, the  $CB$  point should be fixed by using the respective volume and floating center of the submersed components. Finally some hydrostatic coefficients such as the water plane stiffness, Roll/pitch stiffness and some structural characteristic parameters, e.g. radius of gyration about  $X/Y$  axis are captured. Table 2 summarizes the main dimensions and mass characteristics, and  $H_{KB}$  denotes the distance between the keel and the center of buoyancy.

### 3.2 Stability analysis

The stability analysis is conducted according to the MODU CODE (American Bureau of Shipping, 2006). The wind

loading condition is for operating draft (192 m) and the platform is freely floating. For the intact and damaged stability, the recommended wind velocities are 51.4 m/s and 25.7 m/s respectively. The main purpose of stability analysis is to validate the structural dimensions. The wind incidence direction is  $45^\circ$  which is generally the worst case for intact condition. Table 3 and Table 4 summarize the results of intact and damage stability, and  $H_{GZ}$  and  $H_{WHL}$  represent the righting lever and wind heeling lever. As for the intact stability, the first intercept of righting moment and overturning moment curves is  $1.6^\circ$ , and the area ratio is more than 1.3 as well as all the  $H_{GZ}$  values are positive. Thus, the intact stability is satisfied. As for the damage stability, the first intercept is  $1.5^\circ$  which is less than  $17^\circ$ , and stability range is more than  $7^\circ$  as well as the value of maximum  $H_{GZ}$  divided by  $H_{WHL}$  is more than 2. Therefore, the damage stability is satisfied.

**Table 3 Intact stability**

Angles/( $^\circ$ )	0	5	10	20	30	40
$H_{GZ}$ /m	0	2.60	5.23	10.7	16.7	24
$H_{WHL}$ /m	1.00	1.03	1.03	1.11	1.08	0.95

**Table 4 Damage stability**

Angles/( $^\circ$ )	0	5	10	20	30	40
$H_{GZ}$ /m	-0.4	2.41	5.01	10.3	15.5	22.4
$H_{WHL}$ /m	0.41	0.44	0.45	0.54	0.49	0.39

### 3.3 Mooring configuration

The mooring system is usually used for station keeping of the floaters or ships such as SEMI and FPSO. The mooring lines primarily provide a certain horizontal restoring force to restrict the surge/sway offset. The DDMS employs 12 mooring lines which are shown in Fig.5 and marked with the number from 1 to 12 respectively. All of the lines are separated into 4 groups and symmetrically arranged on the four spars. Each group is  $90^\circ$  from another and the lines of each group are  $5^\circ$  azimuth spread. The fairleads are located near the position of VCG in order to avoid baneful moment induced by the mooring lines. Each line consists of a top chain section, a cable section and a seafloor chain section. The symmetrical mooring configuration is a typical arrangement, however the unsymmetrical configuration is also suitable for an installation site which is specified with the commonly direction of wind or current. One important principle of mooring design is the total restoring force must equal to zero at the initial equilibrium position. DDMS platform is a compliant floater with small horizontal restoring stiffness and the surge/sway natural period is usually at 150–300 s. The mooring restoring force is typically nonlinear and calculated by using the classical catenary theory in this paper.

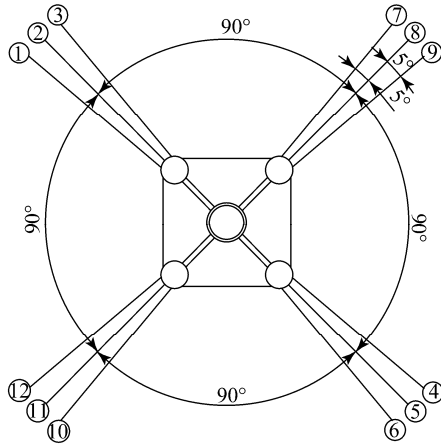


Fig.5 Mooring configuration

### 3.4 Riser configuration

The riser system for DDMS includes 1 drilling riser and 8 production risers and the catenary risers are also supported. All the vertical risers are top-tensioned which is provided by the buoyancy cans. The cross-section of moonpool is circular in this case, however the rectangular section can also be used and the dimensions depend on the quantity of risers. The diameter of moonpool is 15.4 m and the distance between well slots is 3.5 m. The riser arrangement is shown in Fig.6. The top-tensioned risers are restrained from lateral motion at keel and the buoyancy-cans are restrained by several guides.

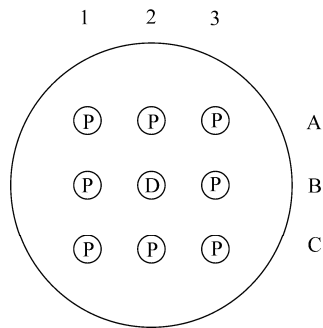


Fig.6 Riser arrangement

## 4 Hydrodynamic and motion models

Due to the large dimensional components of DDMS such as spars and moonpool, the high order boundary element method for diffraction and radiation and also the Modified Morison Equation are applied to predict the exciting forces and hydrodynamic coefficients. The motion equation for 3 degrees of freedom, i.e. surge, heave and pitch are established.

### 4.1 Potential theory model

The large dimensional components, e.g. spars, moonpool, pontoons, heave plates and soft tank disturb the motion of wave, and the potential theory is adopted to predict the

hydrodynamic information. The HODBEM is employed to integrate the hydrodynamic pressure along the wet surface to obtain the 1st order wave exciting forces, added mass and radiation damping.

$$F_j = \text{Re} \left[ i \int_s \rho \omega (\varphi_0 + \varphi_7) n_j ds e^{-i\omega t} \right]$$

$$i\omega a_{mn} + b_{mn} = i\rho \omega \int_s \varphi_n n_m ds \quad (j, m, n = 1, \dots, 6) \quad (2)$$

where  $F_j$ ,  $a_{mn}$  and  $b_{mn}$  are the 1st order wave exciting force, added mass and radiation damping respectively.  $\rho$ ,  $\omega$  and  $S$  are water density, wave frequency and wet surface.  $\varphi_0$ ,  $\varphi_7$ ,  $\varphi_n$  and  $n_m$  denote the incident potential, diffraction potential, radiation potential and normal vector. The computation of diffraction and radiation is solved by using WAFDUT which is developed by Dalian University of Technology (Li and Teng, 2002). The diffraction panel model in this case is shown in Fig.7.

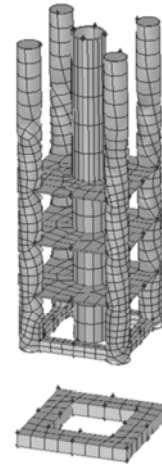


Fig.7 Diffraction panel model

### 4.2 Modified Morison equation

The hydrodynamic coefficients of small columns connecting the spars and the soft tank as well as the vertical viscous damping of heave plates are predicted by the modified Morison equation. The viscous damping of surge/sway has been proven to influence the amplitude motion, especially the resonant oscillation. Therefore, the viscous damping induced by motions of spars and moonpool is accounted by using the viscous item of Morison equation. The modified Morison equation for unit length is

$$dF = C_I \rho \frac{\pi D^2}{4} \dot{u} - C_a \rho \frac{\pi D^2}{4} \ddot{x} + \frac{1}{2} \rho C_d D (u - \dot{x}) |u - \dot{x}| \quad (3)$$

where  $C_I$ ,  $C_a$  and  $C_d$  are coefficients of inertia force, added mass and drag force respectively.  $u$ ,  $\dot{x}$ ,  $\ddot{x}$  and  $D$  express the surge velocity of wave particle, surge velocity, acceleration and the column diameter. The modified Morison equation considers the relative velocity in drag item. The viscous damping of heave plate is estimated by using the drag item of Morison equation for the thin plate

which is expressed below:

$$F_{hp} = \frac{1}{2} \rho C_d L^2 U |U| + \rho C_a L^3 \frac{\partial U}{\partial t} \quad (4)$$

where  $U$  and  $L$  are the vertical relative velocity of water particle and platform as well as the length of plate. The linear Airy wave theory is adopted to represent the velocity of water particle

$$\eta = \frac{H_w}{2} \cos(kx - \omega t) \quad (5)$$

$$u = \frac{gkH_w}{2\omega} \frac{\cosh k(y + W_D)}{\cosh kW_D} \cos(kx - \omega t) \quad (6)$$

$$v = \frac{gkH_w}{2\omega} \frac{\sinh k(y + W_D)}{\cosh kW_D} \sin(kx - \omega t) \quad (7)$$

where  $\eta$ ,  $v$  and  $k$  are the wave elevation, vertical velocities and wave number respectively. The wave number is determined by the dispersion equation  $\omega^2 = gk \tanh(kW_D)$ .

### 4.3 Classic catenary theory

The classic catenary theory is a simple and common method for mooring lines based on the static analysis as shown in Fig.8. This theory supposes the anchor point is always free and with no uplift. Considering the in-line force  $F_{il}$  and transverse force  $D_{iv}$ , we have the formulas below:

$$dT_m - \rho g A_m dz = [w \sin \varphi - F_{il} (T_m / E_m A_m)] ds \quad (8)$$

$$T_m d\varphi - \rho g A_m z d\varphi = [w \cos \varphi + D_{iv} (1 + T_m / E_m A_m)] ds \quad (9)$$

where  $T_m$ ,  $w$ ,  $E_m$ ,  $A_m$  and  $\varphi$  denote the line tension, wet weight per unit length, elastic modulus, cross-sectional area, horizontal angle respectively. Ignoring the forces  $F_{il}$  and  $D_{iv}$  with elasticity allows simplification of the equations. The suspended line length  $s$  is delivered below

$$s = (T_H / w) \sinh(wx / T_H) \quad (10)$$

where  $T_H$  denotes the horizontal component of tension.

The resultant tension  $T_m$  and  $T_H$  in the line at the top are

$$T_m = w(s^2 + d_m^2) / 2d_m, \quad T_H = T_m \cos \varphi \quad (11)$$

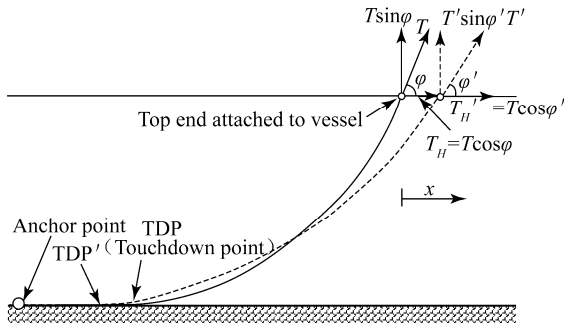


Fig.8 Diffraction panel model

Firstly, the offset-restoring force curves as shown in Fig.9 for each mooring line are calculated. Then the

offset-restoring force curve of the mooring system is obtained as shown in Fig.10. Finally the curve of offset and restoring force is inputted into the motion calculation. The Fig.10 clearly reflects the nonlinear effect of mooring system. When we need to increase or decrease the horizontal stiffness, the quantity of mooring lines or wet weight could be adjusted.

### 4.4 Numerical motion equations

The DDMS platform is considered as a floating rigid body of 3 characteristic degrees of freedom, i.e. the surge, heave and pitch. The wave exciting forces, hydrodynamic coefficients, hydrostatic coefficients, mass, restoring forces, etc. are inputted into the motion equations.

The surge motion equation

$$M\ddot{x} + m_x\ddot{x} + m_{x\theta}\ddot{\theta} + b_{rx}\dot{x} + b_{rx\theta}\dot{\theta} + R(x) + b_{vx}U_x|U_x| = F_x \quad (12)$$

where  $M$ ,  $m_x$ ,  $m_{x\theta}$ ,  $b_{rx}$ ,  $b_{rx\theta}$  and  $b_{vx}$  are mass of platform, added mass of surge, added mass of surge due to pitch, radiation damping for surge, radiation damping for surge due to pitch and surge viscous damping coefficient.  $x$ ,  $U_x$ ,  $R(x)$  and  $F_x$  represent the surge displacement, relative velocity for surge, restoring force, wave exciting force.

The heave motion equation

$$M\ddot{y} + m_y\ddot{y} + b_{ry}\dot{y} + C_y y + b_{vy}U_y|U_y| = F_y \quad (13)$$

where  $C_y$  denotes the water plane stiffness for heave. The other parameters are similar to that of surge.

The pitch motion equation

$$I\ddot{\theta} + m_\theta\ddot{\theta} + m_{\theta x}\ddot{x} + b_{r\theta}\dot{\theta} + b_{r\theta x}\dot{x} + C_\theta\theta + b_{v\theta}U_\theta|U_\theta| = M_\theta \quad (14)$$

where  $I = Mr^2$  and  $C_\theta$  denote the moment of inertia and hydrostatic restoring stiffness for pitch. The symbol  $r$  is the pitch radius of gyration. The other parameters are similar to that of surge.

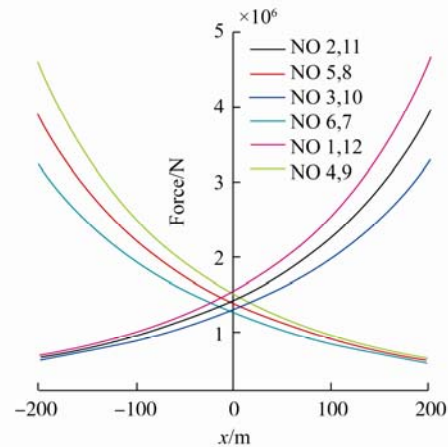


Fig.9 Offset-restoring force curves of mooring lines

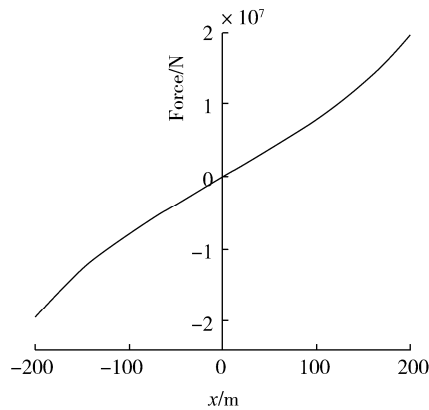


Fig.10 Offset-restoring force curve of mooring system

## 5 Hydrodynamic and motion analysis

Due to the conceptual design stage of DDMS, this paper is primarily concerned with the 1st order wave exciting. By the numerical iteration method (Li and Ou, 2009), the RAOs for surge, heave and pitch are obtained and compared with a typical Truss Spar platform. Table 5 summarizes the main parameters of the Truss Spar. The JONSWAP spectra for 3 extreme conditions are adopted to calculate the random responses of DDMS in different sea area. The wave incident directions are  $0^\circ$  and  $45^\circ$  respectively.

### 5.1 Exciting force spectra

Fig.11 shows the 1st order wave exciting force spectra, and the corresponding environment parameters for GOM are shown in Table 7. The pitch moment spectra are not given here because of the similar trend with surge. The results reveal that the smaller surge exciting force of DDMS compared with the one of Truss Spar may bring some benefits for structure strength. The main reason is the configuration of hard tank composed of 4 spars effectively decreases the acting area. Because the wave surge force of  $0^\circ$  is larger than that of  $45^\circ$  as shown in Fig.11, the RAOs and other calculated results later depend on  $0^\circ$  incident wave only. The quite deep draft of DDMS determines the smaller heave exciting force obviously compared with the Truss Spar as shown in Fig.12. It is an important improvement compared with the platform of similar cross-section such as the SEMI and TLP.

Table 5 Feature parameters of Truss Spar

Items	Value
Diameter of hard tank/m	40
Height of hard tank/m	75
Total mass/t	98132
Topside mass/t	22000
Radius of gyration/m	91.7
Average draft/m	231.8

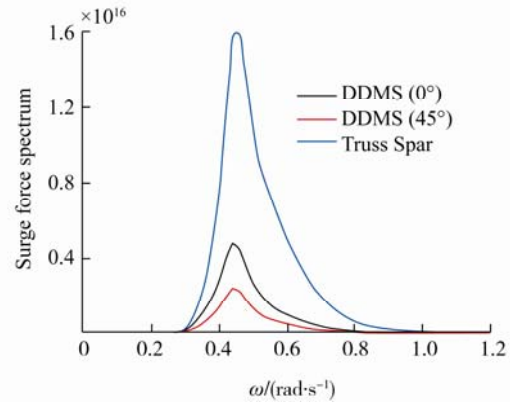


Fig.11 Surge force spectra

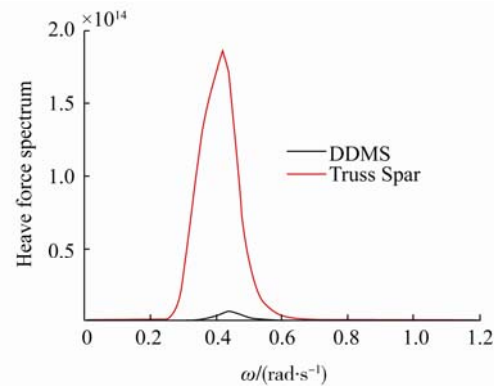


Fig.12 Heave force spectra

### 5.2 Response amplitude operators

The RAOs of surge, heave and pitch are shown in Figs.13–15. The surge RAO is smaller in the whole frequency range due to the smaller exciting force. The curve is softly varied and retains low in W-F range, which indicates the favorable seakeeping ability. It is noted that the viscous damping doesn't affect the surge motion obviously at W-F range except the range around the natural period, which is very important for the slow drift motion. The pitch RAO reveals the similar conclusions with surge. It is noted that the coupled effect for surge and pitch motions is very weak. The heave RAO of DDMS obviously shows the smaller response compared with that of Truss Spar because of the lower exciting force and benefits from the heave plates. It also means that the dry tree system is available due to the small heave motion. Because the heave natural period is higher than the wave period, the heave RAO also varies smoothly. The natural periods of surge, heave and pitch are summarized in Table 6.

Table 6 Natural periods of DDMS /s

Surge	Heave	Pitch
314	28.5	66.1



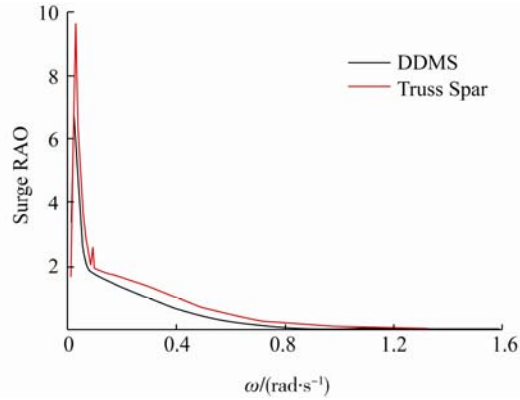


Fig.13 Surge RAOs

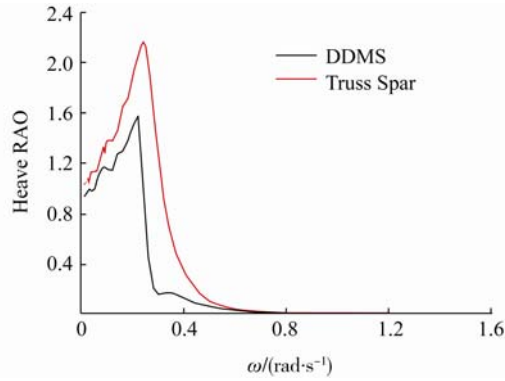


Fig.14 Heave RAOs

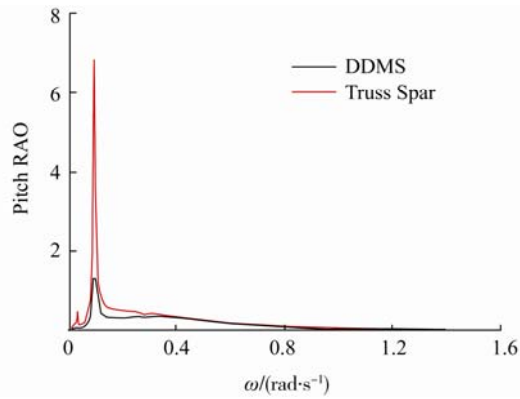


Fig.15 Pitch RAOs

### 5.3 Random responses

The random wave theory is commonly used to represent the real ocean condition. In order to validate the adaptability of DDMS for different sea areas, 3 extreme sea conditions marked A–C are selected and subsequently the maximal response, standard deviation, mean period are captured. Table 7 shows the details of the environment conditions, and  $H_s$ ,  $T_p$  and  $\gamma$  are significant wave height, peak period and peak parameter respectively.

Table 7 Extreme environment conditions

Cases	$H_s$ /m	$T_p$ /s	$\gamma$
A: 100-y return period in GOM	12.3	14.2	2
B: Swell wave in West Africa	1.7	25.0	6
C: South China sea (typhoon)	13.3	15.5	2.8

As an exhibition, the surge, heave and pitch response spectra for condition C are shown in Figs.16–18. Table 8 summarizes all the statistical results. The calculated results clearly reveal the perfect motion performance for extreme environments of different sea areas. Especially for condition B with the extremely long wave period which is close to the heave natural period, the maximal peak value is also well controlled. However, the maximal heave response of Truss Spar for condition B is 2.60 m (Li and Ou, 2009).

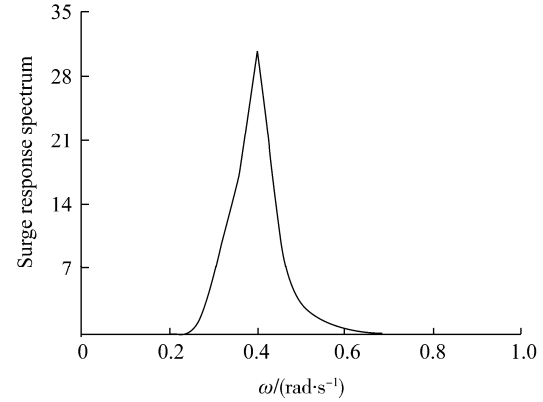


Fig.16 Surge response spectrum

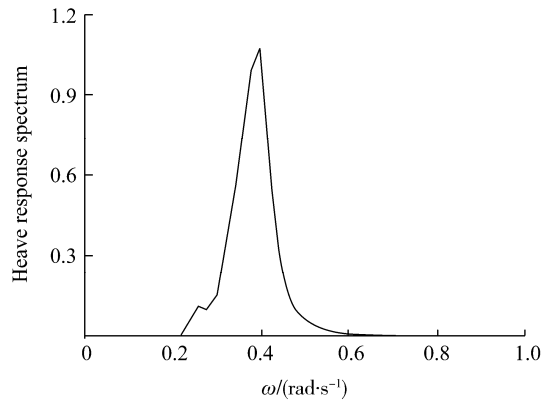


Fig.17 Heave response spectrum

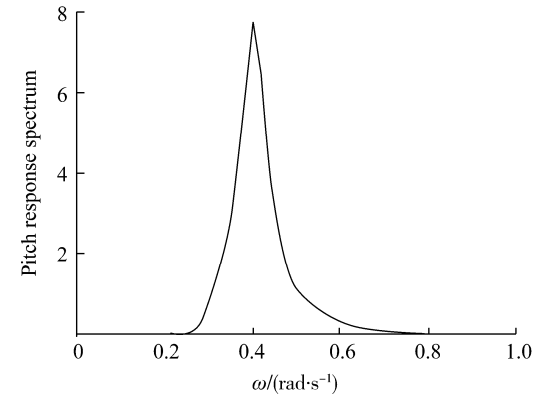


Fig.18 Pitch response spectrum



**Table 8 Random response statistics**

Items	Degree of freedom	A	B	C
Standard deviation	Surge/m	1.41	0.45	1.81
	Heave/m	0.24	0.31	0.33
	Pitch/(°)	0.013	0.0024	0.016
Mean period	Surge/s	14.5	24.0	15.6
	Heave/s	15.3	27.1	16.3
	Pitch/s	13.76	22.1	14.83
Max response	Surge/m	5.34	1.65	6.85
	Heave/m	0.89	1.13	1.23
	Pitch/(°)	2.87	0.5	3.44

## 6 Conclusions

This paper introduces a novel deep draft platform, i.e. Deep Draft Multi-Spar which integrates the advantages of Truss Spar, SEMI and TLP. The detailed concept design, the hydrodynamics and the motion performance are exhibited, calculated and analyzed. The hydrodynamic model taking account of the potential theory and modified Morison equation as well as the viscous damping effect is established and detailedly described. The RAOs of DDMS platform are acquired and analyzed. The motion predicting for 3 different extreme conditions are also executed. Finally, we draw some conclusions as bellow:

1) The DDMS platform is perfectly optimized for low fabricative difficulty, low cost, large topside area, dry tree system available, flexible design and favorable motion performance for different environmental conditions.

2) The comparison of exciting force between the DDMS and Truss Spar indicates that the lower hydrodynamic loading may benefit the structural strength for DDMS.

3) Owing to the deep draft of hard tank and the employment of heave plate, the peak heave response is very small. Besides, the trends of RAO curves of surge and pitch are similar to that of Truss Spar; however the values are smaller in the entire frequency range. The calculated results for 3 extreme sea conditions distinctly reflect the excellent adaptability of DDMS.

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