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Full scale measurement for FPSO on motions in six-degrees of freedom and environmental loads and deduction of mooring system loads

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A joint industry project on a full scale measurement of Fenjin FPSO, headed by Shanghai Jiao Tong University and sponsored by CNOOC, was initiated in October 2007 and has been going on for more than 25 months. The purpose of the project is to measure and collect the motions in six-degrees of freedom of an FPSO, and to collect the environmental loads at the offshore oil-field. A motion data measuring system is designed and installed on the FPSO. Another environmental data measuring system is installed on a fixed jacket platform nearby. A large quantity of valuable first-hand data is obtained. With the data collected, motion characteristics of the FPSO in a long-term period are concluded. A short- term analysis for the FPSO in one of the typhoons is also completed. The mean periods of wave-frequency motions are calculated by the spectrum analysis. The tension loads of the mooring system, which is of great concern, are calculated by the decoupled technique.

full scale measurement, FPSO, motions in six-degrees of freedom, environmental loads, decoupled analysis

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1 Introduction

Full scale measurement is one of the most direct ways to achieve characteristics of motions and sea loads on the floating offshore unit, with higher credibility than those obtained by numerical methods or by model tests, provided that the measuring techniques and apparatus are reliable. However, during the recent two decades, there are not many full scale measurement research studies on the floating offshore unit. Only the results of two typical real time monitoring research studies executed on measuring vessel motions, environmental loads and structural properties [1,2], have been published. One of them is the full scale measuring project on Marco Polo TLP in the Gulf of Mexico. From March 2004 to May 2008, a joint industry project (simplified as JIP) for full scale measurement of Marco Polo TLP in the Gulf of Mexico was executed, headed by MARIN and supported by Anadarko, ABS, BHP Billition, BP, Enterprise, Hess, Modec, MMS, and WorleyParsons Sea [3]. The Marco Polo TLP experienced the hurricane Lita in 2005 [4]. The other full scale measurement JIP is the project on the monitoring of *Glas Dowr* FPSO in the North Sea [5–8]. The two projects invited many famous offshore participants. Although the full scale measurement is able to obtain the most accurate results, it has some considerable disadvantages. One of the most obvious disadvantages is its high cost, which is always unaffordable by a single research institute and has to be shared by many corporations. The Marco Polo TLP JIP is a good example which asked for ten participants. Therefore, the full scale measurement project always comes as a form of JIP, which is financially supported by industries.

Besides, although full scale measurement has some simi-

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larity with the model test skill, it always requires more complicated measuring and collecting techniques than those used in model tests. All of the apparatus installed on the floating offshore unit must meet the safety requirements of the offshore oil field. The maintenance of the apparatus asks for a strict demand to sustain the high temperature and the high humidity, and to be able to work automatically. The electricity power supply is another big challenge for the full scale measurement, for the measuring system has to be supported by its own electricity power during the typhoon and the evacuation.

China owns the greatest number of FPSO in the world. In 2007, China started the full scale measurement for floating offshore unit. With the financial support of CNOOC and its sub-companies, State Key Lab of Ocean Engineering in Shanghai Jiao Tong University initiated a full scale measurement JIP on *Fenjin FPSO*, one of the largest FPSOs in the South China Sea. The plan of the JIP is to measure and collect the data of the FPSO's motions in six-degrees of freedom and the environmental loads. Shanghai Jiao Tong University is responsible for the measurement and collection of 6 DOF motion of *Fenjin* FPSO. A company under CNOOC deals with the collection of the environmental load data. The project has lasted for 25 months, and a large amount of the first-hand data is obtained. With the collected data, the characteristics of 6 DOF motion of the FPSO can be summarized, which may benefit the FPSO design in the future.

The paper introduces the process of executing the JIP, including the introduction of the FPSO, and the design, installation and maintenance of the full-scale measuring system. The characteristics of the 6 DOF motion of the FPSO are summarized with the long-term analysis. A short-term analysis for the FPSO in typhoon is also accomplished, and the mooring system loads are calculated with the input of the STP motion by the decoupled method in the time domain.

2 *Fenjin* FPSO and the mooring system disposal

Fenjin FPSO, located at Wenchang offshore oil-field, is one of the largest FPSOs serving in the South China Sea. It is about 150 km away to the east coastline of Hainan Island and the water depth is 119.5 m. It is generally acknowledged that the South China Sea is one of the three areas whose sea conditions are most complicated in the world. *Fenjin* FPSO possesses the typical scantlings and arrangement of those FPSOs serving in the South China Sea. Therefore, *Fenjin* FPSO was chosen to be the first FPSO for a full scale measurement JIP. *Fenjin* FPSO is not alone in the Wenchang offshore oil-field. Two jacket platforms located near the FPSO, are named platform 13-1 and 13-2. Platform 13-2 is about 4 km away from the FPSO, chosen as the supporter for installing the environmental data measuring apparatus. The major scantlings of *Fenjin* FPSO are listed in Table 1.

Fenjin FPSO is moored by a STP mooring system, which is composed of 9 moorings in a 3×3 disposal. The moorings are numbered from 1 to 9. Any two groups are 120 degrees away from each other, and the angle between any two adjacent moorings is 5 degrees in one group. The disposal of the mooring system is shown in Figure 1.

3 Motion measuring system design

3.1 Determination of location choices for the measuring apparatus

The determination of the location choices for the measuring apparatus systems on the FPSO is of crucial importance. To decide where the measuring apparatus system to install, one has to consider the following aspects.

The installation location should be the place where the motion data is of great concern.

The installation location should be in a friendly condition. For example, a closed room is preferred, to protect the apparatus from sunshine and rain. It will be better if an air-conditioner is equipped, for the high temperature and

Table 1 Major scantlings of *Fenjin* FPSO

Scantling	Full loading	Ballast loading
Length overall (m)	262.2	
Length between perpendiculars (m)	250.0	
Scantling width (m)	46.0	
Scantling depth (m)	24.6	
Operation draft (m)	16.5	7.0
Displacement (ton)	176000	73000
Vertical center of gravity above the baseline (m)	16.0	11.0

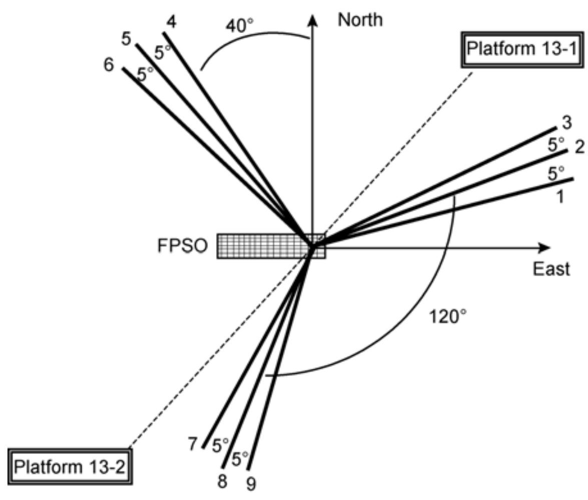

Figure 1 Mooring system disposal.

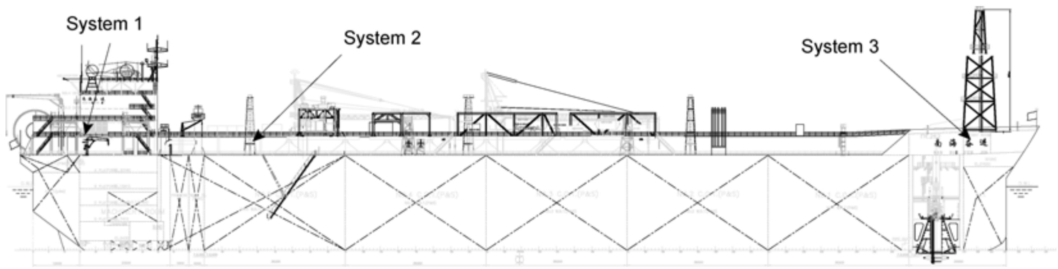

Figure 2 Location choices for the measuring systems on *Fenjin* FPSO.

humidity in the South China Sea in summer will lower the reliability of the apparatus.

The choice of the installation location must comply with the requirements of the oil field. It must not be a place close to the storage compartments of dangerous goods. The electricity power supply system must be installed within a compartment which is able to sustain explosion.

The connections between different apparatus of the systems should be within easy reach. The connections include electricity power supply and transmission of the collected data from the measuring apparatus to the central computer.

The determination of the installation location has to be accepted by the manager of the oil-field.

Three full scale motion measuring systems are decided to be installed at three locations of *Fenjin* FPSO, nominated as system 1, system 2 and system 3, and shown in Figure 2.

3.2 Motion measurement system design

Motion measurement system 1 is located at the stern, where a compartment is chosen with an air-conditioner equipped. The electricity power supply system is also included in system 1. Thus, system 1 plays the dominate role, for it can measure 6 DOF motion of the FPSO and the local accelerations, not only at the usual time, but also during the typhoon period when the FPSO is evacuated. System 2 is located at a compartment which is about one fourth of the FPSO length to the stern. System 3 is located at a compartment adjacent to the STP compartment. Systems 2 and 3 are only designed to measure local accelerations at the usual time.

The composition of system 1 consists of the following apparatus.

Central unit is composed of CPU, compass, acceleration sensors, and amplifiers. The compass has the capability to measure heave, roll, pitch and yaw motion of the FPSO. The acceleration sensors measure the local accelerations in three directions.

UPS is responsible for providing stable electricity supply.

GPS, installed on an open deck, collects the horizontal position of the FPSO.

Electricity power supply system is composed of two series of batteries. Each of them can support system 1 to work independently for 60 h, and they can switch automatically when one series is exhausted.

Connection system is composed of lines for electricity supply and data transmission.

All of the data measured and collected is stored in the central unit. The composition of system 1 is depicted in Figure 3, and the apparatus is shown in Figure 4.

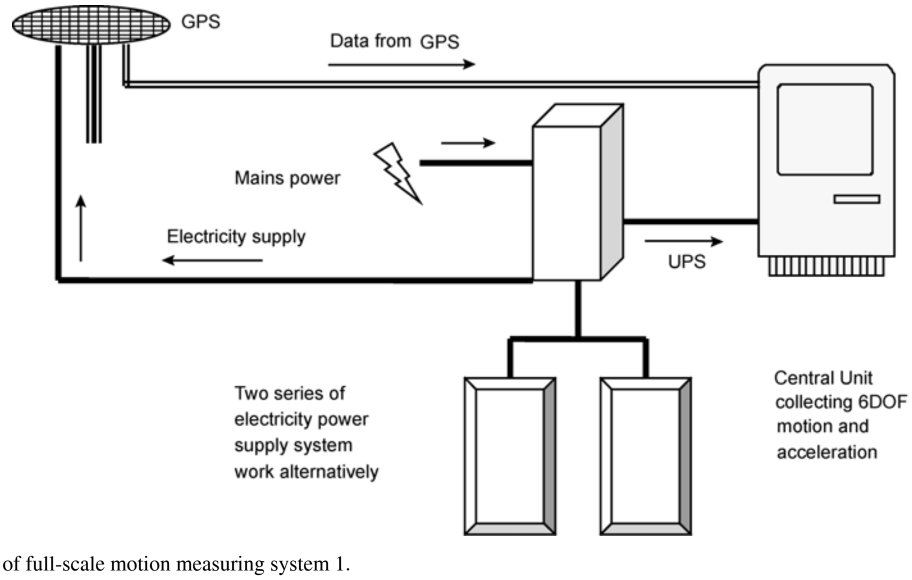

Figure 3 Composition of full-scale motion measuring system 1.

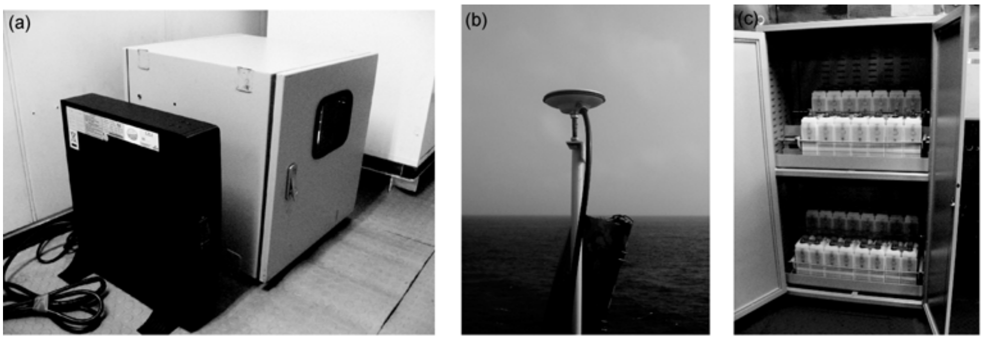

Figure 4 Apparatus of system 1. (a) Central unit and UPS; (b) GPS; (c) electricity power supply.

3.3 Environmental loads measurement system

The environmental loads measurement system is installed on the jacket platform 13-2, for it provides a fixed support in the sea. The system is composed of five parts.

Wave-measuring radar, which can measure the wave in a 360 degree scope, and the maximal wave height of its measuring capability, is 30 m. Besides, the radar can also measure the surface current velocity and direction.

ADCP, which measures the current profile for the site where the Wenchang oil-field is located.

Anemometer, which measures the wind speed and direction.

Central Unit, which controls and stores the measured data of the environmental loads.

Electricity power supply system.

4 Measured and collected data analysis

4.1 New definitions for coordinates and motions

To analyze the measured motion data of the FPSO, one has to define three coordinates separately, which are different from the usual coordinates used in model tests and hydrodynamic analyses. Besides, the definitions of some motions are also different from the normal ones.

Motions of floating structures are always divided into two groups, which are wave-frequency motion and low-frequency motion. The wave-frequency rigid-body motions are referred to as heave, roll and pitch, and the low-frequency rigid-body motions are referred to as surge, sway and yaw. The normal definitions of motions and coordinates are always described as a following-body coordinate. The origin of the coordinate is always the center of the floating structure. In model test research, there is a mandatory process, which is to find the zero position of the center of the floating structure model, and no environmental loads are applied in that process. Surge, sway and yaw motions are defined as those displacements that depart away from the zero position. These motion definitions are common in most numerical analysis codes.

However, these motion definitions of surge, sway and yaw lose their meanings in the full scale measurement research. It is impossible to find a zero position of the floating structure, for the environmental loads acting on it never stop. Therefore, new motion definitions for surge, sway and yaw have to be created, and three coordinates are also to be defined correspondingly.

Firstly, coordinate 1 is defined for wave-frequency motions of heave, roll and pitch. The motion definitions and the coordinates are of the same as those defined usually. The definition of coordinate 1 is shown in Figure 5. Secondly, coordinate 2 is defined for the low-frequency motions of surge and sway. The STP installation position is chosen as the origin of the coordinate, for it is the unique fixed position of the FPSO system. The surge motion is defined as the displacement of the center of the FPSO that departs away from the origin in the latitude line direction, which can also be referred as the displacement in the east-west direction. The sway motion is defined as the displacement of the center of the FPSO that departs away from the origin in the altitude line direction, which can also be referred as the displacement in the north-south direction. The definition of coordinate 2 is shown in Figure 6. Finally, coordinate 3 is defined for the yaw motion. Coordinate 3 coincides with the orientation definition of GPS system. Zero degree means the FPSO points to north and the yaw

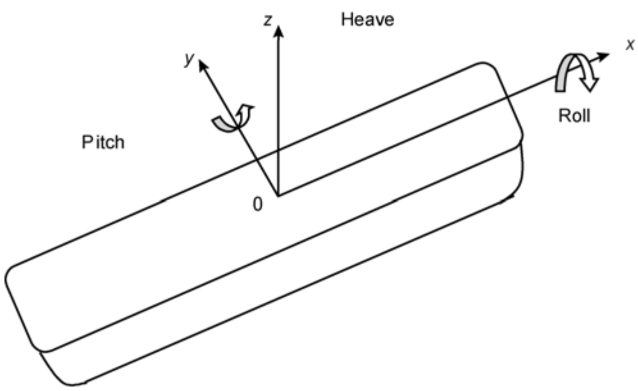

Figure 5 Definitions of coordinate 1 and the motion heave, roll and pitch.

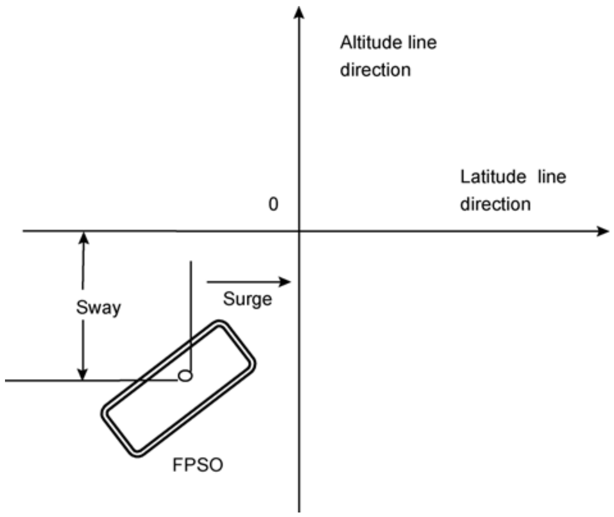

Figure 6 Definition of coordinate 2 and the motion surge and sway.

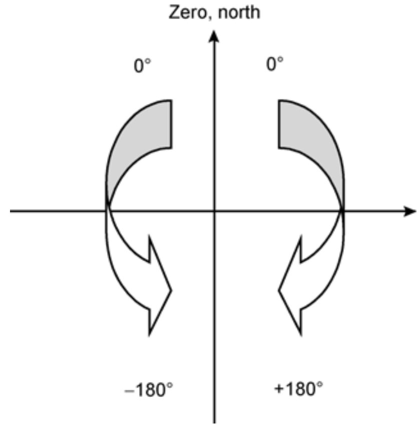

Figure 7 Definition of coordinate 3 and the motion yaw.

motion varies from −180 degrees to +180 degrees. The definition of coordinate 3 is shown in Figure 7.

4.2 Long-term analysis

The full scale measurement JIP for *Fenjin* FPSO, initiated in October 2007, has been operating for 25 months. A large amount of first-hand data before October 2009 was obtained. Two kinds of method are employed to analyze the hydrodynamic characteristics of *Fenjin* FPSO. Long-term analysis is one of the methods, for it provides the overall characteristics of the measured motion data.

The low-frequency motions of *Fenjin* FPSO in 2009 are sorted out by the long-term analysis method. Each day is divided into eight sections and each section represents three hours. The maximal values of the wave-frequency motions in each section are picked out, and they are demonstrated in a long-term view. The long-term characteristics of heave, roll and pitch motions are shown from Figure 8 to 10.

The above figures show that the sea condition is quite complicated in the Wenchang oil-field. The severe sea conditions are not only caused by typhoons in summer and autumn, but also by storm winds in winter and spring. The points A, B, C, D and E represent the five typhoons passing the oil-field during the typhoon season in 2009, and the points F and G represent two periods when wind storm swept the oil-field in the monsoon season. It can be seen that during the period from May to August, the sea is

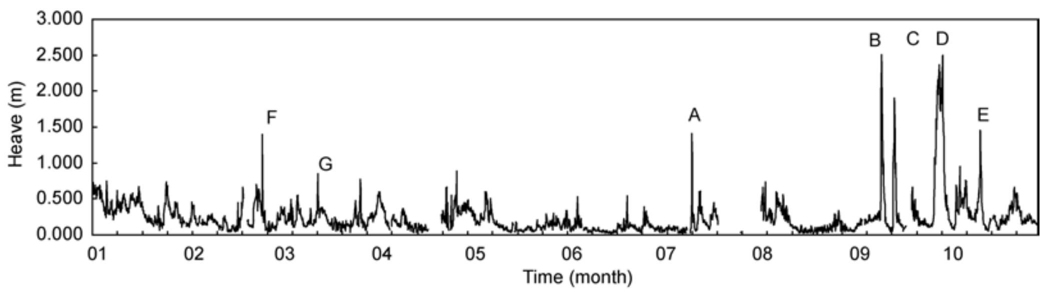

Figure 8 Long-term result of the maximal value of heave motion of *Fenjin* FPSO in 2009.

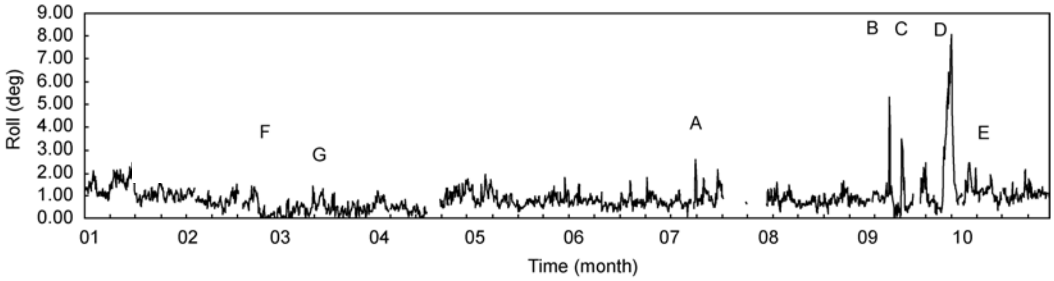

Figure 9 Long-term result of the maximal value of roll motion of *Fenjin* FPSO in 2009.

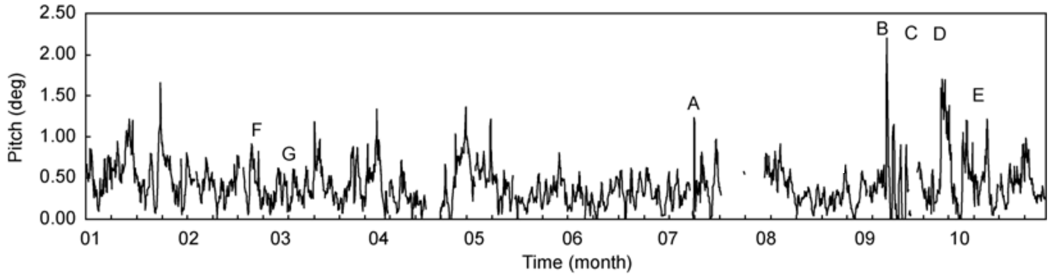

Figure 10 Long-term result of the maximal value of pitch motion of *Fenjin* FPSO in 2009.

somewhat quiet, for the heave motion stays at a low level, only with some jump points standing for occasional typhoons passing. The sea condition falls into a severe period in September and October, for most typhoons originate and sweep the South China Sea during these two months, when the FPSO has to endure the most serious motion loads and the mooring system has to sustain the highest tension loads. In winter and spring, the storms always sweep the oil-field, for the heave motion keeps a relative high level for a long time.

4.3 Short-term analysis

Short-term analysis is the other method to analyze the hydrodynamic characteristics of the FPSO by the full-scale measured data. Point A in Figure 8 stands for the passing of typhoon *Soudelor* on July 11th in 2009. It is one of the most severe typhoons passing the Wenchang oil-field, and the eye of the typhoon is close to the *Fenjin* FPSO. A typical 3-h period of this typhoon, from 18:30 to 21:30, is selected to show the motion characteristics of the FPSO, for the heave motion during the three hours is relatively strong during the typhoon period.

In the period of typhoon *Soudelor*, environmental loads data is measured by the environmental loads measuring system. The maximal wind speed is 24.6 m/s, the significant wave height is 3.1 m, the mean wave period is 12.7 s, and the average current speed is 0.512 m/s. The draft of *Fenjin* FPSO is 13.9 m.

The 6 DOF motions in time series for the first one and a half hour are shown in Figure 11, and the statistical results of the motions in the three hours are concluded in Table 2.

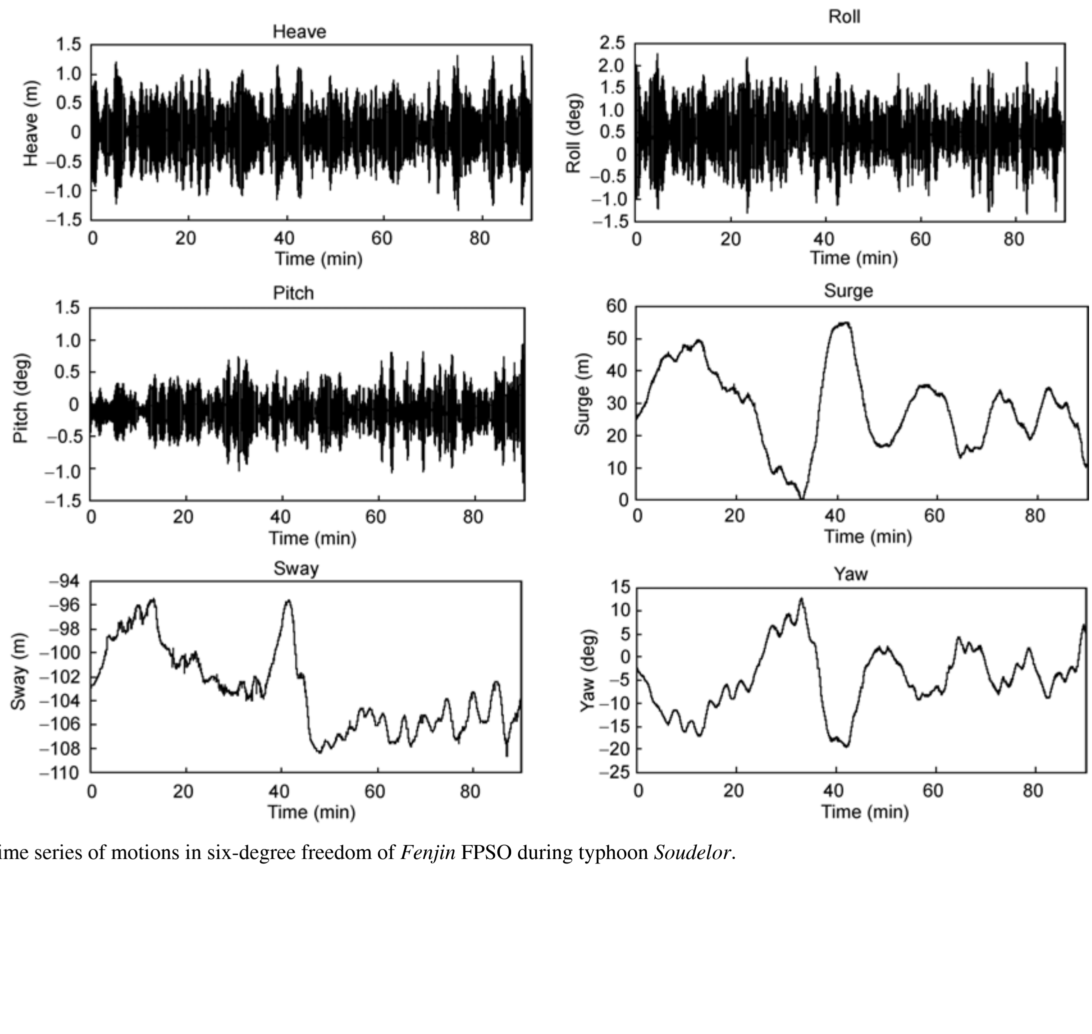

Figure 11 Time series of motions in six-degree freedom of *Fenjin* FPSO during typhoon *Soudelor*.

Table 2 Statistical results of the motions in six-degrees of freedom of *Fenjin* FPSO during typhoon *Soudelor*

Item	Max	Min	Mean	Standard deviation
Heave (m)	1.4089	−1.3631	−0.0001	0.3618
Roll (deg)	2.2490	−1.4800	0.4367	0.5073
Pitch (deg)	1.2298	−1.5305	−0.1264	0.3316
Surge (m)	55.0945	−3.6805	24.3911	12.2747
Sway (m)	−95.446	−109.59	−104.01	2.9129
Yaw (deg)	12.9718	−19.473	−2.5174	6.6664

With the full scale measured data for the motions in wave-frequency, the spectrum density function can be obtained by Fourier analysis. The spectrum density functions of heave, roll and pitch are shown in Figure 12. The mean wave period and peak wave period is calculated according to the spectrum density functions for the three wave-frequency motions, and they are listed in Table 3.

In Table 3, m_0, m_1 and m_2 are spectrum density function parameters and they are defined as eq. (1). The mean period T_2 can be calculated by eq. (2). The period T_p corresponding to the peak frequency of the spectrum can for the same spectrum be written according to eq. (3).

$$m_k = \int_0^\infty \omega^k S(\omega)\mathrm{d}\omega, \tag{1}$$

$$T_2 = 2\pi\sqrt{m_0/m_2}, \tag{2}$$

$$T_p = 1.408T_2. \tag{3}$$

In the equations, ω is the frequency and $S(\omega)$ is the spectrum density function.

4.4 Calculation of the mooring system load

The arrangement of the mooring system of *Fenjin* FPSO is shown in Figure 1, and the properties of each mooring line are listed in Table 4. The length of each mooring line is 900 m, the horizontal span is 877 m, and the pretension force on each line is 330 kN.

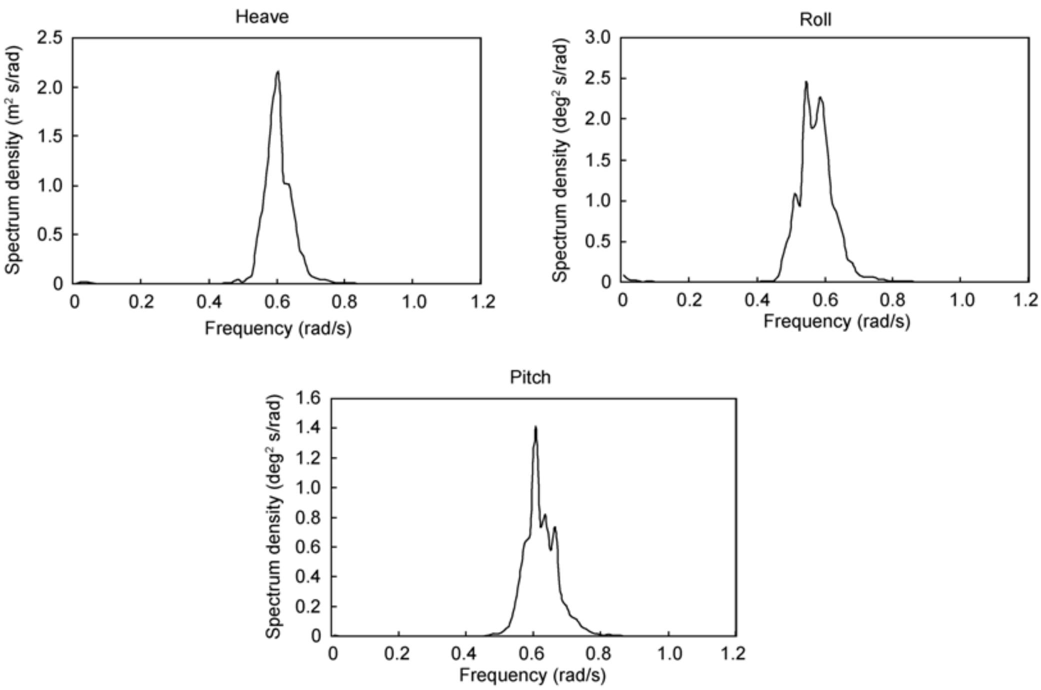

Figure 12 Spectrum density functions of the wave-frequency motions during typhoon *Soudelor*.

Table 3 Periods of the wave-frequency motions by the spectrum analysis

	m_0	m_1	m_2	T_2 (s)	T_p (s)
Heave	0.161	0.098	0.061	10.170	14.319
Roll	0.262	0.151	0.091	10.637	14.977
Pitch	0.111	0.069	0.046	9.800	13.798

Table 4 Properties of the mooring line

Item	Length (m)	Diameter (mm)	Line density (kg/m)	Axial stiffness (kN)	Broken strength (kN)
Low chain segment	50	142	407.3	1193015	18030
Low wire segment	500	140	98.1	1800000	17800
Upper chain segment	100	142	407.3	1193015	18030
Upper wire segment	250	140	98.1	1800000	17800

The calculation method of mooring system load is one of the core techniques of the JIP. Because the environmental data measuring system is installed on the jacket platform 13-2, which is about 4 km away from the FPSO, there may exist some kind of differences between the true environmental loads acting on the FPSO and those measured by the apparatus. Thus, the prevailing method, coupled analysis technique, is not adopted in the research, for the different environmental loads would bring different tension force loads of the mooring system. For a more accurate result of the tension forces of the mooring system, a simple but more suitable method is adopted in the calculation. That is the decoupled analysis technique, which can directly use the full-scale measured motion data of the FPSO.

In the decoupled method, the motions of the STP in three directions are taken as the incentive motions at the top of the mooring system. The incentive motions of the STP can be deduced by the motions in six-degrees of freedom of the FPSO, which are measured by the full scale measuring system.

The motion of any point on a floating body can be obtained by eq. (4) [9]:

$$s = \eta_1 i + \eta_2 j + \eta_3 k + \omega \times r. \tag{4}$$

It is a vector calculation in eq. (4). The vectors η_1, η_2, η_3 represent the motion surge, sway and heave of the rigid-body motion. The vector ω represents the rotation of the body, and r is the displacement vector of the target point relative to the center of the body, which represents the rigid-body motion. They are defined in eq. (5):

$$\begin{aligned} \omega &= \eta_4 i + \eta_5 j + \eta_6 k, \\ r &= xi + yj + zk. \end{aligned} \tag{5}$$

Therefore, the motions of any point of the body can be carried out by eq. (6):

$$\begin{aligned} s = {} & (\eta_1 + z\eta_5 - y\eta_6) i + (\eta_2 - z\eta_4 + x\eta_6) j \\ & + (\eta_3 + y\eta_4 - x\eta_5) k. \end{aligned} \tag{6}$$

However, eq. (6) can not be used to calculate the motions of STP point totally. Only the last part of eq. (6) is valid to calculate the vertical motion of the STP. The first two parts of the equation are not valid for the horizontal motions of the STP, because the surge and sway motions do not refer to the center of the FPSO.

The vertical displacements of the STP in time series can be carried out by eq. (7), for both the center of the FPSO and the STP are located at the mid-longitudinal section of the FPSO and y equals zero. z is the vertical motion of the STP. L is the length between the center of FPSO and the STP. η_3 is the heave motion and η_5 is the pitch motion of the FPSO, and both of them are the full scale measured data.

$$z = \eta_3 - L \times \eta_5. \tag{7}$$

The horizontal displacements of the STP are carried out by eqs. (8) and (9), which are deduced according to the special low-frequency motion definitions in chapter 4.1.

$$x = \eta_1 \pm L \times \cos\varphi, \tag{8}$$

$$y = \eta_2 \pm L \times \sin\varphi. \tag{9}$$

In eqs. (8) and (9), x and y are the horizontal motions of the STP in the latitude direction and the altitude direction respectively. η_1 and η_2 are the surge and sway of the FPSO, φ is the yaw of the FPSO, and they are the field data collected.

With eqs. (7)–(9), displacements of the STP can be carried out in time series. Because the origin of the heave, surge and sway are all defined as zero in their coordinates, the motions of the STP equal the displacements carried out by eqs. (7)–(9).

The code, Riflex, which is developed by Marintek, is employed to do the calculation of the tension forces of the mooring system. The decoupled analysis of the mooring system during the three hours in typhoon *Soudelor* is made, and the statistical results are summarized in Table 5. The time series of the tension force of a typical mooring line is shown in Figure 13.

5 Conclusions

With the full-scale measuring data of motions in six-degrees of freedom and the environmental loads of *Fenjin* FPSO, and the long-term and short-term analyses for the motions and mooring line tension force, we make the following conclusions.

(1) The full scale measurement research asks for high requirements on the apparatus system design, installation,

Table 5 Statistical results of the mooring line forces of *Fenjin* FPSO in typhoon *Soudelor*

Item	Max	Min	Mean	Standard deviation
Line1 (N)	682959	225900	242761	8805
Line2 (N)	679406	225948	243254	8996
Line3 (N)	678023	226426	244501	9333
Line4 (N)	5397580	384038	2380100	519448
Line5 (N)	5928314	423599	2755578	614648
Line6 (N)	6466800	503764	3207672	737192
Line7 (N)	4340510	679941	2107300	526437
Line8 (N)	3812660	678653	1809970	438507
Line9 (N)	3377551	648016	1550266	378546

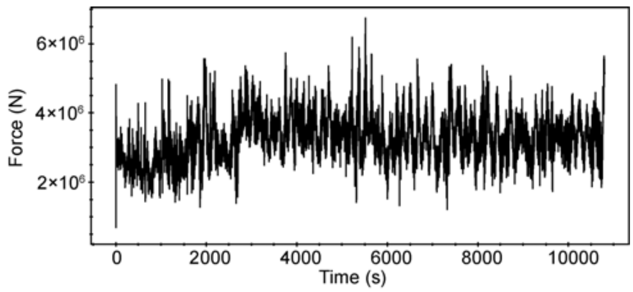

Figure 13 Time series of the tension force of mooring line 6 in typhoon *Soudelor*.

data download, and data processing. Particular care should be taken for the safety and reliability of the measuring apparatus system. New definitions of the low-frequency motions are needed, to overcome the difficulty in the full scale measuring work.

(2) The wave-frequency motions of *Fenjin* FPSO, referred to as heave, roll and pitch, keep a relatively high level during the monsoon season in winter and early spring. In summer, the wave-frequency motions keep a relatively low level, but with some high jumps, corresponding to the passing of typhoons. Overall, January, September and October are the periods with most severe sea conditions.

(3) The short-term analysis of the motions in six-degrees of freedom of the FPSO during a typhoon is finished. Statistical results of the motions are summarized, and the spectrum analysis is fulfilled, to acquire the mean period of the wave-frequency motions. The tension forces of the mooring lines can be calculated by the decoupled method, with the input of motions of the STP.

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