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Mooring analysis of a weathervaning FPSO in bi-directional sea-states

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ABSTRACT

Experimental studies were carried out at the Institute for Ocean Technology, Canada, in collaboration with the University of Western Australia (UWA) to assess the response of a moored 1:60 scaled Floating Production Storage and Offloading (FPSO) model in bi-directional sea-states. The seastates comprise of a regular swell approaching in the head sea condition, and a JONSWAP wind sea approaching at various angles. The FPSO was moored in position by four spring-loaded mooring lines attached to an internal turret about which the model could weathervane. Previous papers by the authors have described the unpredictable yaw instability of the FPSO driven by long period swells, which was evidenced in the experiments. This creates difficulties in comparing motions from uni-directional and bi-directional seas, because the headings alter the response. However, the mooring tensions are relatively immune to yaw instabilities and this paper discusses effects of bi-directional seas on the mooring tensions.

Numerical simulations are conducted using a time domain analysis software which simulates the motions of floating and moored structures in response to irregular seas. Simulations based on the software when compared with model tests at 45, 60 and 90 deg separation between the sea and swell shows reasonable agreement in terms of mooring tensions. Simulations are then conducted for a range of separation angles, and the effects of bi-directionality are further evaluated. It is found that a linear addition of the individual seastates can produce non-conservative results, which reinforces the fact that bi-directional seastates are important considerations for offshore operations of an FPSO.

INTRODUCTION

Floating Production, Storage and Offloading (FPSO) systems are attractive options in the development of marginal fields with a short field life. FPSOs are ship-shaped vessels deployed to produce from subsea wells. They can be disconnected at the end of the field life, in principle, and moved to other locations for further production. The ability to store produced fluid is an important feature of FPSO, and enables application in remote fields. Offloading is made possible by means of shuttle tankers.

An FPSO may be moored by several lines connected to a freely rotating internal turret. Thus the FPSO can rotate naturally and position itself in the direction of maximum environmental forces. This process is called as "weathervaning". The weathervaning process is strongly influenced by the nonlinear drift loads on the hull. Further, in complex sea states different environmental forces such as wind-sea, swell, wind and current arrive from different directions. This makes any prediction of intended weathervaning direction unreliable. Leite et al. (1999) discuss the directional stability of an FPSO in waves and current. These authors have discussed the use of rudders to maintain the heading of the FPSO.

Some studies on multi-directional metocean conditions have been published. Bitner-Gregerson (2005) for example published a model for joint probability of seas and swells. Young (2003) suggests that there is no universal correlation between wind-driven seas and long period swells, and these can virtually have any relative direction of propagation. Toffoli et al. (2006) found that the nonlinear interaction between various sea components can be significant if the components are slightly separated in their directions.

The responses of moored floating offshore structures in a complex sea are essential for the analysis of mooring and positioning problems. For a weathervaning FPSO, the surge, sway and yaw motions are driven by the slow-drift effects, while heave, roll and pitch are mainly wave-frequency responses. The actual motions may depend on specific details of the sea state such as directionality. Yadav et al. (2007) found that an FPSO exhibited yaw instabilities in regular waves when the wave length to ship length ratio was in the range 0.6 – 1.7. This affected the motion response due to relative heading changes. Sphaier et al. (2002) discussed the stability of an FPSO during offloading and emphasized the importance of eigenvalue analysis for stable design of single point mooring (SPM) units.

Ewans and Shaw (2003) described the response statistics of a weathervaning LNG FPSO. They illustrated the dependency of the vessel heading on the direction of the wind-seas and swells and how these contributed to the motions of the FPSO. They pointed out the significance of roll motions as the single most important response parameter for a side-by-side offloading operation. Roll was in turn critically dependent on the relative direction of the swell to

the vessel which itself was largely aligned with the wind-sea and wind.

Wave bi-directionality plays an important role in fatigue damage estimates. Conventional fatigue calculations are normally based on one scatter diagram combined with a Pierson-Moskowitz, JONSWAP or Torsethaugen wave spectrum. Different directions and contributions between sea and swell are not taken into account. A refinement of this methodology for bi-directional seastate would be to calculate fatigue damages separately due to sea and swell and sum to obtain the total damage. Andersen et al (2008) proposed a new approach on fatigue assessment for non-collinear sea and swell. Their methodology combines the stress response spectra from sea and swell in order to calculate the total damage. The results showed that the conventional approach may give non-conservative fatigue damage estimates on the swell exposed side of the FPSO. The importance of wave directionality on fatigue design of flexible risers was emphasized by the study de Lemos et al. (2003), in particular for those deployed with a weathervaning FPSO.

Our research is focused on behavior of FPSO in complex, bi-directional and bi-modal sea states. The seastates considered here comprise of a monochromatic swell in the head sea direction, combined with a wind-generated spectral sea coming from various angles with respect to the swell (Fig. 1). Previous papers by the authors (see e.g. Yadav et al. 2007) showed complex motion behavior of the FPSO in such seastates. In this paper, we present the influence of seastates on mooring tensions. Further, we wish to investigate the conservatism of common industry practice of linearly superposing the loads from various directions. Numerical simulations backed by experimental studies are reported in this paper.

EXPERIMENTAL CAMPAIGN

The tests were conducted at the Ocean Basin, Institute of Ocean Technology, National Research Council, Canada. The basin is 75m long, 32m wide and 3.2m deep. The basin is equipped with 168 hydraulically actuated individual wave-maker segments in 'L' configuration. This allowed wind seas and swells to be generated at a relative angle varying from around $30^\circ - 90^\circ$. Fixed and movable passive absorbers were installed at the opposite ends of the basin to maintain reflected energy under 5% incident.

The experiments were carried out on a 1:60 scaled down model of a generic FPSO fitted with an internal turret. The FPSO model characteristics are given in Table 1. The bottom of the turret was a circular turntable where four mooring lines were attached at 90° separation (Figs. 1 and 2). The mooring lines were pre-tensioned and equipped with inline load cells (Fig. 3) for measuring the tension in the lines. The model was free to pivot around the turret. A water depth of 2.8 m (168 m full scale) was used for the tests. It was equipped with a 6 DOF optical tracking system to measure the motions. In addition, a six-axis inertial system was used to record the three linear accelerations and the three angular velocities. An accelerometer was also used to record the vertical accelerations of the FPSO model. All

Figure 1. FPSO orientation and convention

Figure 2. Model test mooring layout

Figure 3. Load cells attached to FPSO Model

the instruments had a very good resolution and repeatability, with measured errors typically in the order of 0.1 - 0.5%.

Prior to installing the FPSO model in the basin, all the sea states were run with an array of wave probes in place of the model. The measured waves were compared against input conditions. In regular waves, the measured wave heights were used for calculating the Response Amplitude Operators for the FPSO model.

Table 1 Model Characteristics

Parameter	Notation	Value	Unit
Overall Length	L	5.849	M
Length between perpendiculars	L _{pp}	5.300	M
Beam	W	0.954	M
Depth	D	0.470	M
Draft	d _f	0.176	M
Displacement	D _{hydro}	672	Kg
Displacement (measured)	D _{measure}	675	Kg
Metacentric Height	GM	0.462	M
Vertical Centre of Gravity, above keel	VCG	0.284	M
Longitudinal Centre of Gravity, fore of aft perpendicular	LCG	2.873	M
Transverse Centre of Gravity	TCG	0.000	M
Vertical Centre of Buoyancy	VCB	0.091	M
Longitudinal Centre of Buoyancy, fore of aft perpendicular	LCB	2.873	M
Transverse Centre of Buoyancy	TCB	0.000	M
Longitudinal Centre of Flotation, fore of aft perpendicular	LCF	2.811	M
Transverse Centre of Flotation	TCF	0.000	M
Radius of Gyration about Roll Axis	r _{roll}	0.272	M
Radius of Gyration about Pitch Axis	r _{pitch}	1.404	M
Radius of Gyration about Yaw Axis	r _{yaw}	1.417	M
Prismatic Co-efficient		0.772	
Block Co-efficient		0.770	
Midship Co-efficient		0.998	
Waterplane Co-efficient		0.822	
Waterplane Area		4.076	m ²
Wetted Surface Area		5.427	m ²

Table 2 Decay Test Analysis

Degree of Freedom	Natural Period (sec)	Damping Ratio (%)
Surge	18.69	1.800
Sway	18.75	0.012
Pitch	1.46	1.070
Roll	1.56	1.310

Mooring stiffness tests were carried out to measure the restoring force characteristic of the moored FPSO model. Incremental forcing in the longitudinal and transverse directions with concurrent measurement of displacements were used to estimate the stiffness. Each mooring line consisted of a spring of spring stiffness 40N/m $\pm$ 5% and 1.5 mm (1/16 inch) stainless steel, 7x7 wire rope, which has a manufacturer listed Young's Modulus of 57.3 kN/mm².

Once the FPSO model was in place, decay tests were conducted in surge, sway, roll and pitch. A log-decrement calculation was performed to evaluate the natural periods and critical damping ratios as shown in Table 2. Heave

decay tests were not carried out since the relatively large heave stiffness makes setting up initial conditions difficult.

Tests were conducted in regular waves, uni-directional spectral waves, and a combination of the two at different angles. The swell was modelled by regular sinusoidal waves, and the wind-seas by a JONSWAP spectrum of different significant wave heights and periods. The relative separation between the sea and swell was set at 45°, 60° and 90°. Table 3 lists the wave conditions used in this study. Experimental data was acquired at a sampling frequency of 50 Hz and the center of gravity was the reference point for the motions.

Table 3. Environmental conditions used

Wave System	H _{ship}	T _{ship}	H _{model}	T _{model}
Swell 1	4.26	11.65	0.071	1.504
Swell 2	9.54	12.363	0.159	1.596
Swell 3	15.9	12.363	0.265	1.596
Wind -sea	7.98	11.999	0.133	1.549

NUMERICAL MODELLING

The numerical modelling was done with help of a boundary element software suite, AQWA. The full scale FPSO model was developed. The following software tools were used to perform analysis sequentially.

AQWA-LINE, a 3-D diffraction and radiation analysis program for structure response calculations, hydrostatic analysis and hydrodynamic analysis. AQWA-LINE file coordinates was derived from a table of offsets to define half the hull structure. A half-hull discretization was used as the model was symmetrical about the x-axis. A total of 861 diffracting elements were required as shown in Fig. 4.

AQWA-LIBRIUM, an eigen value analysis program to find the equilibrium characteristics of a moored or freely floating body or bodies. AQWA-LIBRIUM was used to investigate the natural periods of the FPSO model and to verify the same with the model decay tests. An important aspect of this is the iterative procedure as shown in Figure 5. The

Figure 4. AQWA model showing diffracting elements and mooring lines

linear damping from the decay tests were used as input into AQWA to obtain a good match in natural periods.

AQWA-DRIFT, is a time domain program for wave forces, structure motion and mooring analysis in sea spectrum. The hydrodynamic coefficients calculated in AQWA-LINE are used in AQWA-DRIFT for the time integration based on an input time step. A time step of one second was used in the analysis of the FPSO model in all analysis.

AQWA Post Processing

After the time domain calculations in AQWA-DRIFT, the results were post processed in AQWA-GS which hosts many tools for signal processing, result statistics etc.

DISCUSSION OF RESULTS

Validation of mooring line loads

In uni-directional wind sea condition, the RMS line tensions obtained from AQWA were compared with the model test results in Fig. 6. The graph shows that the simulated tensions for the SE mooring line are slightly higher than model test results by 5 – 8%. Intermediate heading angles were also run with AQWA, and a systematic trend is noticed in good agreement with model tests. Fig. 7 shows similar results for bi-directional seastates where the swell is in the head sea condition. Here too, AQWA results are over-predicting by 4 – 7%.

Figure 5. Numerical processing flow chart

Comparison of Wind Sea + Swell and Bidirectional sea states

Figures 8 - 11 show the maximum tensions for the four mooring lines for different environmental conditions. The common variable is the wind sea heading relative to swell (Fig. 1). There is clearly an increase in tension with increasing seastates corresponding to increased swell height.

The most loaded line is the SW line, corresponding to the occurrence of maximum loads. Also shown in the figures with filled symbols are corresponding results obtained by a linear sum of swell and seas. At the lower two seastates, the bi-directional condition consistently produces a higher tension for all headings. At the smaller heading of 30°, the tension obtained by linear summation can be up to 100%

Figure 6. SE Mooring Line load comparison for Unidirectional Wind sea

Figure 7. SE Mooring Line load comparison for Bidirectional Seas

lower than the result from bi-directional sea. This shows that loads on mooring lines may be under-predicted if a linear addition of seastate approach is used.

An interesting transition is observed at the highest seastate for a heading of 60°. For headings greater than 60°, the linear addition seems to produce a higher tension than the bi-directional seas. This difference is not as dramatic as the former case, and a maximum difference of 30% is noted.

Figs. 12 - 15 show corresponding results for RMS tension for the four lines. These tensions are important for evaluating fatigue loads on the lines. Again the bi-directional sea condition shows a much larger tension for most heading conditions. In moderate seastate condition, the most loaded line (SW) shows a maximum of 50% higher RMS tension in the bi-directional condition compared to linear addition of uni-directional conditions. Furthermore, it is seen that the 60° heading is most critical, with the most loaded line showing almost 50% higher loading in this heading.

Figure 8. SE mooring line maximum tension vs. wind sea heading

Figure 9. SW mooring line maximum tension vs. wind sea heading

Figure 10. NE mooring line maximum tension vs. wind sea heading

CONCLUSIONS

Model test results on a generic FPSO in bi-directional seastates were used to validate the numerical results for mooring loads. A good agreement between numerical results and model test results was found.

Further numerical studies highlighted the following:

- The loads on the mooring lines were dependent on the directionality of the wind sea and the ratio of the wave heights of the wind-sea and swell.
- The linear addition of the individual sea state mooring line tensions can produce non-conservative results.

Figure 11 NW mooring line maximum tension vs. wind sea heading

Figure 12. SE mooring line RMS tension vs. wind sea heading

Figure 13. SW mooring line RMS tension vs. wind sea heading

Figure 14. NE mooring line RMS tension vs. wind sea heading

Figure 15. NW mooring line RMS tension vs. wind sea heading

- The 60° wind sea heading appears to be critical for RMS tensions when the wind-sea and swell conditions are almost equal.
- For the higher ratios of swell to wind sea wave heights the linear summation of wind sea + swell mooring line tensions were in good agreement with bi-directional mooring line tensions.

In parts of the world where bi-directional sea states are regular features, the findings could have important considerations for fatigue life predictions of mooring lines. In particular, linear addition of seastates (and by extension cyclical loading) from various directions may lead to non-conservative estimates, as seen in this paper. Time domain simulations with multi-directional seastates would perhaps be a better indicator of the cyclical loading experienced by the mooring lines of a FPSO.

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