Effect of Water Depths on the Hydrodynamic Responses of an FPSO Platform

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Abstract. Ship-shaped Floating Production Storage Offloading platforms (FPSO) are commonly used in the production of oil and gas in offshore deepwater regions. The vessel is held in place by mooring lines anchored to the seabed during operation, either in spread or turret mooring arrangement. When designing such systems, water depth is a main factor that needs to be considered. At greater depths, the hydrodynamic properties of mooring lines become important and may not be accurately predicted through traditional experiments or numerical quasi-static models. Numerical simulation using coupled dynamic analysis is thus recommended, as the hull-mooring behaviour is analysed simultaneously, and the damping and added mass properties of the entire mooring line system is taken into account. This paper investigates the motions and mooring line tensions of a turret-moored FPSO at various water depths ranging from 1000 m to 2000 m. The analysis focuses on numerical simulations in the fully coupled dynamic time domain. The study utilizes the commercial software AQWA, with the FPSO model subjected to a unidirectional random wave condition. The hull hydrodynamics is first solved using the 3D radiation/diffraction panel method, and the hull response equation is then coupled with the mooring line equation. The dynamic motions and mooring line tensions results are presented in terms of statistical parameters as well as response spectrum. The results highlight the significance of greater water depths on low frequency responses in surge motions and mooring line tensions, and provides insight on the increasing and decreasing trend of these responses.

1 Introduction

In recent years, the offshore industry has seen an increased interest in the development of deep and ultra-deepwater fields. Floating platforms are the most viable option in these areas. The vessels generally utilise a system of mooring lines anchored to the seabed to keep the platform in place.

In shallow waters, the effects of mooring line damping due to environmental forces are relatively small. Such systems may be satisfactorily predicted via computationally inexpensive quasi-static uncoupled analysis, or physical testing of a full-scale model.

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At greater depths however, the mooring lines significantly affect the behavior of the system. Traditional and simplified methods used for predicting shallow water systems may thus be unfeasible or yield inaccurate results [1–4]. Therefore, it is important to incorporate the dynamics of the mooring lines in the analysis and design procedure. The coupled dynamic analysis is thus recommended and applied for a rigorous and accurate estimations of deepwater systems. Research have shown that the mooring line damping significantly affects the low frequency motions and mooring line tensions of an FPSO [5, 6].

This study further explores the influence of water depth on a floating platform and its mooring system. A shipped-shaped turret-moored FPSO is taken as a case study. The fully coupled dynamic analysis method is employed, concentrating on water depths between 1000 –2000 m. Prior to this, the numerical model has been validated against published results [7].

2 Methodology

2.1 Dynamics of a floating system

In analyzing the mooring lines, assuming no torque or twisting moment, the linear momentum conservation equation can be represented with respect to a position vector $\vec{r} = (s, t)$, in which s = arc length and t = time:

$$-(B\vec{r}'')'' + (\lambda\vec{r}')' + \vec{q} = m\ddot{\vec{r}} \quad (1)$$

$$\lambda = T - B\kappa^2 \quad (2)$$

The primes and dots are the spatial s-derivative and time derivative respectively; B = bending stiffness, T = local effective tension, κ = local curvature, m = mass per unit length, $\vec{q}$ = distributed force on the rod per unit length, and λ = Lagrange multiplier.

Assuming the rod is elastic and extensible:

$$\frac{1}{2}(\vec{r} \cdot \vec{r} - 1) = \frac{T}{A_t E} \approx \frac{\lambda}{A_t E} \quad (3)$$

Where E = Young's modulus, $A_t = A_e - A_i$ (outer – inner cross-sectional area).

The generalized Morison equation is used to define the normal component of the distributed external force on the rod per unit length, given as:

$$q_n = \rho C_I A_e \dot{v}_n + \rho C_D \frac{D}{2} |v_{nr}| v_{nr} + \rho C_m A_e |\ddot{r}_n| \quad (4)$$

C_I , C_D and C_m are the inertia, drag and added mass coefficients respectively; v_{nr} , $\dot{v}_n$ and $\ddot{r}_n$ are normal relative velocity, normal fluid acceleration and normal structure acceleration respectively; ρ = fluid density and D = local diameter. The rod's effective weight (net buoyancy) should also be included in q_n as a static load.

The cable dynamics is solved by discretizing the length of the cable into a number of finite elements. The equation is then combined with the hull response to compute the time domain equation of motion:

$$[M + M_a(\infty)]\ddot{u}_p + \int_0^\infty R(t - \tau)\dot{u}_p d\tau + K_H u_p = F_D + F^{(1)} + F^{(2)} + F_p + F_w + F_c + F_{WD} \quad (5)$$

where $\tilde{M}$ and $\tilde{M}_a$ are the mass and added mass matrix respectively, $\tilde{R}$ = retardation function matrix, $\tilde{K}_H$ = hydrostatic restoring coefficient, $\tilde{F}_D$ = drag force matrix on the hull, $\tilde{F}^{(1)}$ and $\tilde{F}^{(2)}$ = 1st and 2nd wave load matrix on the hull respectively, $\tilde{F}_p$ = transmitted force matrix from the interface, $\tilde{F}_w$ = wind loading, $\tilde{F}_c$ = current loading on hull, and $\tilde{F}_{WD}$ = wave drift damping force matrix.

2.2 Numerical simulation

Numerical simulations were carried out using the commercial software AQWA. The software is capable of analyzing floating platform responses using coupled dynamic analysis in either time or frequency domain. The 3D radiation/diffraction analysis was calculated for the hull hydrodynamics. The panel method was applied to compute the velocity potential using Green’s function. For the analysis of mooring lines, AQWA adopts the discrete lumped mass method to calculate the line responses. The general process is depicted in Figure 1.

Fig. 1. Numerical simulation process.

A turret moored FPSO is considered for case study. The hull design is based on the model provided by Kim et al. [5], and is found in Table 1 in the Appendix.

The FPSO is connected to a mooring system composing of 12 lines in a 4x3 configuration. The arrangement of the lines is depicted in Figure 2. The lines in each group are spaced five degrees apart from the adjacent line, and the location radius of chain stoppers on the turret turntable is 7 m. The general mooring line properties are found in Table 2.

Fig. 2. Mooring arrangement.

In order to maintain the mooring lines inclination angle from the seabed to the turret as close as possible to the system at 2000 m depth for all cases, the systems with depths less than 2000 m were artificially “truncated” and adjusted to match the total horizontal restoring forces. A visualization on the steps taken to achieve the above requirement is shown in Figure 3, some as suggested by [8]: by adjusting mooring line segments’ length, the extending the line length lying on the seabed, introducing clump weights and modifying the properties of the line lower segment. Table 3 provides the mooring line pretension and lengths of the segments suspended above the seabed in order to achieve the required state. Each line is composed of a combination of chain and polyester segments, with the top and bottom segment being chain and the middle segment as polyester.

Fig. 3. Mooring line inclination (side view).

The FPSO system is subjected to a unidirectional wave condition shown in Table 4, propagating from the vessel bow (the end where the turret is located) to stern (see Figure 3). The JONSWAP spectrum model is used, given below:

$$S(\omega) = \frac{\alpha g^2 \gamma^a}{\omega^5} \exp\left(-\frac{5\omega_p^4}{4\omega^4}\right) \tag{6}$$

Where ω_p = peak frequency, γ = peak enhancement factor, and α = constant relating the wind speed and wave peak frequency.

Current and wind are not considered in this study.

3 Results

3.1 Parametric study

Analysis was carried out for water depths ranging from 1000 m to 2000 m. All cases were simulated using coupled dynamic analyses, and were carried out in time domain.

3.2 Static offset

In order to maintain static equivalence for all cases during analysis, the static offset of each system was made to match as close as possible for all tested depths. Figure 4 shows the corresponding static offset results, which are relatively similar for all cases. In all cases, the systems showed a slight non-linear weakening in surge force due to the geometric non-linearity of the catenary mooring lines.

Fig. 4. Surge static offset.

3.3 Motions and mooring line tension

The motions and mooring line tension data are presented below. Tables 5 to 9 show the data of the surge, heave, roll and pitch motions, as well as tension of the combined major loaded lines 7, 8 and 9. Figures 5, 7-10 shows the corresponding motion and line tension spectrum of the systems. On the other hand, Figures 6 and 11 plot the peak responses of the surge and line tension spectrum respectively. The sway and yaw are assumed to have minor effects on the weathervane FPSO in unidirectional wave, hence are not included in this study.

It can be seen from Figure 5 that the surge is LF dominated, and one can observe, from Figure 6, a general linear decrease in peak response as water depth increases. Increasing the water depth also resulted in decreasing maximum offset and standard deviation for surge (Table 5). Meanwhile, water depth is shown to have a minimal effect on the mean surge motion, with a variation of less than 1 m throughout all cases. It is noted in Figure 6 however, that the surge response experiences a sudden jump in the response at the 1500 m depth, before resuming its declining trend.

Fig. 5. Surge spectrum

Fig. 6. Surge peak spectrum response.

For the heave, roll and pitch, the responses are wave frequency (WF) dominated, and no meaningful changes are observed by varying water depth (Figs. 7-9; Tables 6-8).

Fig. 7. Heave spectrum

Fig. 8. Roll spectrum

Fig. 9. Pitch spectrum

Concerning the major loaded mooring line tension, from Table 9 it is found that the mean value generally increases with increasing depth. The same is observed, although more erratically, for the maximum tension. Figure 11 shows that, for major loaded lines 7, 8 and 9, the response decreases with increasing water depth. The trend is observed to be similar to that of the surge response. It is noted that the mooring line tension is largely dominated by LF responses as shown in Figure 10, while the effects of WF responses are minimal.

Fig. 10. Combined line tensions 7,8,9 spectrum **Fig. 11.** Combined line tensions 7,8 ad 9 peak spectrum response.

From the analysis, it is clearly shown that the mooring system mainly defines the LF responses of a floating system. The hull itself has effectively little to no hydrostatic stiffness in the surge and sway, and thus the system is wholly reliant on the mooring lines for station keeping. This, coupled with the low mooring line damping, causes the natural period of the surge to be significantly larger compared to the peak wave period.

Additionally, the effects of the mooring line increases with increasing depth. As the water depth increases, the length of the line increases. Additional damping due to the mooring line drag and inertia becomes larger. In shallow waters where the line length is relatively short, these properties are small and can be; however, its influence increases at deeper waters. Thus, the mooring line damping plays a significant role in reducing the LF motions of a floating system in deepwater.

Consequently, as the mooring line forces in a turret-moored vessel is mainly dictated by the LF surge and sway, the response is naturally expected to follow that of the surge in this case.

Previously it is noted in Figures 6 and 11 that the responses experience a jump at the 1500 m depth. This is thought to be due mainly to the sudden increase in the mooring line pretension. The difference in pretension to the next analysed depth case is less than 8% until reaching 1400 m. At 1500 m, the pretension difference is 39%, nearly five times greater than that of the previous cases. The difference is then reduced to not more than 20% for the subsequent cases up to 2000 m.

In the floating system, the hydrostatic stiffness of the hull mainly influences the WF responses. The contribution of the mooring line stiffness is small compared to the hull itself. Due to the large hydrostatic stiffness of the FPSO, the natural period of heave, roll and pitch is short compared to the surge. Hence, WF responses of heave pitch and roll are independent of water depth.

In all cases, changes in water depth does not have an effect on the natural frequency of the system.

4 Conclusion

A study is conducted to investigate the response of a floating FPSO system at depths ranging from 1000 m to 2000 m, using coupled dynamic analysis. The system had previously been validated with an existing published study. Based on the results, the following conclusions can be drawn:

- The surge motion is governed by LF responses, and are mainly influenced by mooring line damping. As the water depth increases, the damping increases, and thereby reducing the surge response and maximum offset.
- Consequently, the mooring line tension spectrum response decreases as the depth increases, as the line tensions is directly affected by the LF motions, particularly the surge. The mean line tension however, increases with increasing depth.
- The WF responses heave, roll and pitch are primarily influenced by the hydrostatic stiffness of the floating hull, and are not affected by water depth.

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Appendix

Table 1. FPSO details.

Parameter	Units	Value
Production level	bpd	120000
Storage	bbls	1440000
Vessel size	kDWT	200
Length between perpendicular, Lpp	m	310
Breadth	m	47.17
Height	m	28.04
Draft (80% loaded)	m	15.121
Displacement	MT	186051
Surge centre of gravity from turret, CGx	m	-109.67
Heave centre of gravity from mean water level, CGx	m	-1.8
Frontal wind area	m ²	4209.6
Transverse wind area	m ²	16018.6
Roll radius of gyration at CG, Rxx	m	14.036
Sway radius of gyration at CG, Ryy	m	77.47
Yaw radius of gyration at CG, Rzz	m	79.3
Turret in center line behind Fpp	m	38.75
Turret diameter	m	15.85

Table 2. Mooring line details.

Parameter	Units	Chain	Polyester
Mass per unit length	kg/m	189.2	16.7
Diameter	mm	95.3	160
Stiffness, EA	kN	820900	187000
Normal drag coefficient, C _{DN}	-	2.45	1.2
Normal added inertia coefficient, C _{IN}	-	2	1.1

Table 3. Individual mooring line properties.

Depth (m)	Pretention (kN)	Line segment (m)		
		Top	Middle	Bottom
100	103	10	120	-
1000	589	121.9	1327.5	-
1100	585	121.9	1474.6	-
1200	612	121.9	1621	-
1300	601	121.9	1758.25	10
1400	644	121.9	1893.9	20
1500	896	121.9	1968	90.25
1600	1078	121.9	2092.5	110
1700	1283	121.9	2216.25	130
1800	1397	121.9	2360.5	130
1900	1330	121.9	2487	150
2000	1429	121.9	2689.4	91.4

Table 4. Environmental condition.

Parameter	Units	Value
Water depth	m	1829
Wave		
Significant wave height, H_s	m	12.19
Peak period, T_p	s	14
Spectrum	JONSWAP	-
Peak factor, γ	-	2.5
Direction	degree	180

Table 5. Surge statistical results.

Depth	1000	1100	1200	1300	1400	1500
Max (m)	126.95	126.50	126.31	125.88	125.87	126.89
Min (m)	95.71	96.01	95.96	96.07	96.07	96.15
Mean (m)	111.62	111.63	111.68	111.60	111.74	111.65
Std. dev. (m)	5.33	5.13	4.95	4.80	4.71	5.40
Depth	1600	1700	1800	1900	2000	
Max (m)	126.76	126.54	126.47	126.23	125.85	
Min (m)	96.34	96.61	96.72	96.90	97.17	
Mean (m)	111.71	111.72	111.75	111.77	111.74	
Std. dev. (m)	5.28	5.21	5.16	5.05	4.96	

Table 6. Heave statistical results.

Depth	1000	1100	1200	1300	1400	1500
Max (m)	6.41	6.40	6.40	6.39	6.40	6.37
Min (m)	-11.62	-11.59	-11.60	-11.59	-11.61	-11.65
Mean (m)	-1.89	-1.89	-1.89	-1.89	-1.90	-1.94
Std. dev. (m)	2.35	2.34	2.34	2.34	2.35	2.36
Depth	1600	1700	1800	1900	2000	
Max (m)	6.34	6.30	6.29	6.30	6.29	
Min (m)	-11.69	-11.72	-11.74	-11.73	-11.75	
Mean (m)	-1.98	-2.01	-2.03	-2.02	-2.03	
Std. dev. (m)	2.36	2.36	2.36	2.36	2.36	

Table 7. Roll statistical results.

Depth	1000	1100	1200	1300	1400	1500
Max (rad)	0.0167	0.0158	0.0158	0.0159	0.0156	0.0164
Min (rad)	-0.0168	-0.0156	-0.0153	-0.0153	-0.0149	-0.0169
Mean (rad)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Std. dev. (rad)	0.0042	0.0041	0.0041	0.0041	0.0040	0.0039
Depth	1600	1700	1800	1900	2000	
Max (rad)	0.0157	0.0151	0.0145	0.0140	0.0142	
Min (rad)	-0.0162	-0.0157	-0.0150	-0.0145	-0.0139	
Mean (rad)	0.0002	0.0002	0.0002	0.0002	0.0002	
Std. dev. (rad)	0.0038	0.0037	0.0037	0.0037	0.0037	

Table 8. Pitch statistical results.

Depth	1000	1100	1200	1300	1400	1500
Max (rad)	0.07422	0.07409	0.0741	0.0741	0.0742	0.0744
Min (rad)	-0.0643	-0.0643	-0.0643	-0.0642	-0.0643	-0.0640
Mean (rad)	0.0019	0.0019	0.0020	0.0019	0.0020	0.0023
Std. dev. (rad)	0.0178	0.0177	0.0177	0.0177	0.0178	0.0178
Depth	1600	1700	1800	1900	2000	
Max (rad)	0.0746	0.0748	0.0750	0.0749	0.0750	
Min (rad)	-0.0639	-0.0636	-0.0635	-0.0637	-0.0636	
Mean (rad)	0.0024	0.0027	0.0028	0.0027	0.0028	
Std. dev. (rad)	0.0178	0.0178	0.0178	0.0178	0.0179	

Table 9. Statistical results of combined line tensions 7,8,9.

Depth	1000	1100	1200	1300	1400	1500
Max (kN)	5072.1	5060.0	5077.0	5095.4	5125.0	5673.5
Min (kN)	520.0	436.9	498.3	499.4	633.8	1635.4
Mean (kN)	2380.3	2370.0	2434.5	2408.0	2562.8	3249.1
Std. dev. (kN)	757.8	755.8	727.4	722.9	683.0	698.3
Depth	1600	1700	1800	1900	2000	
Max (kN)	6006.8	6445.3	6655.9	6356.1	6526.6	
Min (kN)	2116.8	2705.0	3019.1	2772.1	3098.3	
Mean (kN)	3757.2	4340.0	4659.8	4448.0	4728.2	
Std. dev. (kN)	658.5	627.3	607.0	588.1	560.5	