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Numerical Study on Hydrodynamic Behavior of Deepwater Spar Platform with Different Mooring Configurations

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Abstract. The motion performance of Spar platform and dynamic characteristics for the mooring lines under different mooring configurations have been studied both in static analysis and coupled dynamic analysis. First, 3D hydrodynamic finite element model is built and the effects of the mooring system are taken into account by giving the specified pre-tension, angle and stiffness of the mooring lines on the fairleads. And hydrodynamic analysis of Spar platform is performed by the way of utilizing potential flow theory in frequency domain in order to calculate the hydrodynamic coefficients. Then, static analysis is applied to obtain restoring stiffness curves for the mooring system, structure displacements and mooring line tensions etc.. At last, coupled time domain analysis of the motion response of Spar is conducted for the coupled system and the dynamic tensions of mooring lines are calculated. The research results can be served as a reference for the selection and the performance study for mooring systems during preliminary design.

Introduction

In the exploitation of deepwater and extra-deepwater oil and gas, all kinds of floating platforms play more and more important role. Spar platform is one of the good engineering practices in deepwater oil exploitation which has deep draft, low center of gravity, low sensitivity to water depth, low cost, excellent protection to the risers connected, excellent stability and motion performance in harsh environment. Spar is located to the specified water area by mooring system which has a low natural frequency. The slowly varying low frequency wave, wind and current force can induce the platform to make long distance low frequency drift motion and the wave frequency force and current can make big geometric alteration and transverse drag loads to the mooring lines. All of the loads applied can cause strong dynamic response of the mooring system. So it is very necessary and important to study the motion behavior of the mooring system and deepwater Spar platforms.

The mooring system for a deepwater platform is usually composed of several multiple-segment mooring lines. Considering structure motion, hydrodynamic load and seabed friction, the dynamic analysis for mooring system is very complicated. Tong bo[1] studies the dynamic characteristics of catenary mooring system for the deepwater semi-submerged platform and presents the effect of its length, diameter and pretension angle on the dynamic characteristics of the mooring lines. Chen xu jun[2] derives equations of the restoring roll moment and yaw moment of a mooring system theoretically and analyzes the uncertainty of the value and direction of the restoring roll moment.

T.M.Smith[3] finds that as the displacement of floating structure increases, restoring forces of mooring system with mooring lines included angel from 22.5 degree to 67.5 degree shows excellent directon stability. Xiao yue[4] calculates the response function of a moored FPSO under the finite water depth by the method in which the FPSO motion is coupled with the mooring system in the frequency domain. Per. I. Johansson[5] builds a finite model to study on dynamic characteristics of mooring system considering damping, displacement of floating structure and other nonlinear effects, which can be used in transient analysis. Mark A. Grosenbaug [6]presents an experience model to describe the dynamic tension at the top of a mooring line induced by its vertical motion which takes the coupled effect of inertia and damping into consideration.

Configuration of mooring lines is an important parameter in the preliminary design of deepwater mooring system which has great influence to platform motion and dynamic behavior of mooring system. This paper studies on the motion performance of deepwater spar mooring platform by the way of static analysis and dynamic analysis and analyzes the impact on the motion behavior and dynamic characteristics of mooring system from different mooring lines configurations. First, 3D hydrodynamic finite element model is built and the effects of the mooring system are taken into account by giving the specified pre-tension, angle and stiffness of the mooring lines on the fairleads. And hydrodynamic analysis of Spar platform is performed by the way of utilizing potential flow theory in frequency domain in order to calculate the hydrodynamic coefficients. Then, static analysis is applied to obtain restoring stiffness curves for the mooring system, structure displacements and mooring line tensions etc.. At last, coupled time domain analysis[7] of the motion response of Spar is conducted for the coupled system and the dynamic tensions of mooring lines are calculated. Meaningful conclusions can be made form the static and dynamic analysis results.

Main structure

Main dimension of hull. A truss Spar is studied in this paper which includes a top cylinder hard tank, a bottom cylinder soft tank and intermediate structures connecting the hard tank and the soft tank with three heave plates. Table 1 shows the main dimension of the Truss Spar.

Table 1 Main dimension of the Truss Spar

Overall length	169.16 [m]
Design draft	153.924 [m]
Distance from center of buoyancy to keel	107.69 [m]
Distance from center of gravity to keel	90.39 [m]
Total displacement	56400 [t]
Weight of top modules	4037 [t]
Diameter of hard tank	32.31 [m]
Length of hard tank	68.88 [m]
Radius of roll	60.96 [m]
Radius of pitch	60.96 [m]
Radius of yaw	12.50 [m]

Configuration of mooring lines. There are nine mooring lines for the half-taut catenary mooring system. The mooring line is a combination of steel chain, steel wire and steel chain. The nine mooring lines are divided into three groups with three lines in each. The angle between each group is 120 degree and the included line angle between two lines in every line group is variable which is

5 degree, 10 degree and 15 degree for mooring systems 1, 2 and 3 respectively. All the mooring lines are 2409.9 meters long with the fairleads located on the hull 50 meters below the sea level and the anchor points located at a horizontal distance of 1800 meters from the hull. Motion performance of Spar and dynamic characteristics of mooring lines are calculated. Figure 1 shows the configuration for the three different mooring systems and table 2 shows the property of mooring lines.

Table 2 Property of mooring line

Items	Unit	Steel chain(near fairleads)	Steel wire	Steel chain(near seabed)
Length	[m]	82.3	2252.3	77.3
Diameter	[cm]	14.61	12.7	14.61
Dry weight	[kg/m]	402.4	77.45	402.4
Wet weight	[kg/m]	385.63	64.79	385.63
Minimum break load	[kN]	18909	14012	18909
Axial stiffness	[kN]	1592267	148348	1592267

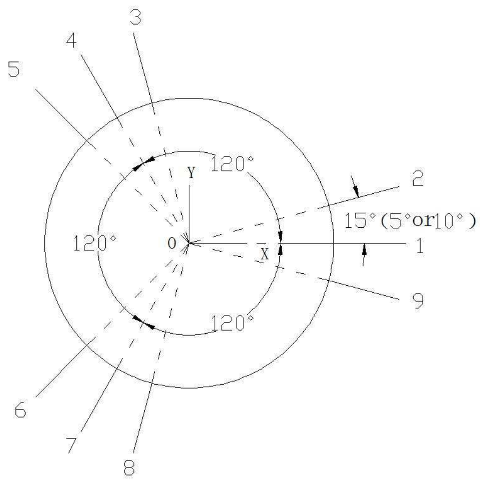

Fig. 1 Configuration for three mooring systems

Basic Theory

Potential flow theory. In ocean engineering field, for a large scale structure with small amplitude motion in wave field, the total wave load acting on structure is the superimposition of wave diffraction load and radiation load.

Potential flow theory is the most commonly used method to calculate wave force on wet surface of floating structures. In potential flow theory, the assumption is made that the velocity potential meets Laplace equation and four kinds of boundary conditions which are the free surface condition, seabed condition, structure wet surface condition and radiation conditions. According to Laplace equations and the boundary conditions, the velocity potential can be uniquely determined, and then pressure on the wet surface can be calculated according to the Bernoulli formula. Total velocity potential in the flow field should include contributions from the incident wave, flow field perturbation from existence of floating body and motion of floating body.

$$\Phi = \Phi_R + \Phi_D, \Phi_R = i\omega \sum_{j=1,6} \xi_j \Phi_j, \Phi_D = \Phi_0 + \Phi_7. \tag{1}$$

Where Φ is the total velocity potential; ξ_j is the motion amplitude of floating structure for six degree s of freedom; Φ_j is unit radiation velocity potential; Φ_0 is incident velocity potential and Φ_7 is unit diffraction velocity potential.

Radiation velocity potential and diffraction velocity potential meet wet surface boundary condition which is

$$\Phi_{jn} = n_j, \Phi_{Dn} = 0. \tag{2}$$

Selecting the free surface source potential as the Green function, the total velocity potential can be obtained by solving the boundary conditions using Green theorem, and the wave force and moment acting on the structure can be gained from the surface pressure distribution.

Motion equation. Motion equation of spar platform including the influence of mooring system is

$$[M+\mu]\{\ddot{x}\}+[\lambda]\{\dot{x}\}+[K]\{x\}=F^{fk}+F^{d}+F^{w}+F^{c}+F^{m}. \tag{3}$$

Where $[M]$ is generalized mass matrix of floating structure; $[\mu]$, $[\lambda]$ and $[K]$ is added mass matrix, damping matrix and restoring stiffness matrix respectively; $\{\ddot{x}\}$, $\{\dot{x}\}$ and $\{x\}$ is generalized acceleration matrix, generalized velocity matrix and generalized displacement matrix; F^{fk} is Froude force; F^{d} is wave diffraction force; F^{w} is wind force; F^{c} is current force; F^{m} is mooring force.

Considering the nonlinear effect of environmental loads and mooring forces, parameters used in time domain analysis are transformed from frequency domain analysis by FFT. Motion equation in time domain is

$$[M+\mu]\{\ddot{x}\}+\int_{-\infty}^{t}[K(t-\tau)]\{\dot{x}\}d\tau+[K]\{x\}=F^{fk}+F^{d}+F^{w}+F^{c}+F^{m}+F^{sd}. \tag{4}$$

Where $K(t-\tau)$ is retardation function, F^{sd} is second order drift force, other parameters refers to Eq. 3.

Hydrodynamic model

The hydrodynamic model of Spar platform is built, as shown in figure 2. The mass distribution of Spar is determined by defining the location of center of gravity and radius of gyration. The origin of Cartesian coordinate system lies at the bottom of the platform with the center of gravity at (0,0,91) and the center of buoyancy at (0,0,108).

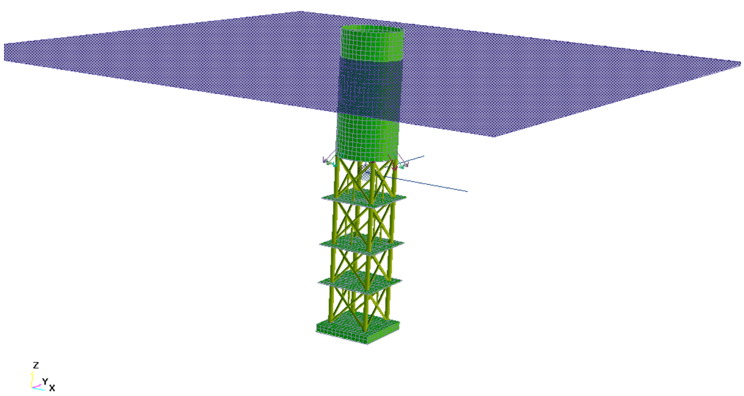

Fig. 2 Hydrodynamic model of Spar

Water depth for Spar platform's service site is 1645 meter. The density for seawater is 1025 kg/m^3 and the gravity acceleration is 9.8m/s^2. Considering symmetry of the Spar platform, the regular waves with incident directions of 0 degree, 30 degree and 90 degree and wave periods from

4 seconds to 35 seconds with an interval of 1 second are chosen. The calculation results, such as motion response amplitude operator (RAO), added mass, potential damping and wave force can be obtained, which will be used in the following static and dynamic analysis.

Static analysis

Environmental condition. The marine environmental condition chosen for static analysis is extreme storm with return period of 100 years, see as table 3.

Table 3 Marine environmental condition

Wave：jonswap spectrum		Wind：NPD spectrum			Current：profile flow		
Significant wave height	12.3[m]	Surface friction factor		0.02	Current profile	At surface	0.926[m/s]
Spectrum period	14.6[s]	Wind profile	Velocity	51.2[m/s]		At -260[m]	0.926[m/s]
			Reference height	10[m]		At -914[m]	0.491[m/s]
Shape factor	2		Profile exponent	0.11		At -1653.54[m]	0.091[m/s]

Analysis results. According to catenary theory and finite element method, static analysis is done considering five different wave incident angles which are 0°,45°,90°,135° and 180°. Surge and sway restoring stiffness curves are calculated under giving marine environmental condition, see figure 3 and 4. Table 4 shows the static analysis results and figure 6 shows extreme tension of line 5 in mooring system 1 under 0 degree incident wave angle.

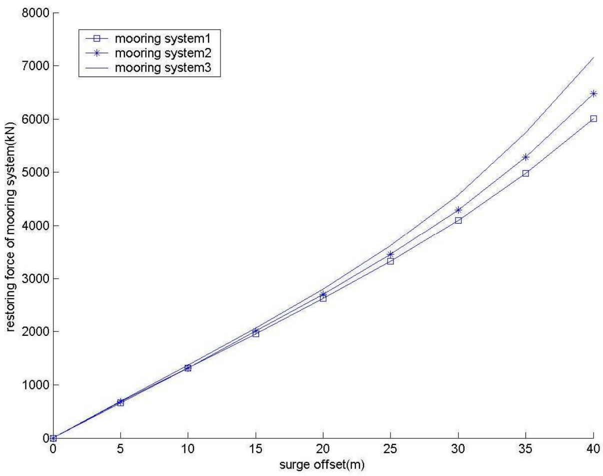

Fig. 3 Surge restoring stiffness curve of three mooring systems

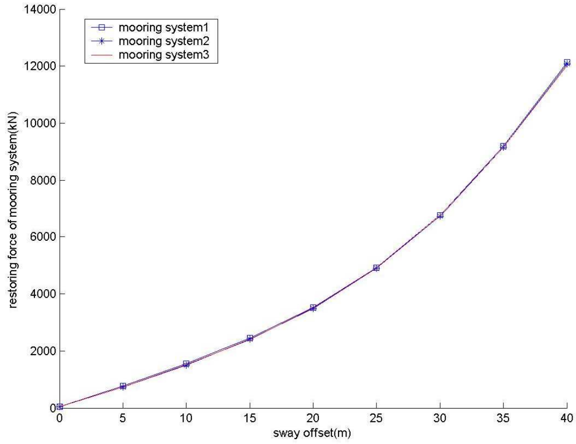

Fig. 4 Sway restoring stiffness curve of three mooring systems

Table 4 Static analysis result of three mooring systems

	Mooring system1		Mooring system 2		Mooring system3	
Direction	Spar displacement[m]	Extreme tension[kN] /line number	Spar displacement[m]	Extreme tension[kN] /line number	Spar displacement[m]	Extreme tension[kN] /line number
0°	36.06	4610/5#	34.57	4784/5#,6#	32.84	4946/5#,6#
45°	23.48	4651/6#	23.26	4756/6#	23.06	4835/6#
90°	30.75	4952/8#	30.07	5197/8#	29.00	5359/8#
135°	27.41	4552/9#	28.39	4777/9#	29.14	4927/9#
180°	22.30	4768/1#	22.49	4798/1#	22.85	4858/1#

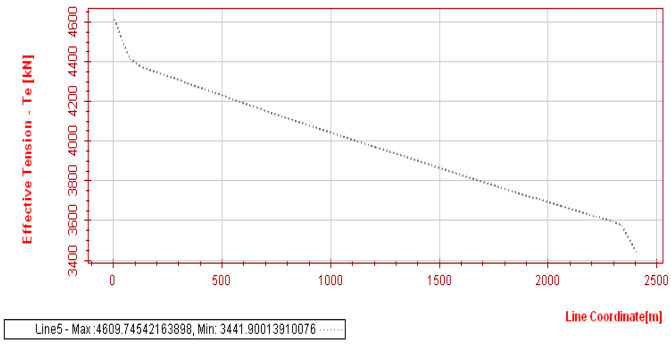

Fig. 5 Extreme tension of line 5 in mooring system 1 under 0 degree incident wave angle

According to figure 3 and 4, sway restoring stiffness is larger than surge restoring stiffness for all the three mooring systems. As the included line angle increases, surge restoring stiffness of mooring system increases but sway restoring stiffness remains the same. From figure 5, we can know that the line tension reaches its maximum at fairlead and decreases as water depth increases. There are two inflection points for the line tension at the connection points between steel chain and steel wire. The static characteristics fit for all the nine mooring lines.

From table 4 we can know that the line number of maximum tension changes as incident load direction changes. Generally speaking, the tension of the line facing the wave is much bigger than the lines back the wave. For three mooring systems, the numbers for the lines which has maximum tension are the same and as the included angle increases, the maximum line tension increases under the same marine environmental condition.

Coupled dynamic analysis

Because the water is very deep, dynamic effect of mooring lines gets very large. It becomes very important to take viscous effect, inertia mass, current force and restoring force of mooring system into considerations in the analysis of predicting the spar motion response. Response of spar platform and mooring system should be calculated together as a coupled dynamic system which means solving the equations constituted of dynamic characteristics of mooring system and rigid body motion of spar at six degree of freedoms at the same time.

The overall coupled model for spar and mooring system is built, see figure 6. In dynamic analysis, the tangential drag coefficient for steel chain and steel wire is 2.45 and 1.2 respectively, and tangential added mass coefficient for steel chain and steel wire is 2 and 1 respectively. Numerical simulation in time domain for the coupled system has been conducted for three hours with interval of 0.2 second under extreme storm environmental conditions.

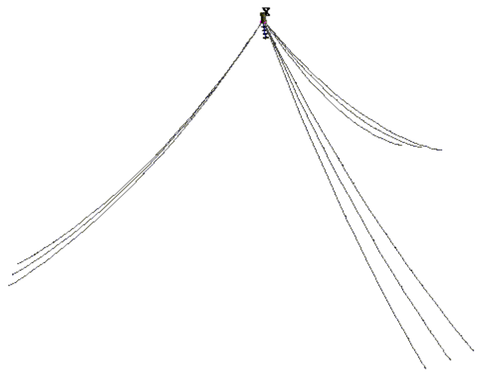

Fig. 6 Coupled model for spar platform and mooring system

Spar motion response. Spar motion response of six degree of freedoms has been obtained after coupled dynamic analysis. Figure 7 and 8 shows extreme response values for surge and sway respectively for three mooring systems.

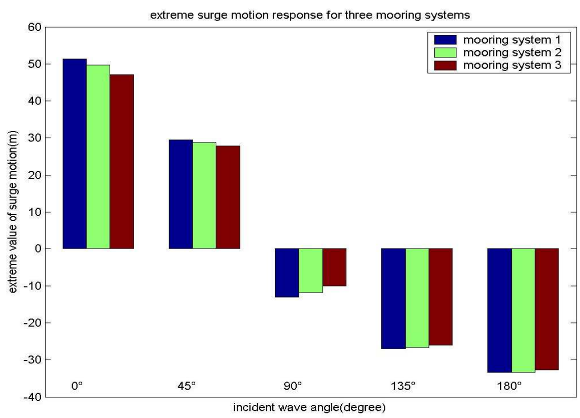

Fig. 7 Extreme response for surge motion

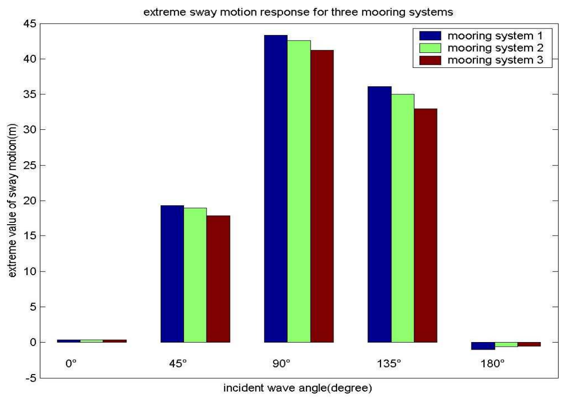

Fig. 8 Extreme response for sway motion

From above we can find that as the included line angle between each two lines increases, extreme values for surge and sway response of spar platform decrease, which means the resistance ability for the environmental load increases. The result is in accordance with the static analysis.

Line tension. Table 6 and figure 9 are mooring line extreme tension results for all the three mooring systems.

Table 6 Extreme tension of mooring lines

	Mooring system1		Mooring system 2		Mooring system3	
Direction	Line tension	Line number	Line tension	Line number	Line tension	Line number
0°	7163 [kN]	5	7630 [kN]	5	8020[kN]	5
45°	8500 [kN]	6	8686 [kN]	6	8773 [kN]	6
90°	8726 [kN]	8	9154 [kN]	8	9402 [kN]	8
135°	7640 [kN]	9	8101 [kN]	9	8409 [kN]	9
180°	8877 [kN]	1	8948 [kN]	1	8983 [kN]	1

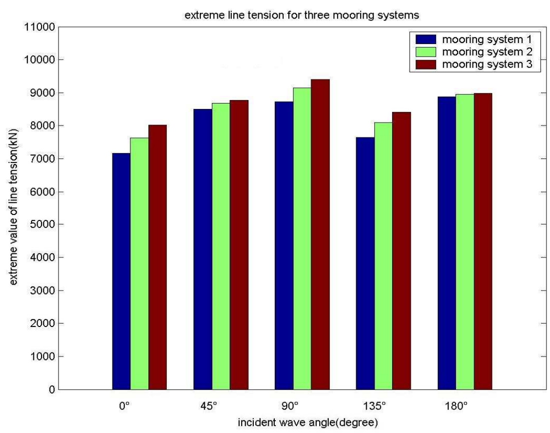

Fig. 9 Extreme tension of mooring lines

From table 6 and figure 9, we can find that the number for the line with maximum dynamic tension under the same wave incident angle for the three mooring systems is the same and the maximum dynamic tension increases as included line angle increases. For all the five environmental load incident directions, the extreme line tensions differences are 0.80% to 6.5% for mooring system 1 and mooring system 2, 0.39% to 5.1% for mooring system 2 and mooring system 3, and 1.19% to 12.0% for mooring system 1 and mooring system 3.

The results of motion response of spar and extreme tension of mooring lines show that as the included line angle gets bigger, the motion of the spar platform gets smaller, however the extreme tension of lines gets bigger.

Conclusions

Motion response of spar and dynamic characteristics of mooring systems with different configurations have been studied by static and coupled dynamic analysis, and the following conclusions can be made:

1) Static analysis results show that all the mooring lines have the same static tension characteristics. For the three mooring systems, as the included line angle increases, surge restoring stiffness for mooring system increases and sway restoring stiffness remains the same. As the included line angle between increases, the maximum line tension increases under the same marine environmental condition.

2) Dynamic analysis results show that all the mooring lines have the same dynamic tension characteristics. For the three mooring systems, as the included line angle increases, motion response of spar decreases, however the maximum line dynamic tension increases. And extreme dynamic tension difference between mooring system 1 and 3 is the biggest.

3) After comprehensive comparison of motion response of spar platform and dynamic characteristic of mooring systems from static and dynamic analysis, the conclusion can be made that mooring system 1 with included line angle of 5 degree has the best motion behavior because its motion response is close to the other two systems but its dynamic characteristic of mooring system is much better than the other two.

Acknowledgements

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