Design, implementation and analysis of full coupled monitoring system of FPSO with soft yoke mooring system

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Abstract

Due to the complexity of the marine environment loading and motions of vessels, many uncertainties are involved in the design of mooring systems. This paper designs a fully monitoring system, including meteorological-environmental and mechanical aspects. The environmental monitoring system is composed of current, wave and wind equipments. Fiber Bragg Gauges/ FBG, incline sensors and GPS/INS form the mechanical monitoring system. On the basis of dynamic characteristic of the soft yoke system, a restore force measurement method has been proposed according to the response of the angular information of the soft yoke. The monitoring system has been installed on one FPSO in Bohai Bay, and comprehensive monitoring information has been obtained from 2011. The calculation of the restoration force of the mooring system by the present dynamic method shows high agreements with that of the FBG. The vessel motions in the frequency domain calculated by the measured wave spectrum multiplied by the designed RAO (Response Amplitude Operator) are compared with the in-site monitoring motions. The results of comparisons show the feasibility of the present monitoring system in safety assessments of FPSO and SYMs.

Keywords: monitoring; FPSO; soft yoke mooring system; data processing; RAO

Nomenclatures

M,C,K	Mass, damping and stiffness matrix	u_1, u_2	Generalized velocities in Kane dynamic method
x	Displacement vector	φ_1, φ_2	Angles of yoke and mooring leg, as shown in Fig. 4
F	Environmental force vector	u_v, u_h	Vertical and horizontal movement velocities
σ	$\sigma(z) = 0.15V(z)(z/z_s)^{-0.125}$	X_v, X_h	Vertical and horizontal displacement shown in Fig. 4
F	$F = f / f_p$	$m_i, (i = 1, 2, 3)$	Mass of yoke counter weight and mooring leg
$s_{API}(f)$	API wind spectral energy density at frequency f	$L_i, (i = 1, 2, \dots, 5)$	Characteristic lengths of mooring system
f	Frequency (Hz)	F'_h, F'_v	Nodal force of vertical and horizontal directions of upper mooring leg
z	Height above waterline	F_h, F_v	Nodal force in vertical and horizontal directions of yoke nose
z_s	Thickness of the surface layer at 20m	$\bar{v}_i, (i = 1, 2, 3)$	Centroid velocities of rigid bodies of SYMs
f_p	$f_p = 0.025V(z) / z$	$\bar{\omega}_i, (i = 1, 2, 3)$	Angular velocities of rigid bodies of SYMs
F_{xc}, F_{yc}, M_{xyc}	Tangential, lateral current force and yawing moment of current loading	$\bar{v}_i^{(1)}, \bar{v}_i^{(2)} (i = 1, 2, 3)$	Partial velocities

ρ_c	Density of sea water	$\omega_i^{-(1)}, \omega_i^{-(2)}$ ($i = 1, 2, 3$)	Partial angular velocities
C_{xc}, C_{yc}, C_{xyc}	Parameters with current force	$\bar{F}_i^*, (i = 1, 2, 3)$	Global forces of SYMs
φ_{CR}		$\bar{M}_i^*, (i = 1, 2, 3)$	Global moments of SYMs
d	Mean drift parameter	$J_i, (i = 1, 2, 3)$	Moments of inertia of yoke, counter weight and mooring leg
B	Width of vessel	F_1, F_2	Generalized driving force
V_{CR}	Current velocity with specific profile	F_1^*, F_2^*	Generalized inertia force
S_y	Spectral density of vessel motions	α, β	Coefficients for mooring restoring force
S_ξ	Spectral density of wave	L_{PP}	Length parameter related to current force
F_{rest}	Global restoring force of SYMs		

Introduction

In recent years, the safety and reliability of offshore structural systems subjected to hurricanes has increasingly attracted greater attention. In deep waters, such as the Gulf of Mexico and South China Sea, many platforms have been damaged by hurricane and uncorrected operations[1]; while in shallow waters, such as the Bohai Bay, some FPSOs which were fixed by single point mooring systems (SPMs) have also been damaged during in storm or even under ordinary operation[2]. In view of these accidents, the lack of offshore standards in the design phase and model testing are major factors in offshore engineering. Soft yoke mooring systems (SYMs)[3, 4], as one of the best types of single point mooring systems, are widely used in the Bohai Bay for connecting FPSOs and fixed platforms.

Typically, SYMs are composed of a counter weight, mooring legs, an “A”-frame structure, a yoke nose etc. (as shown in Fig. 1.)

Insert Figure 1

In most cases, the conceptual design of SYMs in certain sea states is performed with the aid of commercial software. The meteorological-oceanographical environmental loading and hydrodynamic parameters of the FPSO are the most fundamental and important indexes. Static and dynamic analyses are conducted with concurrent environmental forces applied in certain directions in which it has been decided the FPSO will restore force. The results of these analyses are then checked against API 2SK [5] or other similar guidelines. The final design was dictated by meeting all the mooring objectives and pertinent regulations in API 2SK, as well as minimizing price. However, due to the non-linearity of the soft yoke system, thorough model testing with certain scale rate should be performed to investigate the hydrodynamic abilities. Typically, static testing is performed to verify the excursion characteristics and decay behavior of the FPSO with SYMs. Next, a series of dynamic tests is performed within the defined wind, current and irregular wave state [6]. Due to the complexity of oceanographical conditions and the limitation of reduced scaling effect in laboratory conditions, in model testing it is difficult to obtain all of design parameters with a high degree of accuracy. Therefore, the traditional numerical analysis and model testing cannot meet all requirements of the design of offshore structure. Furthermore, there are more than ten hinges in the soft yoke mooring system. The multi-body dynamic system, composed of a multi-hinge-connection mode, causes difficulties when making the numerical simulation in the commercial hydrodynamic analysis, and the determination of the failure mode of SYMs remains a challenge. Recently, some accidents involving SYMs have still occurred in the Bohai Bay.

Monitoring technology, as an advantage tool, is widely used in civil engineering[7]. Proto-type measurements based on monitoring systems for offshore structures may collect useful information through advanced monitoring technology. The data obtained by the in-site measurement strategy can then be used to study mechanical properties and design indexes of offshore structures, and propose the improvement to the calculation of hydrodynamic analysis and model testing.

Different from proto-type monitoring of civil structure, there have been few in-site monitoring projects developed with an international scope. Masuda et. al.[8] performed the early-warning research of vessel planar motions of single point mooring system. The hydrodynamic force subject to small angle current is estimated via from the slender body theory. Simos et. al. [9] discussed the dynamic characteristic of internal turret single point system with tandem offloading operation by neural network algorithm. Sun LP. et. al. [10] analyzed the safety behavior of FPSO by FTA (Fault Tree Analysis) and FMEA (Failure Mode and Effect Analysis) during crude transfer and fire events. Moan et. al. [11] reviewed the safety design method of FPSO via limit state function. failure mode of FPSO are analyzed by risk assessment method and accident index. Lotsberg[12] performed the monitoring JIP to address the fatigue design standards on FPSO. Van den Boom et al.[13] established another JIP with a 22-month period to obtain fatigue load information through long period measurements. Zhiqiang Hu et al.[14] measured the six degrees of freedom for “Fenjin” FPSO, to analyze special motion behavior subject to wind and current.

In the present paper, a proto-type monitoring system is developed and implemented for FPSO with SYMs in the Bohai Bay, based on the analysis of mechanical properties and characteristic of structure of SYMs. The full-scale monitoring system is composed of three subsystems, i.e. a meteorological-oceanographical monitoring system including wave, wind and current gauges; motions of an FPSO monitoring system mainly composed of GPS/INS; and a motions and restore force monitoring system composed of FBG and incline sensors. Currently, the present monitoring system has been installed in one FPSO in the Bohai Bay. Massive data have been gained and recorded in storage for the deep analysis of the design verification and safety assessment.

The motions of the vessel are illustrated by the measured wave spectrum multiplied by the designed RAO of FPSO in the frequency domain. The spectral analysis of the monitoring motion data of the vessel are also performed and compared to those of the calculated ones. Strong agreements can be observed to verify the correctness of the present floating motions monitoring system. Restorative forces of SYMs have been compared between the present dynamic method and direct measurement by FBG, and the consistency of the comparison shows the feasibility and reliability of the present monitoring system for SYMs.

2 Soft yoke mooring system of FPSO

The soft yoke mooring system is designed and constructed to moor the FPSO to the jacket platform in shallow water. The standard SYMs are traditionally composed of two mooring legs, two counterweight ballasts, an “A”-frame structure (YOKE), a fixed jacket, and a frame connected with the FPSO, as shown in Fig. 1.

Two universal joints (respectively marked as X1 and X2) are installed at the upper and lower ends of the mooring leg, to release the relative roll and pitch motions. There are two thrust bearings assembled at each of the mooring legs near the upper articulation to release the torsional degree of freedom. The “A”-frame structure, together with the counterweight ballasts, is suspended between the mooring legs and fixed jacket. The antifreeze inside the large counterweight ballast provides the restoring force to limit the FPSO to a certain position. There is a roller bearing (marked as X4) connecting the “A”-frame structure to the fixed jacket, which allows the pitch and roll motions of the “A”-frame structure to the fixed jacket. Finally, a swivel stack (marked as X3) is arranged in the fixed jacket to achieve the weathervane ability of the FPSO. Table 1 presents the motion-released states of all the joints marked from X1 to X4, where X, Y and Z are the translational degrees of freedom, and R1, R2 and R3 are the rotational degrees of freedom.

Insert table 1

The above joint-connection modes and restoring force mode by counterweight ballasts exhibit the strong weathervane effect of the FPSO. The FPSO may be positioned in the direction of the composition forces of wind, wave and current. Furthermore, SYMs provide their advantageous ability to be used and maintained in the sea ice zone of the Bohai Bay. Typically, the FPSO with SYMs can be hypothesized as the spring-mass mechanical model shown in Fig. 2:

insert figure 2

The governing equations for describing the kinematic mechanisms of FPSO and SYMs can be summarized as follows:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \quad (1)$$

where $\mathbf{M}$ is the mass matrix (real mass and added mass) of FPSO, $\mathbf{C}$ the damping matrix,

$\mathbf{K}$ the stiffness matrix, $\mathbf{x}$ is the displacement vector of FPSO, and $\mathbf{F}$ is the environmental forces caused by wind, wave and current. The environmental loading and six degrees of freedom of the FPSO serve the major roles in the design and operation of the single point mooring system.

3 Proto-type monitoring system of SYMs

On the basis of the design criteria of the mooring system in API 2SK, combined with the hydrodynamic simulation and model testing, the present proto-type monitoring system is consistent with the following three subsystems: meteorological-oceanographical environmental loading monitoring system; motions and attitudes monitoring system of FPSO; and restoration force monitoring system of SYMs.

3.1 Meteorological -oceanographical environmental loading monitoring system

Similar to most offshore structures, oceanographical environmental loading which is caused by marine meteorology and hydrology consists of the main external loading conditions of FPSO and SYMs.

The guidance on actual values to be used in design refer to API guidance [5] and meteorological and oceanographic numerical models. In general the design response should be based on the jointly distributed environmental phenomena. Environmental data, such as wind, wave, current and tide have site-specific relationships governing their interactions. So the hydrology factor is composed of wind parameters (speed and direction), air temperature, relative wet, gas pressure, current parameters, wave, water temperature, salinity etc.. Among these, the loading parameters of wind, current and wave are the major factors influencing the design and mechanical characteristics of the mooring system. Of particular importance are the wind speed/direction, wave height/period, and wave/current relationships and their relative directions. The present oceanographical environmental monitoring system includes wind load factor, current load factor and wave load factor

- Wind monitoring

As indicated in API 2SK[5], maximum operating condition is defined as the combination of maximum wind ,waves and current. Wind load is one of the most important load cases for the section above the waterline of a platform structure. The wind loads for the design of the

platform should be determined using one of the following procedures [5, 15].

Method 1: Wind is treated as a constant in terms of direction and speed, taken as the 1-minute average.

Method 2: Fluctuating wind is modeled and considered by a steady component based on the 1-hour average velocity plus a time-varying component calculated from a suitable empirical wind gust spectrum. The recommended wind gust spectrum $S(f)$ in offshore engineering is taken from the Appendix B in API 2SK[5], and expressed as follows:

$$S_{API}(f) = \frac{\sigma^2(z)}{f} \bullet \frac{F}{(1+1.5F)^{5/3}} \quad (2)$$

in which $F = f/f_p$, $f_p = 0.025V(z)/z$, $\sigma(z) = 0.15V(z)(z/z_s)^{-0.125}$, f frequency of fluctuating wind, $V(z)$ is the 1-hour mean wind speed at elevation z m above the waterline, and z_s is the thickness of the "surface layer" and is always equal to 20 m.

If the location of the wind gauge is chosen, then the wind speed and wind direction are the main monitoring parameters for the wind load monitoring. By analyzing the standard wind spectrum, a sampling frequency of 1 Hz satisfied the requirement of the data processing. Considering the relationship of the motions of the FPSO and wind load, the relative wind direction to the FPSO bow should be decided and collected in the wind monitoring system.

- Wave monitoring

Waves play important roles in the designs of moorings and vessels in offshore structures. In offshore engineering, the spectrum density analysis method of irregular waves is always utilized and adopted. The standard spectrum density matrix shows the energy distribution state of harmonic waves and expresses the main affection of the essential wave frequency.

The proto-type wave spectrum from the wave load monitoring provides a direct method for the response calculation of the platform system. Wave height, wave period and wave direction should be recorded and further summarized to the standard wave spectrum (P-M or JONSWAP spectrum). In recent years, Acoustic Doppler Current Profile (ADCP)[16, 17], wave radar, and so on are often utilized in proto-type measurement.

- Current monitoring

Current is the most essential factor in the design of underwater structures, such as pontoons, risers and mooring systems. The following equation[15] can be used to determine

the current force of the platform under the water line:

$$\begin{cases} F_{xc} = \frac{1}{2} d C_{xc}(\varphi_{cR}) \rho_c V_{cR}^2 B \\ F_{yc} = \frac{1}{2} d C_{yc}(\varphi_{cR}) \rho_c V_{cR}^2 L_{pp} \\ M_{xyc} = \frac{1}{2} d C_{xyc}(\varphi_{cR}) \rho_c V_{cR}^2 L_{pp}^2 \end{cases} \quad (3)$$

where ρ_c is the density of sea water kg/m^3 ; F_{xc} , F_{yc} and M_{xyc} are the tangential, lateral force and yawing moment, respectively; $C_{xc}(\varphi_{cR})$, $C_{yc}(\varphi_{cR})$ and $C_{xyc}(\varphi_{cR})$ are the parameters respectively related to F_{xc} , F_{yc} and M_{xyc} ; d is the mean drift; B is the width of the vessel; and V_{cR} is the current velocity with the full profile of the vessel, L_{pp} length parameter related to current force.

In Eq. (3), the current speed and current direction in the different water layers are the key factors for the calculation of current force. ADCP[5, 16] provides high accuracy and resolution for the multi-profile measurement of currents.

3.2 Motion monitoring system of FPSO vessel

Under the oceanographical environmental force, the FPSO exhibits complex motions. As shown in Fig. 3, three translational degrees of freedom (sway, surge and heave) and three rotational ones (roll, pitch and yaw) are often treated as the main unknown variations in hydrodynamic numerical simulations.

Insert figure 3

GPS, as the most common monitoring technique, is often utilized to measure the variations of the positions. Traditional GPS provides a low accuracy for measuring the positions and displacements of ocean floaters. The real-time kinematic (RTK) technique, that is, a base is located in a jacket and a move is built in the FPSO, should be adopted to enhance the data precision. In the RTK mode, measurements of the phase of the signal's carrier wave are used rather than the initial signal content, and it relies on a single reference station to provide real-time corrections, providing accuracy up to cm level[18].

For the measurement of attitudes, the inclinometer, gyroscopes, inertial navigation system (INS) etc. are used widely in engineering aspects. Typically, the inclinometer shows

strong advantages in measuring static or quasi static inclination. The rotational motions (roll, pitch and yaw) of the FPSO subject to wave and wind loads show the dynamic characteristic. INS, which includes three gyros and three accelerometers, proposes advantageous abilities to continuously calculate via dead reckoning the position, orientation, and velocity of FPSO, without the need for external references. A summarized table is present in the following to show the vessel motions and related sensors used in motion monitoring system of FPSO vessel.

Insert table 2

3.3 Restoration force monitoring system of SYMs

The restoration force is the essential design index for a mooring system. For an in-site FPSO, it is difficult or forbidden to install the direct pressure/tensile sensors on the mooring structure. Traditionally, FBGs or strain gauges are always installed on industrial equipment to measure the stress variations, but to the author's knowledge, the above sensor cannot provide long-term reliability for marine structures, due to the harsh ocean environment.

In the next section, a dynamic algorithm of the restoration force of a mooring system is presented for SYMs, on the basis of the Kane dynamic method[19].

Insert figure 4

As shown in Fig. 4, two generalized velocities are defined as $u_1 = \dot{\varphi}_1$ and $u_2 = \dot{\varphi}_2$, and the positive direction is defined as the increase of the angles of φ_1 and φ_2 . $u_v = \dot{X}_v$ is the vertical movement velocity and positive is defined as the upward direction. $u_h = \dot{X}_h$ is the horizontal movement velocity, and the positive direction is pointed to the right. m_1, m_2, m_3 are the weights of the yoke, counter weight and mooring leg, respectively.

For the considered configuration of SYMs, we set the following geometrical boundary conditions:

$$\begin{cases} X_h = \cos \varphi_1 \cdot L_4 + \sin \varphi_2 \cdot L_5 \\ X_v = \cos \varphi_2 \cdot L_5 - \sin \varphi_1 \cdot L_4 \end{cases} \quad (4)$$

where L_4, L_5 are the respective lengths of the yoke and mooring leg.

The global equilibrium equations for entire SYM system are simply expressed in the horizontal and vertical directions.

$$\begin{cases} F_h = F'_h \\ F_v + F'_v = (m_1 + m_2 + m_3)g \end{cases} \quad (5)$$

According to the moment equilibrium theory, the moment balance relations for point ‘O’ in Fig. 4 are established and expressed as follows:

$$\begin{cases} m_2 g(L_4 - L_2) \cos \varphi_1 + m_1 g(L_4 - L_1) \cos \varphi_1 + F'_h L_4 \sin \varphi_1 = F'_v L_4 \cos \varphi_1 \\ m_3 g(L_5 - L_3) \sin \varphi_2 + F_h L_5 \cos \varphi_2 = F_v L_5 \sin \varphi_2 \end{cases} \quad (6)$$

where L_1 is the distance from point ‘O’ to the gravity center of the yoke, L_2 is the distance from point ‘O’ to the gravity center of the ballista, and $L_2 = L_5 / 2$.

By applying the mathematical derivatives (time-domain differentiation) to Eq. (4), we can obtain the velocity boundary conditions in the rate form:

$$\begin{cases} L_5 u_2 \cos \varphi_2 - L_4 u_1 \sin \varphi_1 = u_h \\ L_5 u_2 \sin \varphi_2 + L_4 u_1 \cos \varphi_1 = -u_v \end{cases} \quad (7)$$

It may then be easily observed that φ_1 and φ_2 are independent of each other. Therefore, u_1 and u_2 are treated as individual variables, and u_h and u_v are expressed as the functions of u_1 and u_2 .

Next, the centroid velocity $\bar{v}_1, \bar{v}_2, \bar{v}_3$ and angular velocity $\bar{\omega}_1, \bar{\omega}_2, \bar{\omega}_3$ can be written by using the generalized velocity (u_1, u_2) , as follows:

$$\begin{cases} \bar{v}_1 = -L_1 u_1 (\sin \varphi_1 \bar{i} + \cos \varphi_1 \bar{j}) \\ \bar{v}_2 = -L_2 u_1 (\sin \varphi_1 \bar{i} + \cos \varphi_1 \bar{j}) \\ \bar{v}_3 = (u_h - L_3 u_2 \cos \varphi_2) \bar{i} + (u_v + L_3 u_2 \sin \varphi_2) \bar{j} \\ \bar{\omega}_1 = -u_1 \bar{k} \\ \bar{\omega}_2 = -u_1 \bar{k} \\ \bar{\omega}_3 = -u_2 \bar{k} \end{cases} \quad (8)$$

Defining the conceptions of partial velocity and partial angular velocity relative to u_1

as $\bar{v}_i^{(1)} = \frac{\partial \bar{v}_i}{\partial u_1}, (i=1, 2, 3), \bar{\omega}_i^{(1)} = \frac{\partial \bar{\omega}_i}{\partial u_1}, (i=1, 2, 3)$, we then obtain

$$\left\{ \begin{array}{l} \overline{v}_1^{(1)} = -L_1 (\sin \varphi_1 \bar{i} + \cos \varphi_1 \bar{j}) \\ \overline{v}_2^{(1)} = -L_2 (\sin \varphi_1 \bar{i} + \cos \varphi_1 \bar{j}) \\ \overline{v}_3^{(1)} = -L_4 \sin \varphi_1 \bar{i} - L_4 \cos \varphi_1 \bar{j} \\ \overline{\omega}_1^{(1)} = -\bar{k} \\ \overline{\omega}_2^{(1)} = -\bar{k} \\ \overline{\omega}_3^{(1)} = 0 \end{array} \right. \quad (9)$$

Similarly, we can also obtain the partial velocity $\overline{v}_i^{(2)} = \frac{\partial v_i}{\partial u_2}, (i=1,2,3)$ and partial angular velocity $\overline{\omega}_i^{(2)} = \frac{\partial \omega_i}{\partial u_2}, (i=1,2,3)$ relative to u_2

Assuming J_1, J_2, J_3 are the moments of the inertia of yoke, counter weight and mooring leg, respectively, the external forces of the whole SYMs are written as

$$\left\{ \begin{array}{l} \overline{F}_1 = -m_1 g \bar{j} \\ \overline{F}_2 = -m_2 g \bar{j} \\ \overline{F}_3 = F_h \bar{i} + (F_v - m_3 g) \bar{j} \\ \overline{M}_1 = 0 \\ \overline{M}_2 = 0 \\ \overline{M}_3 = (L_3 \sin \varphi_2 F_v - L_3 \cos \varphi_2 F_h) \bar{k} \end{array} \right. \quad (10)$$

The global inertial forces are written as

$$\left\{ \begin{array}{l} \overline{F}_1^* = m_1 L_1 \left[(\dot{u}_1 \sin \varphi_1 + u_1^2 \cos \varphi_1) \bar{i} + (\dot{u}_1 \cos \varphi_1 - u_1^2 \sin \varphi_1) \bar{j} \right] \\ \overline{F}_2^* = m_2 L_2 \left[(\dot{u}_1 \sin \varphi_1 + u_1^2 \cos \varphi_1) \bar{i} + (\dot{u}_1 \cos \varphi_1 - u_1^2 \sin \varphi_1) \bar{j} \right] \\ \overline{F}_3^* = (-m_3 \dot{u}_h + m_3 L_3 \dot{u}_2 \cos \varphi_2 - m_3 L_3 u_2^2 \sin \varphi_2) \bar{i} - (m_3 \dot{u}_v + m_3 L_3 \dot{u}_2 \sin \varphi_2 + m_3 L_3 u_2^2 \cos \varphi_2) \bar{j} \\ \overline{M}_1^* = J_1 \dot{u}_1 \bar{k} \\ \overline{M}_2^* = J_2 \dot{u}_1 \bar{k} \\ \overline{M}_3^* = J_3 \dot{u}_2 \bar{k} \end{array} \right. \quad (11)$$

Combining Eqs. (8)-(10), we can obtain the global equation for the whole dynamic system of SYMs, as follows:

$$\begin{cases} F_1 = \overline{F}_1 \cdot \overline{v}_1^{(1)} + \overline{F}_2 \cdot \overline{v}_2^{(1)} + \overline{F}_3 \cdot \overline{v}_3^{(1)} + \overline{M}_1 \cdot \overline{\omega}_1^{(1)} + \overline{M}_2 \cdot \overline{\omega}_2^{(1)} + \overline{M}_3 \cdot \overline{\omega}_3^{(1)} \\ F_1^* = \overline{F}_1^* \cdot \overline{v}_1^{(1)} + \overline{F}_2^* \cdot \overline{v}_2^{(1)} + \overline{F}_3^* \cdot \overline{v}_3^{(1)} + \overline{M}_1^* \cdot \overline{\omega}_1^{(1)} + \overline{M}_2^* \cdot \overline{\omega}_2^{(1)} + \overline{M}_3^* \cdot \overline{\omega}_3^{(1)} \\ F_2 = \overline{F}_1 \cdot \overline{v}_1^{(2)} + \overline{F}_2 \cdot \overline{v}_2^{(2)} + \overline{F}_3 \cdot \overline{v}_3^{(2)} + \overline{M}_1 \cdot \overline{\omega}_1^{(2)} + \overline{M}_2 \cdot \overline{\omega}_2^{(2)} + \overline{M}_3 \cdot \overline{\omega}_3^{(2)} \\ \overline{F}_2^* = \overline{F}_1^* \cdot \overline{v}_1^{(2)} + \overline{F}_2^* \cdot \overline{v}_2^{(2)} + \overline{F}_3^* \cdot \overline{v}_3^{(2)} + \overline{M}_1^* \cdot \overline{\omega}_1^{(2)} + \overline{M}_2^* \cdot \overline{\omega}_2^{(2)} + \overline{M}_3^* \cdot \overline{\omega}_3^{(2)} \end{cases} \quad (12)$$

Substituting Eq. (10) in to global balance relation $\begin{cases} F_1 + F_1^* = 0 \\ F_2 + F_2^* = 0 \end{cases}$, the horizontal

restoring force of mooring system F_h and restoring force in the vertical direction F_v can be finally obtained in the following form

$$F_h = \left(\frac{\alpha}{\cos \varphi_1} - \frac{\beta}{\sin \varphi_2} \right) / (\cot \varphi_2 + \tan \varphi_1) \quad (13)$$

$$F_v = (\alpha - \sin \varphi_1 \cdot F_h) / \cos \varphi_1 \quad (14)$$

The global restoring force of mooring system F_{rest} is obtained as $F_{rest} = \sqrt{F_h^2 + F_v^2}$.
in which

$$\begin{aligned} \alpha \cdot L_4 = & (m_1 L_1 + m_2 L_2) g \cos \varphi_1 + m_3 g L_4 \cos \varphi_1 - m_1 L_1^2 \dot{u}_1 - m_2 L_2^2 \dot{u}_1 - J_1 \dot{u}_1 - J_2 \dot{u}_1 \\ & + m_3 \dot{u}_2 L_3 L_4 \sin(\varphi_2 - \varphi_1) + m_3 u_2^2 L_3 L_4 \cos(\varphi_2 - \varphi_1) + m_3 \dot{u}_h L_4 \sin \varphi_1 + m_3 \dot{u}_v L_4 \cos \varphi_1 \end{aligned} \quad (15)$$

$$\beta = [m_3 (L_3 \dot{u}_2 - \dot{u}_h \cos \varphi_2 + \dot{u}_v \sin \varphi_2) + m_3 g \sin \varphi_2] \cdot (L_5 - L_3) / L_5 - J_3 \dot{u}_2 / L_5 \quad (16)$$

Observing Eqs. (13) and (14), the restoring force F_h F_v can be gained as the function of φ_1 , φ_2 and $u_1, u_2, \dot{u}_1, \dot{u}_2$. $F_h = f(\varphi_1, \varphi_2, u_1, u_2, \dot{u}_1, \dot{u}_2)$ And $u_1, u_2, \dot{u}_1, \dot{u}_2$ are the function of φ_1, φ_2 .

Therefore, the restoring force monitoring system for SYMs can be developed and composed by the angular and its velocity information of the yoke and mooring leg.

The above Kane dynamic method exhibits the advantages in the calculation of mooring restoring force. With difference to the classical Laplace dynamic method, there is no kinetic function in the present dynamic method and the complicated derivation process is avoided in the process of solving mooring force. The final expressions of global horizontal and vertical

restoring force (F_h and F_v) are easy to be implement and displayed at the integrated monitoring system. But it need to be noted that the present algorithm is a 2D rigid-body dynamic method. Mooring legs, ballista, and yoke are assumed as rigid bodies without considering the elastic deformations. The 3D characteristics of SYMs including the inconsistency of motions of two mooring legs, the heave and pitch motions of yoke and the torsion degree along the axial direction of mooring legs are neglected in the formula derivation of dynamic algorithm. The follow up research should focus on the affections of above assumptions.

4 Integrated monitoring system and implementation on FPSO in the Bohai Bay

The monitoring activities were distributed in three monitoring systems (as shown in Fig. 5), namely:

- Meteorological -oceanographic monitoring system
- Position and motions monitoring system
- Restoring force and position of SYMs monitoring system

Insert table 3

Insert figure 5

Full sensors are installed (as present in Table 3 and shown in Fig. 6) in one FPSO in the Bohai Bay and monitored continuously. The global measurement information is presented in numerals, graphics and screens by an integrated monitoring system, as shown in Fig. 7, which was developed in C++.

Insert figure 6-7

5 Monitoring Data Processing and Discussions

5.1 Motion verification of FPSO vessel

RAO (response amplitude operator), as the basic concept in offshore engineering, describes the intrinsic dynamic characteristics of floaters, and is used to evaluate the floaters' response subject to wave loads.

Typically, for the irregular disturbance of waves or wind, the spectral density $S_y(\omega)$ of motion is equal to the RAO multiplied with the input spectral density of $S_\xi(\omega)$, i.e. [6].

$$S_y(\omega) = S_\xi(\omega) \times RAO \quad (17)$$

Therefore, we can make the comparison of the response of FPSO motions between calculated results from Eq. (17) and data monitored by INS and GPS. The monitoring data of FPSO is chosen by the wave direction of 45 degrees relative to the FPSO bow. The FPSO is in its full load state at this time.

Figs. 8(a-c) respectively present the PSD (power spectrum density) of the roll, pitch and heave of the FPSO obtained by INS and GPS. Three curves calculated by Eq. (17) are also shown with blue lines in these same figures. The PSD of low-frequency surge motions of FPSO is present in Fig. (8-d) measured by GPS and calculated by Eq(17).

Insert figure 8

The comparison shows that the above analysis method succeeded to simulate the wave-induced vessel motions. It is noted that the monitoring data show good approximate results to those of the calculated ones in the frequency domain. It is observed that roll pitch motions of calculated is a little bit greater than that of measurement ones. That is because the wave direction is fixed with 45° in calculation cases. But the in-field actual wave direction changes with time during the record periods. The measured heave data which is obtained by RTK GPS is related to the position of base and move. In actual, the move is not easy to be installed in the gravity center of vessel. So affections of roll and pitch bring the error of heave motions and increase the heave amplitude in frequency domain. On the other side, low-frequency motion, such as surge of FPSO, shows the relative difference in the amplitude between measurement and calculated one. That proves the influence of wind and current on the low frequency response of FPSO is significant.

5.2 Restore force verification of SYMs

The Kane dynamic algorithm described in this section is derived on the basis of the 2D SYMs model. The frictions of the hinges are neglected.

In order to verify the errors for the numerical algorithm of restoring force from the above hypothesis, FBG gauges were installed on two mooring legs for short term measurements. The layout of the FBG gauges on the mooring legs is presented in Fig. 9.

Insert figure 9

Two typical sea states are selected to verify the feasibility of the Kane method to the monitoring data of the FBG gauges. The characteristic parameters of the

meteorological-environmental factors and extreme values of FPSO and SYMS are presented in Table 4.

Insert table 4

Insert figure 10-11

Figs. 10 and 11 present the results of the restorative force calculated by the Kane dynamic method and that measured by FBG in two cases. High consistency can be observed to be in present the figures for both the ordinary sea state and harsh sea state. This proves the reliability and effectiveness of the present dynamic method, on the basis of the measurements of angle and angular velocity. The present dynamic method has been implemented into the integrated monitoring system. The restoring force together with the environmental parameters can be displayed to ensure the safety of the operators.

6 Conclusions

In this study, a global integrated monitoring system for soft yoke mooring systems was developed and constructed on a FPSO in the Bohai Bay.

1) The global monitoring system was composed by three parts: the meteorological-oceanographical monitoring system, position and motions monitoring system of FPSO, and restorative force monitoring system for SYMs.

2) At present, more than two years of monitoring data have been collected and recorded. Two types of analysis and verifications have been performed: motions analysis of FPSO by RAO multiplied with wave spectrum, and restorative force verification between the Kane dynamic method and FBG gauges.

3) The good consistency illustrated in data analysis of restore force and vessel motions show the validation and feasibility of the present monitoring system in the safety assessment of FPSO with SYMs.

7 Challenges and future prospects

Single mooring system is one of the major equipment of offshore engineering. The soft

yoke mooring system play the important role for the position-keeping of FPSO especially in cold region. The present monitoring system is composed by three monitoring subsystems. Several challenges and future prospects also need to be improved and further investigated.

The multi-hinge connection mode signifies that SYMs is the new concept floating position-keeping structure. It brings challenges and difficulties in the design process by classical hydrodynamic numerical modeling due to the of flexible-rigid multi-body characteristic. The state-of-the-art monitoring techniques for different kind of hinges of SYMs should be developed and implement to obtain the fatigue and wear behavior.

Secondly, The Independent Remote Monitoring System (IRMS) should be pay enough attention to establish in the global integration system. The motions of FPSO together SYMs can be recorded during harsh weather. The monitoring information can be observed, gained and recorded by remote technique.

Finally, A data base should be established to record all the monitoring data and events in detailed in order for performing risk assessments of FPSO and SYMs with long-term statistical information.

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Fig. 1 Structural configuration of soft yoke mooring system

Fig. 2 Simplified mechanical model of soft yoke mooring system with FPSO

Fig. 3 Definition of six degrees of freedom for FPSO hull

Fig. 4 Definition of major parameters of SYM system

Fig. 5 Monitoring system block diagram

Fig. 6 Layout of global monitoring system for FPSO

Fig. 7 Integrated graphical interface for proto-type monitoring system of FPSO

Fig. 8 PSD curve comparison between vessel motions obtained by INS/GPS and those calculated

Fig. 9 Layout of FBG on mooring legs

Fig. 10 Comparison between restore force of Kane method and FBG (in sea state 1)

Fig.11 Comparison between restore force of Kane method and FBG (in sea state 2)

Table.1 Joint connection modes in SYM system

Joints	Motion release states					
	X	Y	Z	R1	R2	R3
X1	×	×	×	√	√	√
X2	×	×	×	√	√	×
X3	×	×	×	×	×	√
X4	×	×	×	√	√	×

Table. 2 Motion characteristics of FPSO and monitoring sensors

Degree of freedom	Motion characteristic		Sensors
Surge	Translation	Low frequency	RTK GPS
Sway		Wave frequency	

Heave		Wave frequency	INS
Roll	Rotation	Wave frequency	INS
Pitch			incline meters
Yaw		Current Excitation Wave frequency	INS Gyrocompass

Table. 3 Summary of parameters of monitoring system

Objects	Parameters	Sensors	Resolution/range/Sampling rate
Wind	Speed Direction	Wind gauge	(± 0.3 m/s) / (0-100 m/s, 0-360°) / 1Hz
Wave	Height Period	ADCP wave radar	(± 6 mm) / (wave height range 0.2-50m) / half an hour per record
Current	Speed Direction	ADCP	(± 0.5 m/s) / (profiling range 40m velocity range ± 10 m/s) / 0.0167Hz
Floater	Surge	RTK GPS	(± 0.5 m) / (--) / 1Hz
	Sway	Accelerometer	(± 0.005 g) / (± 5 g) / 5Hz
	Heave		
	Pitch	INS	($\pm 0.1^\circ$) / (0-360°) / 1Hz
	Roll	Inclinometers	($\pm 0.01^\circ$) / (0- 360°) / 5Hz
SYM	Yaw		
	Restore force	RTK GPS	(± 0.5 m) / (--) / 1Hz
	Attitude	Inclinometers	($\pm 0.01^\circ$) / (0- 360°) / 5Hz

Table. 4 Typical parameters of monitoring data with two sea states

Sea state	Wind speed	Significant wave height	Max pitch value	Max roll value	Max sway value	Max angle of yoke	Max angle of mooring leg
1 st	4.5 m/s	0.6 m	0.23°	0.15°	0.5 m	1.2°	0.4°
2 nd	23.2 m/s	4.1 m	0.8°	0.85°	2.7 m	25.0°	5.1°