# Experimental Study on the Hydrodynamic Behaviour of an FPSO in a Deepwater Region of the Gulf of Mexico

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## 8 ABSTRACT

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As offshore oil and gas exploration moves progressively toward greater water depths, it 10 becomes more challenging to predict the environmental forces and global responses of floating 11 production storage and offloading (FPSO) systems and the dynamic behaviour of the mooring 12 13 lines and risers. The validation of complex numerical models through scale model experimental testing is restricted by the physical limits of the test facilities. It is not feasible to 14 install the equivalent full length mooring lines and riser systems and select an appropriate 15 16 scale model for reducing the uncertainties in the experimental test programme for deepwater 17 and ultra-deepwater conditions. The combination of an appropriate scale FPSO model with a 18 suitable level of equivalent effect reduced depth using a hybrid passive truncated experimental 19 methodology for the mooring lines and risers is a practical approach.

Following recent discoveries, FPSO has been proposed for a portion of the planned 20 development in the southern Gulf of Mexico (GOM) in water depth ranging from 1000 to 2000 21 metres. Based on a scale model and a hybrid passive truncated experimental method for 22 mooring lines and risers, this paper investigates the global response of an FPSO, as well as 23 24 the dynamics of mooring lines and risers in the context of prevailing environmental conditions 25 for field development in a specific deepwater location in GOM. The experiments revealed that the main horizontal motion response of the FPSO (surge) under non-collinear loading condition 26 is almost two-times that of the collinear loading condition. The mooring lines in the non-27 collinear condition are more sensitive to the dynamic response and risers appear to have an 28 important influence on the low frequency damping. 29

#### 30 Key Words:

31 Hydrodynamics, FPSO, Mooring lines, Non-collinear, Deep-water

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# 33 **1. Introduction**

Scaled model tests of a ship-shaped FPSO, complete with turret mooring lines and risers in deepwater or ultra-deepwater locations, are considered to be the most reliable way to study the complex hydrodynamics and aerodynamics of the complete system (BMT, 2000; Stansberg et al., 2002). Using facilities fitted with advanced equipment, dedicated model tests can closely represent the motion response to realistic environmental conditions and dynamic interactions between waves, current, winds and the total floating system, including mooring and riser systems.

41 The experimental tests help to provide crucial information about the complex linear and nonlinear hydrodynamic behaviour of the total system, such as the total viscous damping 42 43 contributions of the system, the coupled effects of the FPSO vessel with the mooring lines and 44 risers, and the transient green water and slamming forces and wave run-up effects that are difficult to evaluate through numerical simulation alone, without any simplifying assumptions 45 (Faltinsen, 1990; Chakrabarti, 1998; Luo et al., 2004). Thus, a model test is often used to 46 47 validate designs throughout a complex iterative design process, typically using numerical tools. 48

However, when conducting model tests of offshore structures for deepwater and ultradeepwater installations, scale effects become a major issue, and they are very difficult to handle due to the limited physical dimensions of the offshore basins (Stansberg et al., 2002; Chakrabarti, 2005). To limit the scale effect, a scale ratio of 1:50-1:70 has been recommended for model tests of FPSO systems and has been found to be reliable for predicting the full-scale behaviour (ITTC07-3.5, 2008). However, this range of scale ratios is unable to represent a full-

scale water depth when it is equal or greater than 1000 m, and the experiments involve testing
the mooring arrangement and riser system behaviour (ITTC07-3.5, 2008).

57 Continued efforts have been made to overcome the test basin limitations by using relatively small models. A scale ratio of 1:170 is considered to be close to the practical limit, particularly 58 for examining the hull behaviour, based on existing model basin facilities and limitations 59 (Moxnes, 1998). Small-scale testing of 1:150-1:170 has been undertaken, and studies on 60 reliability at this scale have been suggested to evaluate and quantify the uncertainties and to 61 keep them within acceptable levels of accuracy (Stansberg et al., 2004). An alternative 62 procedure, called the hybrid passive methodology, has been explored. It combines an 63 appropriate scale model for the FPSO hull with a depth truncation to yield an equivalent effect 64 of mooring lines and risers in responding to the test basin limitations. Such an effect represents 65 the appropriate forces from mooring lines and risers on the motions of the vessel, which are 66 computed with a numerical simulation procedure by extrapolation to the motion responses of 67 the design prototype system in full water depth (Chakrabarti, 1998; Tahar, 2003; Luo et al., 68 69 2004; Fylling, 2005; Baarholm et al., 2006; ITTC07-3.5, 2008; Su et al., 2009).

Stansberg et al. (2000) investigated this approach and made a comparison for a moderate water depth using both the hybrid passive methodology and a full depth model with a conventional scale model. The results showed that the truncated mooring and riser model approach is technically feasible.

On the other hand, the collinear and non-collinear environmental condition of waves, wind and current often occur in deepwater regions of the GOM. Baar et al. (2000) observed that the extreme response of a turret-moored FPSO is sensitive to the non-collinear environmental conditions of waves, current and wind and the location of the internal turret has influence on the motion response and tension of the mooring lines. Irani et al. (2001) and Ward et al. (2001) showed that the response of moored FPSO is more severe in non-collinear environmental

conditions, but non-collinear conditions have less influence on the tensions of the mooringlines.

82 This paper describes an experimental study on the dynamics of a complete FPSO-mooringriser system in a deepwater location using the hybrid passive truncated experimental method 83 for the behaviour of the lines and risers. The experimental test was undertaken in an offshore 84 basin with 10 m of water depth, and the main focus was to study the nonlinear hydrodynamic 85 effects on the FPSO vessel coupled with both mooring lines and risers. The FPSO global 86 responses for both the full and the ballast loading conditions and the associated dynamics of 87 the mooring lines and risers were studied for collinear and non-collinear environmental 88 conditions. 89

#### 90 2. Model system description

The FPSO used in the study is 300 m in length between perpendiculars with a breadth of 46.20 m and a depth at the side of 26.20 m in prototype dimensions. The hull has a simple form, and the middle cross section of the model is box-shaped (see Fig. 1a and Fig. 1b).

Both the Full load and Ballast load conditions were tested. The Full load condition is associated with a level keel draught equal to 16.5 m with a corresponding displacement of 218,876 tonnes, and in the Ballast load condition, the average draught was 9 m with a corresponding displacement of 122,530 tonnes. The total mass in the scale model was achievement in less than 1 % between the measured and target total (measured values: 216,800 tonnes and 121,400 tonnes) for Full Load condition and Ballast load condition respectively.

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A crude topside arrangement was used with a beam area on the deck of 5190 m<sup>2</sup>, and a bow area on the deck 1448 m<sup>2</sup>, sufficient to allow evaluation of the wind loading on a typical topside area on the FPSO model. The hull of the FPSO included a bilge keel of 1.00 m width and 120 m length.

106 The FPSO model was fitted with an internal turret mooring lines system, which has a diameter of 12 m in the prototype. Its vertical centre line was located 30 m aft of the forward 107 perpendicular of the FPSO vessel. The function of the turret was to provide a tie-in mechanism 108 for the FPSO, with 9 mooring lines and 6 risers enabling the hull to yaw relative to the mooring 109 110 lines and risers. In the experimental test, the Froude and Strouhal number of the model and 111 prototype were kept the same making the gravitational and inertial forces similar. The main particulars of the FPSO vessel in the prototype and the corresponding model scale dimensions 112 113 are summarized in Table 1.

114 A permanent mooring line system was designed to allow for the expected extreme motion values of the FPSO vessel and the maximum tensions of the lines. The mooring system was 115 116 reviewed for both intact and assumed single line damage conditions using both collinear and non-collinear combinations of environment loading cases of one significant event of storm and 117 118 hurricane conditions for a 100-year return period (API-RP-2SK, 2005). The mooring line system has 9 lines with a symmetric configuration arranged in three groups, each group having 119 120 3 lines. The groups were 120 degrees apart, as shown in Fig. 2, Case B. The individual lines are identical, and each one has three integrated chain-spiral and strand-chain segments. Each 121 122 line in a group is separated by 5 degrees from the adjacent line. The mooring system was established, and each line was semi-taut but had a simple catenary mechanism that was 123 subsequently verified through the slightly non-linear behaviour of the restoring force curves 124 and offset as shown in Fig. 3. Comprehensive details and characteristics of the mooring lines 125 are given in Table 2. 126

Six steel catenary risers (SCR) for production and potential injection were assumed with a simple symmetric configuration. The risers were selected only for including and evaluating their typical static and coupled associated dynamic effects on the vessel. The riser arrangement in three groups is shown in Fig. 2, Case C, in which each the groups are all separated by 120 degrees. The main riser characteristics are given in Table 3. Considering the offshore basin dimensions and the instrumentation capacity for environments and measurements, a model scale of 1:64 was chosen for the experiments to minimize the scaling

effect. A passive hybrid method was used to design the truncated mooring lines and risers with an equivalent effect to represent installation at 1000 m. The complete FPSO with truncated mooring and riser system was tested in the Deepwater Offshore Basin at Shanghai Jiao Tong University (SJTU).

Both the mooring lines and risers were thus truncated to 627 m depth in the full-scale. The choice of the model scale and level of truncation were thus selected to minimize the uncertainties related to scaling effects on all system components. The criteria for the design of the truncated mooring system seek to model as closely as possible the following parameters of the full prototype system:

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• Total horizontal stiffness-offset of the system

• Representative single line and riser tensions

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The number of components and layout of mooring lines and risers

A static analysis was performed to design a system of truncated mooring lines and risers that satisfies the horizontal restoring forces characteristics of the full depth prototype system for the three principal horizontal directions (180 degrees, 90 degrees, 0 degrees). A procedure similar to that presented by Waals et al. (2004) and the ITTC (2008) was used to evaluate the design of the truncated mooring line and riser system.

The comparison of the restoring forces of the full depth prototype system and truncation design for the mooring lines and risers is shown in Fig. 3a. Additionally, the top tensions of the most loaded mooring lines and risers of each group is shown in Fig. 3b.

Maximum differences of approximately 8% were observed in the general restoring forces between the truncated and the prototype design in the horizontal aft direction of 0 degrees, which were considered acceptable. In the other directions, 180 degrees and 90 degrees, smaller differences were observed. A similar discrepancy was observed for the most critical line tension and riser tension, demonstrating that good agreement was achieved between the truncated system model and the full depth model. The maximum horizontal spread length at model scale was 15.48 m for the mooring lines and 13.79 m for the risers, which could fit within the length and width of the measuring area of the basin. The main characteristics of the prototype and the corresponding truncated mooring line and riser systems are shown in the Table 2 and Table 3, respectively.

The truncated mooring line system was built using combined chain and spring segments to provide the appropriate submerged weight, axial stiffness (EA), pre-tension and restoring force contributions for each of the mooring lines (Fig. 4).

For the model tests, the six risers were also built of wire and spring segments to satisfy the main requirements of the truncation design, such as the submerged weight, EA, pre-tension, and restoring force characteristics. The bending moment capabilities of the riser section were not taken into account in the design (Fig. 5).

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### 174 3. Experimental setup

#### 175 a. Model setup

The experimental model test was performed in the Deepwater Offshore Basin at Shanghai 176 Jiao Tong University (SJTU) in China. The dimensions of the basin are 50 m by 40 m, with a 177 total available water depth of 10 m that can be adjusted through a vertically moveable bottom 178 179 floor. The plan view of the basin is given in Fig. 6. The basin was fitted with environment simulation equipment, including a multi-flap wave generation system, a current generation 180 system and a wind generation system capable of creating both collinear and non-collinear 181 directional environment loading conditions. The six-degrees-of-freedom motion of the FPSO 182 model were captured through an optical motion tracking system, in which four passive tracking 183 targets were installed on the stern of the FPSO model vessel. The conversion of the tracking 184 target positions to rigid body motions at desired reference point is achieved through proprietary 185 186 software licensed by Qualisys (2010).

187 The tensions in the mooring lines and risers were measured using fifteen sensors installed 188 individually at the fairlead connection points of each lines and risers.

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#### 190 b. Loading conditions

Both collinear and non-collinear environmental conditions are often observed in the specific location of the GOM. For this study, the cases included both situations, which are defined for the storm conditions of a 100 year return period. Fig. 7 shows the three cases of collinear (2 cases) and non-collinear conditions (1 case), with a wind direction of 60 degrees and current direction of 90 degrees of the waves. The irregular waves with current and wind governed the main part of the test programme, and the test duration for each case corresponded to three hours in the prototype.

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- 199 c. Testing matrix
- 200 The experimental test programme consists of the following main components:
- Calm water decay tests in the 6 DOF of the freely floating FPSO model for Full and
   Ballast load conditions
- Calm water decay tests of the floating FPSO model with mooring lines only, and with
   mooring lines and risers for Full and Ballast load conditions
- Horizontal stiffness (restoring forces) of the mooring lines and risers
- White noise wave tests (head, beam and quartering direction)
- FPSO model motions in six DOF at the turret and tension force components at the turret fairleads for the 9 mooring lines and 6 risers
- 209 Collinear 'In-lines' mooring lines loading condition of irregular waves only
- Collinear 'In-line' and 'Between-lines' mooring lines loading conditions of the
   simulated irregular waves, current and wind for Full load conditions
- Non-collinear combinations of environment loading condition of irregular
   waves, current and wind for Full and Ballast load conditions

Three configurations were considered as the basis to study the hydrodynamic behaviour of the FPSO itself and a complete system of the FPSO with mooring lines and risers. The arrangement for "Case A" only considered the FPSO model with temporary horizontal restraining lines fitted above of the water. "Case B" was for the FPSO model with mooring lines
only, and the arrangement for "Case C" was the FPSO model, together with full mooring lines
and risers (see Figure 2).

220 d. Static characteristics of the mooring line and riser systems

221 The static characteristics of the mooring line and riser systems obtained from the experiment and the numerical design were verified. The longitudinal directions (180 degrees 222 and 0 degrees) corresponding to 'In-line', and 'Between-lines' conditions, and transverse 223 224 direction (90 degrees) displacements corresponding to surge and sway were compared. Figs. 225 8 and 9 show a very good agreement of restoring characteristics (maximum offsets) in the 226 alternative fore and aft longitudinal directions (180 degrees and 0 degrees) with mooring lines 227 with and without the risers. Furthermore, the tensions for the most highly loaded mooring line and riser were also examined, and the tension levels obtained in the experiment and the 228 229 numerical design for the surge direction (180 degrees) showed good agreement.

Fig. 10 shows a comparison of the restoring forces of the sway in the transverse direction 230 (90 degrees) between numerical results for the truncated mooring and riser system and those 231 measured in experiment. It is seen that the truncated numerical results agree well with the 232 233 experimental measurements up to 60 m offset and the difference slightly increases afterward. As it is expected that there will be a mean dynamic response of 30 to 50 m in this direction, 234 thus, the similarities of the restoring characteristics were considered to be reasonable in sway. 235 Furthermore, the contribution of restoring forces from the risers in this direction was found to 236 be negligible. 237

#### 238 4. Metocean conditions

A storm condition for a 100-year return period was selected to study the hull motion responses and the associated dynamics of the mooring lines and risers. The JONSWAP spectrum was chosen, with the characteristics of a significant wave height of 9.67 m and a peak wave period of 13.28 s. The wind velocity at 10 m reference height for one hour was 21.95 m/s. The current velocity on the surface was 1.44 m/s (see Table 4).

### 245 a. White noise wave calibration

A generated white noise wave environment was used to represent the full-size and full range environment with wave periods from 5 to 25 s and a significant wave height range of 0-3.25 m. This covered the range of incident wave frequencies for the operational Full load and Ballast load conditions of the FPSO model. Then, the white noise wave generation was calibrated with the specific parameters in the deepwater basin with the FPSO model used in "Case A" (Fig. 2). Fig. 11 shows very good agreement for the spectrum of the wave target and the measurements.

The generated white noise wave spectrum was subsequently used for the calculation of the RAOs in the head, beam and quartering sea conditions through a post-process analysis. For these tests, the FPSO model was held in the required position in the basin with the simple elastic restraining horizontal lines above water surface and set up in the wave heading directions of the studies.

#### 258 b. Irregular wave calibration

The irregular waves in the basin were calibrated in the directions of 180 and 90 degrees. The characteristics were based on the significant wave height, the mean period, gamma shape factor for the JONSWAP wave spectrum (Table 4). These characteristics were selected to represent the typical environment of the southern region of the Gulf of Mexico.

Figs. 12 and 13 compare the generated irregular wave spectrum for the measured and the target waves in the 180 and 90 degree directions, respectively, showing that excellent agreement was achieved. The calibrated irregular waves in two different directions were used in conjunction with the current and wind generated to create the collinear and non-collinear environment loading conditions in the two directions during the experiment.

268 c. Wind load and current speed calibration

The mean wind load was only considered in the model test. The wind load was calibrated according to the total wind force calculated for Full Load ( $F_{full} = 428.68 \text{ kN}$ ) and Ballast Load

conditions (F<sub>ballast</sub> = 531.25 kN) for the FPSO in bow condition. In the case of the current velocity a point located near to the bow of the FPSO model was used to measuring and calibrated the surface current speed. The mean value and standard deviation of the measured current velocity were 1.43 m/s and 0.137 m/s respectively which made reasonable agreement with the target current velocity (1.44 m/s). Fig. 14 shows that the current fluctuations tend to increase significantly in frequencies smaller than 0.023 rad/s and thus a slight influence on the slow-drift motions is expected.

## 278 5. Results and discussion

This section presents the results and analysis of the experimental measurements, and it is organized in the following sub-sections: Decay tests, RAOs from white noise wave tests, spectrum analysis and statistical analysis of the FPSO motion response and the dynamics of the mooring lines.

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284 a. Decay tests

#### 285 -FPSO model only

Decay tests were carried out in calm water for the six DOF of the assumed uncoupled motions of the FPSO model for Full load and Ballast load conditions. The test arrangement Case A shown in Fig. 2 with temporally horizontal restraining lines above of the water was used. Based on the decay tests of the FPSO model in calm water, the natural periods and one average value of the damping ratios of the FPSO hull based on the logarithmic decrement method were calculated (Chakrabarti, 1994).

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The first cycle of measurement for each decay test were discarded to allow a short period of time for attenuation of any transient loads that may have been induced, and the time series of the signals were then recorded for the decay tests.

Table 5 shows that the natural periods of the FPSO model in the Full load condition were in general higher than those in the Ballast Load condition. This shows a strong influence of the

298 model displacement and the hydrodynamic restoring force characteristics on the natural 299 periods.

The relationship between the logarithmic decrement and the peak amplitudes and the local damping ratios for two adjacent cycles can also be evaluated by the relation: (Journee et al., 2001):

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$$\zeta = \frac{1}{2\pi} \ln \left\{ \frac{y_n}{y_{n+1}} \right\} \text{ vs } \bar{y} = \frac{y_n + y_{n+1}}{2} \tag{1}$$

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305 Where:

 $\zeta$  = Local damping ratio (ratio between damping and critical damping)

 $y_n$  and  $y_{n+1}$  = Two succeeding amplitudes at a time interval of period of oscillations

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Then the damping ratios can be shown from two successive positive peak amplitudes.

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311 The damping ratios in surge for both the Full and Ballast load conditions showed similar 312 linear trends. Fig. 15 shows the variation for the surge damping ratios from two successive positive peak amplitudes for the Full load condition (from 0.011 to 0.017), which was slightly 313 higher than that for the Ballast Load condition (from 0.011 to 0.014). The submerged surface 314 315 area of the hull of the FPSO model appeared to have a slightly greater influence on the viscous 316 damping contribution, whereas the dependency on the mean surge amplitude appears to be 317 negligible, indicating that flow separation does not occur in this case under the Reynolds 318 number at model scale. Additionally, skin friction is dominant in the viscous damping for surge motion. 319

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#### 321 -FPSO model together with mooring lines in the Full load condition

Similarly, surge decay tests for the 'In-line' and 'Between-lines' conditions of the FPSO model with the truncated mooring lines for the Full Load condition were carried out. The test arrangement shown in Fig. 2 Case B was used for the decay test in calm water. The natural period for the 'In-line' case was found to be 353.57 s and 362.05 s for the 'Between-lines' case.

The slightly higher natural period for the 'Between-lines' case was due to a reduced contribution of the horizontal restoring forces from the truncated mooring in this direction, as shown in Figs. 8 to 9.

In contrast to case A (Fig. 2), the damping ratios obtained from the decay tests of case B (Fig. 2) were dependent on the amplitude of oscillation, primarily due to the flow separation from the interaction of the mooring lines with the calm water. Fig. 16 shows that the estimated damping ratios are almost at the same level of magnitude for both collinear cases ('In-line' and 'between-lines').

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#### -FPSO model with both mooring lines and risers in the Full load condition

The full arrangement of the FPSO model was also tested, together with the truncated mooring lines and risers. The two different directional arrangements ('In-line' and 'Betweenlines') were also used to evaluate the additional effects of the riser system (see Fig. 2, case C). The natural period for the 'In-line' case was found to be 339.35 s, and for the 'Between lines' case, the natural period was found to be 344.18 s.

Fig. 16 shows the trends of the damping ratios of the FPSO model with mooring lines and the FPSO model with mooring lines and risers, for the 'In-line' and 'Between-lines' cases in surge direction, respectively. Significant contributions of the mooring lines and the risers to the total damping of the complete system are evident. Notably, the riser system makes a greater contribution to the overall damping for the 'In-line' case in the surge direction.

The natural period and the estimated average damping ratios of the 'In-line' and 'Betweenlines' cases are shown in Table 6.

### b. Motion response – linear transfer functions (RAOs)

The RAOs for each of the six DOF were calculated at the C.G. of the FPSO model. The directions of the white noise waves for the studies were, relative to the ship, head seas (180°), quartering seas (135°) and beam seas (90°) conditions.

#### 352 - FPSO motion in head seas

The surge, heave and pitch motion RAOs of the FPSO model are the most important motion 353 354 modes for the head sea conditions (Fig. 17). Both the Full load and Ballast load conditions for surge RAO show a slightly coupled effect, with the heave motion near the heave natural 355 frequency ( $\omega$ =0.54 rad/s) and the maximum amplitude increasing at a lower frequency of 0.45 356 rad/s. Differences between the Full and Ballast load conditions were found to be insignificant. 357 On the other hand, slight differences between the Full and Ballast load conditions for the heave 358 359 RAO were observed near the natural heave frequency, which shows that the magnitude of the 360 heave RAO for Full load condition was slightly higher than that for the Ballast Load condition. Furthermore, the amplitude of the pitch RAO close to the natural frequency, was relatively 361 small, which is attributed to the fact that the length of the FPSO model's is greater than the 362 incident wave length. 363

#### 364 - FPSO motion in beam seas

For the beam seas incident wave condition, roll, sway and yaw RAOs are the most important. For both Full and Ballast load conditions, Fig. 18 shows no significant differences in the sway, pitch and yaw RAOs. However, the roll RAOs for the two load conditions show differences in both amplitude and resonant frequency. The roll RAO for the Full load condition possesses a higher maximum peak amplitude at a frequency equal to 0.47 rad/s than that for the Ballast load condition. In contrast, the shape of the roll RAO for the Ballast Load condition is wider than the roll RAO for the Full load condition.

#### 372 - FPSO motion in quartering seas

Furthermore, for the quartering sea incident wave condition, the six DOF, surge, sway, heave, roll, pitch and yaw motion RAOs are all important. All six DOF motions show coupled effects for both Full load and Ballast load conditions (Fig. 19). The highest amplitude is observed in the roll motion which is similar for Full and Ballast load conditions, whereas the resonance frequency is smaller for the Full load (0.50 rad/s) compared to the Ballast load 378 condition (0.58 rad/s). Differences between the Full load and Ballast load conditions for the
379 other motions were found to be insignificant.

The amplitude of motion responses of the RAOs are sensitive to the direction of the incident wave, and the differences between the Full and Ballast load conditions were found to be insignificant, except for the roll motion, which showed slight differences in resonant frequency responses and maximum peak motion amplitudes.

The motions responses of the RAOs from experimental and calculated numerical using a commercial computer program SESAM (2014) were compared for Full Load condition. The viscous roll damping was identified to be important to the roll RAO while those for surge, sway, yaw, pitch and heave appeared to be less important. This was attribute to that the roll motion RAO is dominated by the resonant response and which has the strong influence from the viscous effects due to the vortices that are generated by the bilge keels of the FPSO model, whereas the other linear motion RAOs are largely governed by the inertia of the FPSO model.

Figs. 20 to 25 show the RAOs for the six DOF in the Full Load condition. It is observed that the experimental results provide a good agreement compared to the numerical analysis. Thus the measured RAOs for the model FPSO reliably reproduced that of the prototype FPSO calculated numerical.

395 c. Motion response spectra for the FPSO

The motion response spectra in frequency domain of the six DOF were calculated using the time series from the experiments using the Fast Fourier transform. A by-pass filter equal to 4 for the low frequency range and 10 for the high frequency were applied to remove possible noise in the initial recorded signal.

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#### 403 *i.* FPSO in Collinear and non-collinear environments for the Full load condition

The motion response spectrum of the FPSO model, complete with the mooring lines and risers exposed to the collinear and non-collinear environmental load conditions of the irregular waves, current and wind were studied for the Full load condition, as illustrated in Fig. 7. The motion response spectra for surge, heave, roll and pitch were analysed. The surge motion response spectra of the FPSO model were analysed with mooring lines only, and with both mooring lines and risers.

#### 410 -FPSO model with mooring lines only

411 The surge motion response spectra of the FPSO model in Full load condition for the 'Between-lines' and Non-collinear cases show the same level of maximum peak energy 412 amplitude in the resonance frequency, whereas the 'In-line' case shows a smaller peak energy 413 amplitude. This indicates that the 'In-line' case provides more damping from the mooring lines, 414 415 while 'Between lines' case and Non-collinear case have less restoring force contribution in the surge direction with slightly lower resonance frequencies (Fig. 26). The motion response 416 spectra show that only energy at the low frequency range has a notable influence on the global 417 response, whereas the wave frequency response contribution is negligible in the surge 418 419 direction. Furthermore, it is known that the wave-current interaction tends to influence the viscous drift damping that is responsible for the low-frequency surge motion (see, e.g., Dev 420 1996). As observed in Fig. 26, the peak of low-frequency surge response in collinear 'In-line' 421 422 environment condition (wave+current+wind) is smaller than that in 'In-line' wave only condition, 423 indicating that the wave-current interaction in collinear 'In-line' environment condition (wave+current+wind) increases the viscous drift damping on the FPSO model. On the 424 contrary, the peak surge response in the non-collinear case (wave+current+wind) is larger 425 than that in collinear environment condition (wave+current+wind), indicating that the wave-426 427 current-wind interaction in non-collinear environment condition decreases the viscous drift 428 damping.

On the other hand, the wave frequency motions (roll, heave and pitch) were analysed for 429 the collinear cases and the non-collinear cases and the results were presented in Figs. 27 to 430 29. Roll motion response for the non-collinear case was observed to have the highest energy 431 amplitude (Fig. 27). The heave and pitch motion responses were also higher in the non-432 collinear case compared to the collinear cases (Figs. 28 to 29). The coupled heave and pitch 433 motion responses were observed in both the collinear and non-collinear cases partly due to 434 the resonance frequencies for pitch and heave are close to each other. Moreover, the origin 435 of the body-fixed coordinate systems at which the surge, sway and heave motions are 436 referenced is the turret location, which is near the bow of the ship. Consequently, the coupled 437 geometric response between heave and pitch motions in which pitch motions tend to show up 438 as heave in addition to pure vertical motions of the FPSO model. As can be seen in Figs. 28 439 and 29, the geometric coupling between heave and pitch is dominant effect than that due to 440 energy transfer between the heave and pitch modes in this case." 441

For the most loaded mooring line, Fig. 30 shows that the highest peak energy amplitude of the line tension response spectrum is observed in the 'In-line' case (L-1) for the Full load condition, which is associated with the higher mean load condition compared to the other cases. The line tension response spectrum (L-1) shows that only the low frequency range energy has a dominant influence on the global response, whereas the wave frequency response contribution is negligible.

448 -FPSO model with mooring lines and risers.

The motion response spectra of the FPSO model with mooring lines and risers for the Full load condition were analysed for the environment loading case with the maximum motion responses identified previously (surge and roll motion in non-collinear cases). Fig. 31 shows the surge motion response with a peak energy associated with a low frequency of 0.018 rad/s, which was observed for the system with mooring lines only, and a frequency of 0.022 rad/s was observed for the system with both mooring lines and risers, respectively. The peak energy

at the resonant frequency of the FPSO model with mooring lines and risers decreases by
approximately 30% compared to the system with mooring lines only, due to the additional
damping contribution from the risers.

In the range of the wave frequency motion, the roll motion spectrum was analysed to 458 examine the influence of the risers on the roll motion response. Fig. 32 shows that the peak 459 amplitude decreases by 31% when the risers are included. However, the frequency associated 460 461 with the peak amplitude appears to be not affected by the risers, due to small contribution of restoring forces from the risers. Fig. 33 shows the mooring line tension response for the 462 maximum loaded line (L-1) in the 'In-line' case, under the Full load condition. The response 463 spectrum for the maximum loaded riser (R-1) is presented in the non-collinear case (Fig. 34) 464 because the wave frequency motion response is slightly higher than the collinear cases. 465

# 466 ii. Full vs. Ballast load condition for the non-collinear environment loading case

The Ballast Load condition of the FPSO model in the test matrix was only considered in the non-collinear case. A comparison between Full load and Ballast load conditions for the noncollinear case was carried out for the maximum low frequency motion (surge motion) and tension in the most critical mooring line.

Fig. 35 shows that the Full load condition has a higher peak amplitude compared with the Ballast Load condition. Moreover, the influence of riser damping in the response amplitude is important. The highest peak energy amplitude of the line tension response spectrum is perceived in the FPSO model with mooring lines only, for the non-collinear case in the Full load condition (Fig. 36).

#### 476 *d. Statistical Analyses*

The time series motion responses in the six DOF of the FPSO model in Full load and Ballast Load conditions and the most loaded mooring line and riser were further examined. The collinear 'In-line', 'Between-line' and Non-collinear environment conditions of the irregular

waves, current and wind, as previously defined, were used in the analysis. The comparisons
were made in terms of their statistical properties such as the mean, minimum and maximum
values and the associated standard deviations in full-scale.

The detailed experimental information of the time series yaw motion responses and offset trajectories along of turret centre for the non-collinear case can be seen in Figs. 37 to 44.

485 i. Collinear vs. non-collinear environment loading cases for the Full load condition

486 -FPSO model with mooring lines

The maximum motion responses were observed to be in the low frequency range in the surge direction for all environmental loading cases. The maximum motions occurred in the surge direction due to the mooring line/internal turret system, which allowed the FPSO to rotate freely about the moorings, similar to a weather vane and to point in the direction of least resistance against the various combined components in the environment loading conditions.

A maximum surge motion response of -86.62 m occurred in the non-collinear case for the arrangement of the FPSO model and mooring lines compared to the corresponding collinear 'In-line' condition (-56.93 m) and collinear 'Between lines' condition (-84.46 m) respectively, as shown in Table 7. Clearly, negative values of surge motion indicate that the vessel is moving in an aftward direction, the reciprocal to the conventional surge sense, as a result of the weather vane rotation about the turret.

This behaviour is mainly due to the non-collinear environment loading condition, with the current at 90 degrees relative to the incident wave, which increases the energy of the incident irregular waves (Chakrabarti, 2005). Therefore, the mean and dynamic surge motion responses increase in the FPSO model (Faltinsen 1994, Stansberg *et al.* 2013) owing to the increase of the mean and slow-drift excitation wave. Based on the comparison was made between collinear and non-collinear environmental loading conditions, the mean motion response in the surge direction was observed to be higher in the non-collinear case (-43.24

505 m) compared with the collinear cases ('In-line' case = -28.86 m, and 'Between-lines' case = -506 35.67 m). The low frequency sway and yaw motions in the non-collinear case, in terms of 507 absolute values, resulted in maximum motions of 34.18 m and 54.53 degrees, respectively, 508 compared with the 'In-line' condition (sway=14.88 m and yaw=17.58 degrees) and the 509 'Between-lines' condition (sway=18.11 m and yaw=15.03 degrees).

510 On the other hand, the effects of the yaw motion in the wave frequency also influenced the 511 motions of roll, heave and pitch. In the non-collinear case, the motions in terms of absolute 512 values, (roll= 8.19 degree, heave = 3.99 m and pitch = 3.50 degrees) were found to be higher 513 to those in the collinear cases. It is worth noting that, in the non-collinear case, the incident 514 wave length effectively increases due to the wave-current interaction, and the length ratio 515 between the FPSO model and wavelength was less than one in the present study leading to 516 the increased wave frequency motions.

517 Furthermore, the maximum tension in the most critical line (L-1) was found to be 3812.17 518 kN in the non-collinear case, mainly because of the higher contribution of the coupled surge-519 sway motion responses while the maximum mean tension was observed in the collinear 'In-520 line' case (L-1, 2665.07 kN), a clear indication that mooring lines in the non-collinear condition 521 are more sensitive to the dynamic response.

#### 522 -FPSO model with mooring lines and risers

523 Table 8 shows the statistical results for the FPSO model complete with mooring lines and risers in the full operational configuration. The non-collinear case also showed slightly higher 524 statistical values for low frequency surge motion (-76.75 m) compared to the results for the 525 526 collinear 'Between-lines' case (surge = -75.53 m), and a much smaller value (surge = -50.90 527 m) for the collinear 'In-line' case. The highest motion response in the non-collinear case was mainly attributed to the interaction wave-current load, which increases the mean drift force and 528 slow-drift excitation forces on the FPSO model. For yaw motions, the non-collinear condition 529 tends to induce the highest mean motion (-43.43 degrees) compared with collinear conditions, 530

as expected. In the case of the wave frequency induced motions of heave, pitch and roll, the
non-collinear case also showed the highest values, which can be attributed to the coupled
effect from the yaw motions.

The maximum tension in the most loaded mooring line (L-1) was 3598.29 kN, which was observed in the 'In-line' case, whereas the most critical tension in the risers for R1 was 2364.77 kN in the non-collinear case, mainly due to the increase in wave frequency motion.

The influence of the riser system on the maximum motion response and dynamic tension 537 response of the mooring lines for the most critical case (Non-collinear) in Full load condition 538 was tested, and the results are presented in Table 7 and 8. The motion response in surge 539 540 direction was reduced by 13%, with a standard deviation of 15%. The differences in mean motion response were relatively small when the riser system was considered. The contribution 541 of risers to the maximum response are mainly from the hydrodynamic damping, which 542 decreased the dynamic motion response. The maximum dynamic tension response of the 543 544 most loaded mooring line (L-1) decreased by 6% and again the difference in mean tension response is neglected when the riser system was considered. 545

546 ii. Full load condition vs. Ballast load condition under the non-collinear environment

#### 547 -FPSO model with mooring lines

548 The statistical values for the Ballast Load condition of the FPSO model were studied for the 549 non-collinear case only. Table 8 shows that the maximum motion response for the Ballast Load condition in the surge direction (-68.94 m), and the results for the Full load condition (-550 86.62 m) is found to be considerably larger. The same trend is observed for the mean motion 551 and standard deviation (Figs. 45 to 47). However, the maximum sway motion response (39.57 552 m) for the Ballast Load condition tends to be marginally larger than that for the Full load 553 condition (34.18 m). This is mainly attributed to the fact that, for the Ballast Load condition, the 554 mean, maximum and minimum values of the yaw response, in terms of absolute values, are 555 556 higher (41.73, 22.98 and 60.09 degrees, respectively) than those for the Full load condition (39.30, 20.88 and 54.53 degrees). The relative increases of the yaw motions can be attributed to the larger projected area of the FPSO model exposed to wind for the Ballast Load condition that for the Full load condition, which is due to the differences in the draughts. The higher yaw responses lead to slight increases of the wave frequency motion in roll, heave and pitch for the Ballast Load condition.

The maximum line tension was observed in L-1 (3999.20 kN) for the Ballast Load condition, which is slightly higher than that for Full load condition (3812.17 kN) in the non-collinear environment. This can be attributed to the higher coupled surge and sway motion responses and the differences in the draughts of the FPSO model.

566

### 567 -FPSO model with mooring lines and risers

The maximum motion response for the Ballast Load condition was -63.64 m in the surge, which is smaller than results of -76.75 m for the Full load condition, both in non-collinear environment, as shown in Table 8 and Figs. 45 to 47. In contrast, the maximum motion response in sway (39.61 m) for the Ballast Load condition is similar than that for the Full load condition (39.15 m) in the same non-collinear environment.

573 For the wave frequency motions, it is noted that the differences in heave, roll and pitch between 574 the Ballast Load condition and Full load condition are small. Furthermore, the maximum critical 575 line tension L-1 (3758.36 kN) for the Ballast Load condition is slightly higher than that for the 576 Full load condition (3585.89 kN), but the maximum tension in the most loaded riser (R-1) 577 (2229.30 kN) for the Ballast Load condition is slightly lower than that for the Full load condition 578 (R-1) (2364.772 kN) in non-collinear environment.

# 579 *iii. Effects of current and wind*

580 In order to examine the effects of current and wind on the dynamics of the coupled system, 581 comparisons are made for the results obtained under the two collinear 'In-line' cases, i.e., one 582 with irregular waves only and the other with irregular waves, current and wind, (Fig. 48). The statistical values for the surge motions of the FPSO model with mooring lines only were 583 analysed. It was clear that the mean drift motion response increased two-fold for the 584 environment with irregular waves, current and wind compared to that of the system under 585 586 irregular waves only. Further, the mean drift motion of the FPSO model tends to govern the total motion response when the irregular waves are influenced by wind and current while the 587 dynamic motion (slow drift motion) component is smaller with an average of 18% compared to 588 589 the FPSO model exposed to irregular waves. This behaviour is mainly due to the collinear 590 wave-current interactions which increase the drift mean forces and the wave-drift damping on 591 the FPSO model (Zhao and Faltinsen, 1989; Faltinsen, 1994; Monroy et al., 2012; Stansberg 592 *et al.*, 2013).

593 On the other hand, the motion response of the FPSO model from current load was slightly 594 higher than the motion response from the wind load, and a small standard deviation was 595 observed for both motions due to the current and wind loads respectively, which confirms that 596 the FPSO system with mooring lines mainly responds to mean motion behaviour. Oscillation 597 loads from the current and wind are insignificant.

Fig. 49 shows the comparison of the tension response of the most loaded mooring line (L-598 599 1) for both collinear cases with irregular waves only and irregular waves, current and wind. The mean tension response is observed to be 15% higher for the system exposed to irregular 600 waves, current and wind compared to that of the system with irregular waves only. The 601 dynamic tension response of the most loaded mooring line was observed similar in both 602 collinear cases (irregular waves, current and wind, and irregular waves only). It is clear that 603 the dynamics of the system when exposed to a collinear case of irregular waves, current and 604 605 wind, is dominated by the mean drift motion response of the FPSO model and mean tension response of the mooring lines. 606

607 The statistical values for the surge motions of the FPSO model with mooring lines only show that, for the non-collinear environment with the irregular waves, current and wind, the mean 608 drift motion response increases by two-fold compared to the system exposed to irregular 609 waves only (Fig. 50). The dynamic motion (slow-drift oscillation) is higher by 27% compared 610 611 to the system under irregular waves only. The mean tension response of the most loaded mooring line (L-1) for the system exposed to irregular waves, current and wind was observed 612 slightly higher (6%) compared to the system under irregular waves only (Fig. 51). The main 613 614 difference was observed in the dynamic tension response. The dynamic tension in the most 615 loaded mooring line increases 21% in the system exposed to irregular waves, current and wind 616 than that of the system under irregular waves only. This is a clear indication that wave-current 617 interaction in non-collinear environment has an important effect on both mean drift motion and 618 the slow-drift oscillation of the FPSO model and the dynamic tension of the mooring lines. The 619 reason is that changes in the mean heading of the vessel when comparing collinear and noncollinear conditions influence the mean yaw motion response of the FPSO model. The different 620 yaw motions cause different first-order and second-order motion responses of the FPSO 621 model for the collinear and non-collinear environment condition. Additionally, wave-current 622 623 interaction changes the fluid flow pattern around of the structure and subsequently impacts on the mean wave loads according to potential theory, and they are connected with the structure's 624 ability to create waves (Faltinsen, 1994). 625

626

## 627 6. Conclusions

Based on the results of the present study, the motion response of the FPSO with mooring and riser system for both the Full load and the Ballast load conditions were observed to be sensitive to the direction of the incident wave. It is confirmed that FPSO system is more critical to the beam and quartering seas. The motion response spectra analysis revealed that risers have a great influence on low-frequency damping, particularly in the surge direction, whereas the damping mainly contributes to roll of the wave frequency motion response. Under the noncollinear environmental condition, the interaction between irregular waves and current 635 increases the steady wave drift force on the FPSO model compared to the collinear cases. The yaw motion response influences the wave frequency motions (heave, roll, and pitch) of 636 the FPSO under the non-collinear condition. The impact of the FPSO loading condition on the 637 wave frequency motions is found to be insignificant. The highest tension response in the 638 639 mooring lines is observed in the Ballast load condition for the non-collinear case due to a higher coupled surge and sway motion response and less draught on the FPSO. The tensions 640 in the risers is slightly higher in the non-collinear environment for the Full load condition and 641 642 the wave frequency motions are sensitive to risers. The changes in the mean heading of the 643 vessel when comparing collinear and non-collinear conditions influence the mean yaw motion 644 response of the FPSO model. The different mean yaw motions cause different first-order and 645 second-order motion responses of the FPSO model for the collinear and non-collinear 646 environment condition.

647 Interaction between waves, current and wind in collinear environment increases the mean drift motion response and reduces the slow-drift oscillation response of the FPSO model due 648 to the increase of the drift damping compared to irregular waves only. However, interaction of 649 waves, current and wind in non-collinear environment is more complex which tends to increase 650 651 the mean drift motion, the drift damping and the slow-drift oscillation response of the FPSO model compared to the system exposed to irregular waves only. Based on the present 652 experiment results confirms that the non-collinear environmental conditions are important in 653 the analysis and design of the hydrodynamic performance of the FPSO with mooring and riser 654 systems. 655

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# 818 Table 1

# 819 Prototype and model scale dimensions and characteristics of the FPSO

Full load Condition			Ballast load Condition	
Description	Prototype	Model Scale	Prototype	Model Scale
Length LPP (m)	300	4.69	300	4.69
Breadth, B (m)	46.20	0.72	46.20	0.72
Depth, H (m)	26.20	0.41	26.20	0.41
Draught, T (m)	16.50	0.26	9.00	0.14
Ta (m)	16.50	0.26	9.50	0.15
Tf (m)	16.50	0.26	8.50	0.13
Length/Beam ratio (L/B)	6.49	0.10	6.49	0.10
Beam/Draught ratio (B/T)	2.80	0.04	5.13	0.08
Displacement (tonnes)	218876	0.82	122530	0.46
XB, XG (m)	2.43	0.04	3.08	0.05
ZG (m)	11.43	0.18	7.87	0.12`
Kxx (m)	16.17	0.25	20.79	0.33
Kyy (m)	86.72	1.36	86.72	1.36

# 823 Table 2

# 824 Mooring line characteristics

Description	Prototype	Truncate Specification
Number of mooring lines	9	9
Pretension (kN)	2025	2025
Total Length of mooring line (m)	2185	1160
Segment 1: Fairlead chain	R4S Studless	
Length (m)	50	50
Diameter (mm)	90	90
Mass in water (tonnes/m)	0.146	0.146
EA (kN)	691740	691740
Breaking strength (kN)	8167	-
Segment 2: Mid-section	Spiral Strand	
Length (m)	1200	580
Diameter (mm)	90	90
Mass in water (tonnes/m)	0.0336	0.116
EA (kN)	766000	68000
Breaking strength (kN)	7938	-
Segment 3: Chain ground section	R4S Studless	
Length (m)	935	530
Diameter (mm)	90	90
Mass in water (tonnes/m)	0.146	0.133
EA (kN)	691740	60000
Breaking strength (kN)	8167	-

# 827 Table 3

# 828 Riser characteristics

Description	Prototype	Truncate Specification
Number of risers	6 symmetric	6 symmetric
Pretension (kN)	1500	1500
Total length of riser (m)	2650	1400
Outside diameter (mm)	273	273
Inside diameter (mm)	235	235
Mass in water (tonnes/m)	0.096	0.234
EA (kN)	3039364	85000
Specification	API-5L-X-65	
		835

# 837 Table 4

# 838 Storm environmental conditions

Description	Unit	Storm environment condition
Waves		
Hs	m	9.67
Тр	s	13.28
Wave spectrum	Jonswap	
Wave direction	deg	180 <sup>0</sup>
Wind speed (1-hr)	m/s	21.95
Wind spectrum	API RP 2A-WSD	
Wind direction	deg	0 <sup>0</sup> and 60 <sup>0</sup> of the wave
Surface current	m/s	1.44
Current direction	deg	0 <sup>0</sup> and 90 <sup>0</sup> of wave

# 842 Table 5

# 843 Natural periods and damping ratio of six DOF for Full load and Ballast load conditions

	Full load			Ballast load		
DOF	T <sub>n</sub> (s)	Damping ratio	Added mass coeff.	T <sub>n</sub> (s)	Damping ratio	Added mass coeff.
Surge	223.58	0.015	-	168.56	0.013	-
Sway	277.39	0.030	-	184.21	0.040	-
Heave	11.55	0.130	1.06	11.15	0.120	2.11
Roll	13.21	0.020	0.17	11.23	0.030	0.14
Pitch	11.60	0.100	0.95	10.38	0.210	1.53
Yaw	166.90	0.030	-	119.66	0.013	-
### 847 Table 6

848 Natural periods and total damping ratio of the free decay tests of the FPSO model, mooring lines and risers for

the 'In-line' and 'Between-lines' cases in the surge direction, in the Full load condition.

Parameters	Only FPSO	FPSO+Mooring lines 'In-line' Case	FPSO+Mooring lines 'Between-Lines' Case	FPSO+Mooring lines+Risers 'In-line' Case	FPSO+Mooring lines+Risers 'Between-Lines' Case
Periods (s)	223.81 s	353.57 s	362.05 s	339.35 s	344.18 s
Damping ratio	0.015	0.030	0.028	0.043	0.034

850

# 853 Table 7

- 854 Statistical values of the motions in the Full load and Ballast load conditions for the Collinear and the Non-Collinear
- 855 cases for the FPSO model with mooring lines

FPSO vessel and Mooring lines "CASE B"								
Environment condition: Irregular Wave-Current-Wind								
Description		FPSO Ballast load Condition						
	Statistical	Collinear 'In-line' Case	Collinear 'Between-lines' Case	Non-Collinear Case	Non-Collinear Case			
	Max	-3.92	-3.02	-3.38	-10.83			
	Min	-56.93	-84.46	-86.62	-68.94			
Surge (m)	Mean	-28.86	-35.67	-43.24	-37.09			
	Stdv	9.16	12.31	12.64	9.05			
	Max	14.88	15.83	34.18	39.57			
	Min	-14.48	-18.11	-16.85	-28.92			
Sway (m)	Mean	0.33	-1.53	5.66	1.06			
	Stdv	6.14	6.49	10.15	10.84			
	Max	2.07	2.24	2.50	3.47			
	Min	-2.37	-2.60	-3.99	-4.01			
Heave (m)	Mean	-0.11	-0.102	-0.44	-0.29			
	Stdv	0.60	0.60	1.00	1.06			
	Max	2.90	2.66	6.49	7.56			
Roll (deg)	Min	-2.83	-2.83	-8.19	-8.20			
	Mean	0.09	0.02	-0.34	-0.21			
	Stdv	0.70	0.65	2.01	2.06			
Pitch (deg)	Max	3.09	2.87	3.50	4.12			
	Min	-2.90	-2.71	-3.18	-3.73			
	Mean	0.02	0.02	0.05	0.05			
	Stdv	0.804	0.78	1.14	1.23			
Yaw (deg)	Max	6.10	5.97	20.88	22.98			
	Min	-17.58	-15.03	54.53	60.09			
	Mean	-5.14	-3.47	39.30	41.73			
	Stdv	4.94	3.89	5.52	5.91			
Critical tension		L-1	L-7	L-1	L-1			
	Max	3729.23	3612.74	3812.17	3999.20			
	Min	1915.24	1873.03	1619.00	1766.53			
	Mean	2665.07	2451.97	2446.61	2467.93			
ίΓ	Stdv	276.84	220.48	311.49	282.00			

#### Table 8

- Statistical values of the motions in the Full load and Ballast load conditions for the Collinear and the Non-Collinear
- cases for the FPSO model complete with mooring lines and risers

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FPSO, Mooring lines and Risers "CASE C"							
Environment condition: Irregular Wave-Current-Wind							
Description		FPSO Ballast load Condition					
	Statistical	Collinear 'In-line' Case	Collinear 'Between- lines' Case	Non-Collinear Case	Non-Collinear Case		
Surge (m)	Max	1.02	-5.76	-10.43	-14.20		
	Min	-50.90	-75.53	-76.75	-63.64		
	Mean	-22.56	-33.28	-42.09	-33.32		
	Stdv	8.49	11.40	10.97	8.12		
	Max	25.03	5.25	22.07	39.61		
Swov (m)	Min	-14.64	-29.10	-39.15	-19.90		
Sway (m)	Mean	0.68	-12.29	-11.89	9.51		
1 1	Stdv	7.32	7.98	10.13	10.32		
	Max	2.19	2.64	3.65	3.04		
	Min	-2.53	-2.50	-4.27	-4.07		
Heave (m)	Mean	-0.15	-0.10	-0.31	-0.51		
	Stdv	0.59	0.60	1.09	0.84		
	Max	4.48	2.94	6.01	6.04		
	Min	-3.93	-2.77	-7.20	-6.80		
Roll (deg)	Mean	0.06	0.03	-0.32	-0.29		
	Stdv	0.71	0.70	1.95	1.66		
	Max	3.11	3.13	4.11	4.17		
Pitch (deg)	Min	-3.04	-2.90	-4.22	-3.84		
	Mean	0.02	0.03	0.03	0.14		
	Stdv	0.79	0.80	1.20	1.15		
Yaw (deg)	Max	5.72	8.38	29.40	7.29		
	Min	-26.45	-11.83	59.67	69.07		
	Mean	-6.37	-0.748	43.43	49.68		
	Stdv	4.40	4.11	5.36	5.55		
		L-1	L-7	L-1	L-1		
Critical tension line (kN)	Max	3598.29	3313.35	3585.89	3758.36		
	Min	1802.29	1846.79	1692.26	1677.92		
	Mean	2508.06	2413.59	2431.79	2485.05		
	Stdv	253.64	194.85	281.88	278.24		
Riser tension - (kN) -		R-1	R-4	R-1	R-1		
	Max	2127.60	2147.79	2364.77	2229.30		
	Min	943.00	978.26	806.74	905.77		
	Mean	1499.15	1544.38	1542.06	1547.68		
	Stdv	161.81	152.77	226.61	203.59		

866



**Fig. 1a.** FPSO model at scale 1/64<sup>th</sup>





**Fig. 2.** Experimental test configurations, "Case A", "Case B" and "Case C"



(a) Restoring forces vs offset



(b) Top tension forces vs offset

Fig. 3. Mooring line and riser restoring forces and top tension forces of the truncated model and the full depth
prototype model



Fig. 4. Mooring lines model at scale 1:64



- 902 Fig. 5. Riser model at scale 1:64



907 Fig. 6. Plan view of the deepwater offshore basin at SJTU



- (c) Non-collinear
- 914 915 916 Fig. 7. (a) Collinear 'In-line' and (b) 'Between-lines' and (c) Non-collinear (relative to the mooring lines)
- environmental loading condition. Note: L- Mooring lines R-Risers





**Fig. 8.** Restoring forces and offset characteristics in the direction (180<sup>0</sup>) (forward direction)















932 Fig. 11. White noise wave calibration









940 Fig. 13. Irregular waves calibration, direction 90 degrees







**Fig. 14.** Spectrum of the calibrated current velocity







956 Fig. 16. Damping ratios for surge decay test of the FPSO model, truncated mooring lines and risers for the 'In-line'

957 and 'Between-lines' cases for the Full load condition



















969 **Fig. 20**. Surge RAOs for Full Load condition (Head condition)





971 Fig. 21. Heave RAOs for Full Load condition (Head condition)

972





974 Fig. 22. Roll RAOs for Full Load condition (Beam condition)



**Fig. 23**. Sway RAOs for Full Load condition (Beam condition)







980 Fig. 25. Yaw RAOs for Full Load condition (Quartering condition)





983 Fig. 26. Surge motion response spectra for the Full load condition













991 Fig. 28. Heave motion response spectra for the Full load condition





**Fig. 29.** Pitch motion response spectra for the Full load condition













1008 Fig. 32. Roll motion spectra, Non-collinear case for the Full load condition





1012 Fig. 33. Line tension response spectra for the Full load condition





1016 Fig. 34. Riser tension response spectra for the Full load condition













**Fig. 36.** Line tension response spectra for the Full and Ballast load condition




- 1031 Fig. 37. Offsets trajectories of the FPSO with mooring lines





- 1034 Fig. 38. Yaw motion response of the FPSO with mooring lines
- 1035 and risers, non-collinear case Full Load condition





1039 Fig. 39. Offsets trajectories of the FPSO with mooring









1043 non-collinear case Full Load condition





- 1046 Fig. 41. Offsets trajectories of the FPSO with mooring lines, non-
- 1047 collinear case Ballast Load condition





- 1050 Fig. 42. Yaw motion response of the FPSO with mooring lines,
- 1051 non-collinear case Ballast Load condition



- 1054 Fig. 43. Offsets trajectories of the FPSO with mooring lines and
- 1055 risers, non-collinear case Ballast Load condition

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- 1059 Fig. 44. Yaw motion response of the FPSO with mooring lines
- 1060 and risers, non-collinear case Ballast Load condition



**Fig. 45.** Comparison of the extreme surge motion non-collinear case, FPSO mooring lines (Case B) vs. FPSO

1066 mooring lines and riser (Case C) for the Full load and Ballast load conditions (in terms of absolute values)



1067

1068 Fig. 46. Comparison of the mean surge motion non-collinear case FPSO mooring lines (Case B) vs. FPSO

1069 mooring lines and riser (Case C) for the Full load and Ballast load conditions (in terms of absolute values)



- **Fig. 47.** Comparison of the standard deviation of surge motion non-collinear case FPSO mooring lines (Case B)
- 1073 vs. FPSO mooring lines and riser (Case C) for the Full load and Ballast load condition





- 1077 Fig. 48. Statistical values of surge motion responses for the Collinear 'In-line' cases for the FPSO with mooring
- 1078 lines exposed to irregular waves only and irregular waves, current and wind.



- 1082 Fig. 49. Statistical values of tension response of the loaded line (L-1) for the Collinear 'In-line' cases for the FPSO
- 1083 with mooring lines exposed to irregular waves only and irregular waves, current and wind.



1086 Fig. 50. Statistical values of surge motion responses for the Collinear 'In-line' case exposed to irregular waves

1087 only and Non-Collinear cases exposed to irregular waves, current and wind, FPSO model with mooring lines





1091 Fig. 51. Statistical values of tension response of the loaded line (L-1) for the Collinear 'In-line' and Non-collinear

1092 cases for the FPSO with mooring lines exposed to irregular waves only and irregular waves, current and wind.