Design Aspects of Positional Mooring System Based on LR FOIFL Rules

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Abstract

Floating offshore units, such as FPSOs, are subject to dynamic excitations from the environment and require to be moored to maintain position at the fix location of operation. In designing positional mooring systems for floating offshore units, systematic analyses must be performed to predict tension levels in the mooring lines and offsets of the floating unit under extreme and ambient service conditions, in order to ensure the mooring arrangement provides a level of safety acceptable to the industry. In order to derive environmental loads pertinent to the location of operation, environmental data should be made available comprising of long and short term current, wind and wave characteristic data specific to the site of operation. Based on LR FOIFL Rules, the performance of positional mooring systems is assessed on the basis of sets of site specific extreme and ambient (or fatigue) environmental conditions. Class rules require consideration of extreme conditions with recurrence period of 100 years (e.g. combination of 100 year waves + 100 year wind + 10 year current). In the process of designing positional mooring systems of FPSOs, designers may start from quasi-static analysis at preliminary design stage, and then investigate various combinations of extreme conditions in the dynamic analysis for a more rigorous approach during the final design stage.The outcomes of the analyses have to be compared against industry standards such as the LR FOIFL rules to confirm the positional mooring system's design meets levels of safety recognised as acceptable to the industry. In this paper, an introduction to positional mooring systems for FPSOs, considering typical strength aspects is given, followed by a general description of hydrodynamic characteristics of ship shape FPSOs The design aspects of mooring system is then given in section outlining methodology in mooring analysis using either quasi-static or dynamic method.

Keywords: *FPSO; spread mooring; hydrodynamics; positional mooring system; station-keeping; quasi-static; Lloyd's Register; Floating Offshore Installation at Fixed Location.*

Introduction

The design of positional mooring systems depends on the motion of FPSO, therefore understanding the motion mechanics of FPSO's in waves and the interaction between the floater and the water waves is important. In many cases, when exposed to irregular waves in sea states, motions of FPSO can be treated as superposition of responses from regular waves of different frequencies. With this assumption, the wave interaction on a FPSO can be decomposed into the followings:

1) The action: the FPSO is restrained from moving and the incident wave makes contact with the FPSO resulting in scattered wave (diffraction wave). The scattering of the incident wave leads to wave frequency excitations (consisting of so-called Froude-Kriloff and diffraction forces and moments).
2) The hydrodynamic reaction: due to transfer of momentum from the above action, there is a tendency for the FPSO to move in 6 degree-of-freedom modes (i.e. 3 translations: surge, sway and heave; and 3 rotations: roll, pitch and yaw). Because the incident wave is regular, the response motion is also regular, and tend to push away the surrounding fluid in a harmonic fashion, generating 6 radiation wave systems (one for each degree of freedom), resulting in oscillating fluid pressure over the wetted surface of the body. The integration of such fluid pressure gives radiation forces and moments in-phase with FPSO motion velocity and FPSO motion acceleration (i.e. damping term and added mass term respectively):

$$F^{hydrodynamic} = -A\ddot{s} - B\dot{s} \qquad (1)$$

in which:

$F^{hydrodynamic}$ = total hydrodynamic reaction forces and moments

A = hydrodynamic added mass coefficients

B = hydrodynamic damping coefficients

$\ddot{s}$ = motion acceleration of FPSO

$\dot{s}$ = motion velocity of FPSO

3) The hydrostatic reaction: due to change in FPSO displacement, associated with heave, roll and pitch motion:

$$F^{hydrostatic} = -C\,s \qquad (2)$$

where:

$F^{hydrostatic}$ = total hydrostatic force

C = hydrostatic stiffness coefficients

s = motion amplitude of FPSO in j-direction

From the above expressions, by invoking Newton's second law (Δ momentum = total forces and moments) and considering that the distribution of mass of the FPSO is known, the equation of motion can be given by:

$$m \cdot \ddot{s} = F^{excitation} - A\ddot{s} - B\dot{s} - C\,s \qquad (3)$$

After ordering the terms, the general linear equation of motion is:

$$F^{excitation} = (m + A)\,\ddot{s} + B\dot{s} + C\,s \qquad (4)$$

where:

m = mass and inertia coefficients

$F^{excitation}$ = wave frequency excitation

Equation (4) governs the motion of FPSO due to one diffraction and six radiation wave systems. All hydrodynamic coefficients are in the order of 6x6 matrices and all motions are fully coupled. However, typical FPSOs have body symmetry to vertical-longitudinal plane, thus "symmetric motions" (surge, heave and pitch) do not couple "anti-symmetric motion" (sway, roll and yaw). This condition reduces complexity of hydrodynamic matrices considerably as some of their elements can be set to zero. A boundary element method can be setup to obtain dynamic pressure and subsequently forces and moments of excitation, thereafter compute the motion through equation (4).

In practice, wave frequency (first order) motions of FPSOs are characterized by their RAO (Response Amplitude Operator) indicating a ratio between input wave heights and output response amplitude over a range of frequencies. Commercial software, e.g. AQWA could be used to compute RAO, associated with respective mode of motion, and would normally be computed at least for head, quartering and beam seas.

Non-linear effect on moored FPSO in waves

When moored in head waves, the total forces experienced by an FPSO can be split into: mean-drift, wave frequency and slowly-varying loads. The mean-drift forces can be regarded as static component of the wave load, while the high (or wave) frequency forces (of first order) and the low frequency forces (of second order and non-linear nature) form the dynamic components of the wave loads. In order to illustrate such forcing components, reference is made to a figure from API RP 2SK (see reproduction in figure 1 below) which depicts well the various components of the wave loading (i.e. steady component of mean-drift, the low frequency component of slowly varying load and the higher component of wave frequency load.

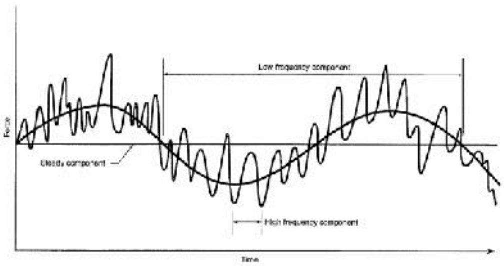

Figure 1 Mean, wave frequency and low frequency wave force components (from API RP 2SK)

In the above figure, the steady component is associated with mean-drift force and stems from second order hydrodynamics. However the drift forces, as well as wave frequency component, are computed through first order solution which can be readily obtained from diffraction analysis software.

Maruo (see, Faltinsen, 1990) proposes that horizontal drift force is dependant on structure ability to create reflected waves. The larger the mean wave-drift, the bigger is the low frequency force. According to Maruo, when the FPSO motion is large, due to resonance, reflected wave is also large. This means for a moored FPSO, low frequency excitations are at their peak around the system natural frequency. Furthermore, horizontal damping for a moored FPSO is low due to relatively larger FPSO hull inertia compared to the mooring line. Such combination of large force and low damping would result in large amplitudes of motion in surge, sway and yaw with frequency lower than wave frequency motion (i.e. heave, roll and pitch). In order to visualize the difference between wave frequency and low frequency motions, below is a time trace extracted from a model FPSO test in regular head waves. Figure 2 shows heave and pitch responses in frequency trend similar to incoming wave frequency, whereas slowly-varying amplitude surge response exhibits lower frequency / larger period.

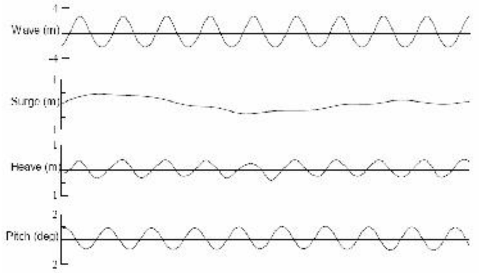

Figure 2 Illustration of response motion of moored FPSO model in head wave (courtesy of IHL)

In shallow water mooring, the non-linear behavior of low frequency component is worsened. The mean-drift force would increase due to shorter wave length and due to the modified FPSO behaviour in low draft / water depth ratio. This is intensified by so-called set-down phenomenon where long waves bound to the incoming short wave contributing to the increase of low frequency force component. (Pinkster, 1992)

In many ways, model tests provide valuable additional results on the positional mooring system's behaviour and enable calibration and and validation of the numerical tools used for FPSO's motions and subsequently mooring line tensions predictions. This is because sources of uncertainties in the compution, e.g. viscosity, are sometimes unable to be discerned by numerical modeling. This appreciation of testing on model scale is recognized by classification societies around the world, such as Lloyd's Register.

1. Mooring Analysis of FPSO

The two previous sections focus on wave excitation of the hull (or floater). In reality, FOIs are also subject to wind and current. Wind contribution is normally taken into account using mean wind speed with associated recognized wind gust spectra and wind load coefficients (from wind tunnel tests) and is regarded as dynamic while the current can generally be regarded as static and can be computed using, in the case of FOIs with ship shape hulls, formula from OCIMF publication. In essence, designers should account for all project-specific environmental parameters for which the FPSO is to be considered. The design environmental criteria are normally given in the form of sets of combinations of 100-year sea state + 100-year wind + 10-year current or 100-year sea state + 10-year wind + 100-year current.

The importance of selecting the correct environmental parameter in mooring analysis can be best shown from turret moored FPSO cases, where the equilibrium position and heading are reached through equilibrium of environmental loads acting simultaneously on the FOI. In such case directionality of environmental data is essential. The sensitivity of the responses of weather vaning FPSOs to the non collinearity of the environmental parameters remains much greater than that of spread moored FPSOs and such aspects need to be accounted for in the design of single point mooring systems to capture critical responses. A method to determine wind-sea dominated response of turret positional mooring system can be found, for example, in Aryawan, et.al.(2008). The design of spread mooring systems for FPSOs is often based on omni-directional criteria, although in such case, as highlighted by Forristall (2004), could result in a spread positional mooring system being designed stronger in one direction than another. For classification, LR requires the positional mooring system of FPSOs be analysed for specific combinations of return periods of environmental parameters as well as for directional combinations of environmental parameters to which the FPSOs may be subject to during their service life.

This paper will now limit its focus to the somewhat simple design aspects (in terms of scope of analysis) of spread positional mooring systems.

Quasi-static analysis

In the process of designing positional mooring systems of FPSOs, a number of different methods are available. Typically, designer may start from static method at preliminary design stage, where designer uses catenary equation in order to determine mooring stiffness and line tension. MacDonald (1984) has developed a non-dimensional catenary relationship, which can be easily used in problems of low numbers of mooring lines and load cases. Based on the catenary equation, the mooring restoring force is obtained by offsetting the FPSO at prescribed horizontal positions in each direction from its origin. A typical result from static analysis is an "offset-tension & restoring curve", as in the figure below.

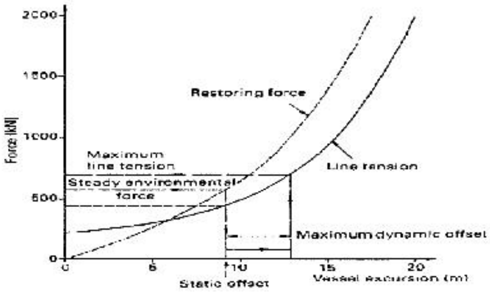

Figure 3 Restoring force and most loaded line from a static analysis (Chakrabarti, 2009)

From the above graph, components of steady environmental forces from wind and current can be computed empirically using OCIMF formula. The static offset from wave-drift and dynamic offset from wave frequency motion can be obtained from model test data of geometrically similar FPSO and comparable Hs / Tp combination. For example, typical output from a statistical analysis in model test of a spread moored FPSO in regular waves is shown in the table below for head sea.

Table 1 Typical statistical analysis based on model test of spread moored FPSO in regular waves (courtesy: Indonesian Hydodynamic Laboratory)

WNW (180deg), Hs = 3.02m Tp = 8.1sec (1 yr return) (Test No. 11.1)

		STATISTICAL ANALYSIS								
		Mean	Std	A1/3 +	A1/3 −	2A1/3	Amax +	Amax −	2Amax	No
Roll	(deg)	0.00	0.15	0.23	−0.23	0.57	0.45	−0.44	0.77	540
Pitch	(deg)	0.00	0.38	0.31	−0.30	1.47	1.51	−1.35	1.88	518
Yaw	(deg)	0.00	0.11	0.14	−0.14	0.21	0.35	−0.42	0.58	1256
Surge	(m)	−0.20	0.58	0.24	−0.31	0.95	2.05	−2.50	2.60	142
Sway	(m)	0.02	0.11	0.17	−0.16	0.21	0.41	−0.35	0.51	1877
Heave	(m)	0.00	0.14	0.21	−0.23	0.37	0.43	−0.49	0.76	614

The dominant motion in the above table is surge, where its mean value is considered as a result from mean wave-drift force. The dynamic offset is read off from maximum amplitude, A_{max}. Noted that the (-) sign in this table is related to the global coordinate system on the bottom of model basin and absolute value can therefore be used without loss of meaning.

This step could be considered as first approach in determining mooring line characteristics where gross preliminary estimates on nominal chain diameter or catenary length can be obtained. Further refined calculation is required to account dynamic effect of wave load.

The next level of complexity is the quasi-static analysis, where the motion of FPSO is computed through hydrodynamic analysis. Either time domain or frequency domain simulation can be applied taking into account mooring line and catenary stiffness. However, line dynamic effects and coupling between FPSO and the mooring lines are ignored (i.e. mooring lines are treated statically). Mooring line tensions are basically obtained from offset-tension and restoring curves similar to Figure 3. The main difference with the static method is that influence of added mass / damping from the FPSO's hydrodynamics are incorporated, but not from the line.

A step-by-step procedure in quasi-static is illustrated in Table 2 with reference to Chakrabarti (2009). In this table, calculation of low frequency force requires careful consideration. As stated in section (3), low frequency excitations are at their peak around the system natural frequency.

Furthermore, horizontal damping for a moored FPSO is low due to relatively larger FPSO hull inertia compared to the mooring line. Such combination of large forces and low damping can result in high dynamic amplification in surge and sway

When time domain method is selected, simulations are to be of sufficient length to establish reasonable confidence levels in the predictions of second order effect contribution to maximum response.

Table 2 Guidance of step-by-step procedure in quasi-static mooring analysis (Chakrabarti, 2009)

Steps	Outcomes
Input: line characteristics including coordinates and unit weight as well as cable stiffness.	-
Systematically offset the FPSO from origin. Calculate line tensions and sum of the vectored tensions representing restoring force of spread mooring	Line tension vs displacement for each catenary line. Line stretching or sea bed friction could be included in catenary equation
	Net horizontal restoring forces (offset curves).
Calculate: 1. steady wind, current and mean wave-drift forces 2. motion at wave frequency and low frequency	Calculate: FPSO offset and peak line tensions based on offset curves.
Calculate safety factor	Check and compare with project specific design standard quasi-static criteria. Adjust suitable parameter accordingly and re-calculate offset and peak tension.
Assume most loaded line broken and repeat the process to determine peak tension	-
Continue with different headings and loading conditions	-

Dynamic analysis

In this analysis, the effects of FPSO's motions on mooring line dynamics are included in the calculations. The most common method in solving line dynamic is the so-called lumped mass method, where a mooring line is discretised into small segments, each of which is associated with dynamic (mass and inertia) and hydrodynamic (added mass and inertia as weel as viscous drag) properties connected by massless springs.

In time domain analysis, the governing equation is solved incorporating wind, current and wave-drift force at each time step. Standard rules such as LR FOIFL 2008 as well as API suggest time domain simulation be repeated with different seeds in order to establish reasonable confidence levels in the predictions of maximum tension loads and offsets. API RP 2SK recommends that determination of extreme value should be taken as average value of five to ten three hours fully dynamic time domain simulations.

Apart from time domain, Lloyd's Register also allows dynamic computation in frequency domain where tensions due to low frequency and wave frequency excitation can be computed separately. In wave frequency analysis, the effects of line dynamic also need to be accounted for but this requires a linearization formulation to capture in so far as possible the non linear behaviour of the mooring lines' dynamics. Tensions and offsets maxima are then derived from combinations of statistical parameters of the responses as indicated below,

1) Maximum Response = mean + significant low frequency + maximum wave frequency

or

2) Maximum Response = mean + maximum low frequency + significant wave frequency

whichever is the greater.

A case study

This section highlights the typical main steps from input and output parameters of mooring analyses based on a fictitious case. A 149,000 tonnes displacement FPSO is permanently spread-moored with 8 mooring legs of 102mm grade R4 chain, at 32m water depth. The project is required to assess the behaviour of the vessel positional mooring system under extreme weather conditions.

<u>Vessel particulars</u>:

Table 3 Particulars of the FPSO

Full load		*Ballast*	
Length OA	: 251.20 m	Length OA	: 251.20 m
Length BP	: 240.00 m	Length BP	: 240.00 m
Breadth	: 37.40 m	Breadth	: 37.40 m
Depth	: 21.05 m	Depth	: 21.05 m
Draft mean	: 15.12 m	Draft mean	: 7.74 m
Draft Fwd	: 15.12 m	Draft Fwd	: 7.74 m
Draft Aft	: 15.12 m	Draft Aft	: 7.74 m
Displacement	: 137,281 tonnes	Displacement	: 72,243 tonnes

<u>Mooring arrangement</u>:

All lines are marked with L1, L2, L3, L4, L5, L6, L7 and L8; with pre-tension = 17mT. The mooring radius and arrangement can be seen as below:

<u>Stage 1</u>:

1) Frequency domain analysis is conducted using diffraction software. The following quantities are obtained, for a range of circular frequency and 30^0 interval angular directions:

   - Response Amplitude Operator (RAO)
   - Diffraction forces
   - Wave-drift force
   - Quadratic Transfer Function (QTF)
   - Hydrostatic stiffness matrix
   - Hydrodynamic frequency dependant added mass and damping matrices

2) Based on project specific environmental study, particulars data relevant to 100-year return period environmental is obtained.

Table 4 Site specific environmental data for the FPSO

Heading	Sig. Wave Height (m)	Peak Period (secs)	3 sec -wind Speed (m/s)	Current surface Speed (m/s)
North	2.5	7.2	44	1
East	2.9	7.6	44	0.7
South	1.4	5.8	44	1
West	2.6	7.3	44	0.7

<u>Stage 2</u>:

In the next stage, a fully dynamic analysis is conducted; therefore data related to mooring equipments are required. It should be noted that a size margin is to be included to allow for the corrosion and wear which can occur over the intended service life. Normal practice would be to associate the breaking strength with reduced nominal diameter of mooring chain based on corrosion and wear margins (e.g. 0.4 mm per year on diameter).

The influence of marine growth on drag and inertia properties of the mooring lines is also to be accounted for.

The following data are provided:

Corrosion allowance	: 0.4 mm/year
Service life	: 10 years
Chain diameter, D_{nom}	: 102 mm
Mass per unit length in water (from chain data)	: 0.194 te/m
Marine growth thickness, ΔT_{growth}	: 0.1 m (for water depth until 40m)
Cd (stud chain)	: 2.6
Specific gravity of growth, ρ_{growth}	: 1325 Kg/m^3
Specific gravity sea water, $\rho_{seawater}$	: 1025 Kg/m^3

Chain characteristic after corrosion:

Corrosion in 10 year	: 4 mm
Equivalent corroded diameter	: 98 mm
Corresponding $MBL_{corroded}$	: 9436 kN

For each direction in the environmental data above, simulation is run on each environmental direction of North, East, South and West with 2 load conditions (i.e. ballast and full load). To ensure that the most critical combinations of low frequency and wave frequency response are covered, a broad range of sea states represented by significant wave heights and peak periods is required to be investigated. In this case example, where adequate wave height/period joint distribution data is not available, a conservative range of wave period needs to be investigated in the design (e.g. in DNV RP-C205 Environmental Loads).

Other designs aspects to be included is the analysis of the positional mooring system in damaged condition (i.e. with any one line broken) demonstrating integrity of the system in the event of most loaded and second most loaded line failed.

The averages of maximum values are computed based on number of simulations using different seeding factor and the safety factors with regard minimum breaking strength are compared against Lloyd's Register minimum safety factor as stipulated in Part 3, Chapter 10 of LR FOIFL rules.

Conclusion

Typical spread moored FPSO subjected to dynamic excitations requires mooring analysis based on recurrence period of 100 years (e.g. combination of 100 year waves + 100 year wind + 10 year current). It has been illustrated in this paper that key elements for designing mooring systems are (1) behaviour of FPSO in irregular sea-wave and (2) characteristic of mooring system.

In the early stage of analysis, the characteristic of mooring system can be simplified by quasi-static assumption where the response of the mooring line follows the catenary equation. Based on this assumption, "offset-tension and restoring curves" can be obtained by stepwise offset of the FPSO radially from its origin in various directions. Once the environmental loads have been calculated, the FPSO offsets and line tensions are then read off from "offset-tension and restoring curve".

In later stage of the design process, more accurate predictions can be obtained in dynamic time domain analysis incorporating couple effect from the mooring line. The time domain mooring hydrodynamic analysis takes into account the inertia, damping and stiffness terms from the floater as well as non linear characterisics (e.g. drag, inertia and damping) of the mooring lines. The equation of motion is solved at each time step.

Lloyd's Register also allows dynamic computation in frequency domain where tensions due to low frequency and wave frequency excitation can be computed separately. Although in such analysis a linearization formulation is required to capture, in so far as possible, the non linear behaviour of the mooring line's dynamics. Maxima of tensions and offsets are derived from combinations of statistical parameters of the responses.

The non-linearity of FPSO's response due to low frequency excitation has been reported to have pronounced effect in the region of FPSO's natural frequency and prediction of such behavior is preferably supported by model test.

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