International Journal of the Physical Sciences Vol. 6(11), pp. 2671-2680, 4 June, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.454
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Effect of time elapse after wave hitting on coupled Spar platform

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Accepted 20 April, 2011

Oil and gas exploration has moved from shallow to much deeper water now-a-days. Offshore compliant floating structure like Spar platforms in this region are competent deep water platform. As water depth increases operational Spar platforms experience more influence of mooring lines suggestively. So the motion analysis of platforms in deep waters requires counting the mooring upshot with spar hull. The most common approach for solving the dynamics of Spar platform is to employ a decoupled quasi-static method, which ignores all or part of the interaction effects between the platform and mooring lines. Coupled analysis in the present study includes the mooring lines and platform in a single model. This model can cope with the coupling conduct and match the forces, displacement, velocities and acceleration at the fairlead position along with all possible significant nonlinearities. The output from such analyses is essentially platform motions as well as a mooring line response. In actual field problems hydrodynamic loads due to wave and currents act simultaneously on Spar platform and mooring lines. In this finite element model, the entire structure acts as coupled in consistent manner. This offshore Spar platform model has been analyzed in regular wave of ocean environment. Surge, heave and pitch motion responses of coupled Spar platform is obtained after 1000 and 6000 s of storm. The behaviors of dynamic responses have been evaluated as noteworthy even for time elapse after wave hitting.

Key words: Deep-water structure, oil and gas exploration, offshore compliant floating, Spar platform, nonlinearities, ocean environment, mooring lines, coupling , time elapse, motion responses, wave hitting.

INTRODUCTION

Exploration and development of offshore oil and gas in shallow and intermediate water depths has traditionally been carried out using the conventional jacket type fixed platforms. As the water depth increases, fixed platforms become expensive and uneconomical. The prominence afterward shifts to floating production systems. Spar platform is such a compliant floating structure used for deep water applications of drilling, production, processing, storage and off-loading of ocean deposits. Numerous studies have recently been performed in order to assess the effect of the coupling on different offshore floating production systems/ Spar buoy (Ran and Kim, 1996; Ran et al., 1996; Ran and Kim, 1997; Omberg and Larsen, 1998; Chen et al., 1999; Gupta et al., 2000; Cobly et al., 2000; Ma et al., 2000; Chen et al., 2001; Kim et al., 2005, 2001a, b, c; Chen et al., 2006). Ma et al. (2000) have conducted parametric studies on Spar and TLP for different depths for deep water. Nonlinear dynamic analysis of structure is very substantial and needed to be considered properly (Islam et al., 2011a, b). Paulling and Webster (1986) established a consistent, nonlinear procedure for the prediction of the large-amplitude coupled motions, which comes from the stroke of wind, waves and currents on the platform and risers. Chen et al. (1999) presented the response of a spar constrained by slack mooring lines to steep ocean waves by two different schemes: a quasi-static approach (SMACOS), and a coupled dynamic approach (COUPLE) to reveal the coupling effects between a spar and its mooring system. In coupled dynamic approach, dynamics of the mooring system are calculated using a numerical

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program, known as CABLE3D. Ran et al. (1999) studied coupled dynamic analysis of a moored spar in random waves and currents (time-domain versus frequency-domain analysis). Tahar and Kim (2008) developed numerical tool for coupled analysis of deepwater floating platform with polyester mooring lines. Low and Langley (2008) presented a hybrid time/frequency domain approach for coupled analysis of vessel/mooring/riser. The vessel was modeled as a rigid body with six degrees-of-freedom, and the lines were discretized as lumped masses connected by linear extensional and rotational springs.

The method was found to be in good agreement with fully coupled time domain analysis, when used for relatively shallow water depths. Low (2008) used the same hybrid method to predict the extreme responses of coupled floating structure. Fan et al. (2008) studied the effect of coupling for cell-truss Spar platform. The Spar mooring/riser was modeled by three methods namely quasi-static coupled, semi-coupled and coupled. The results from frequency-domain and time domain analyses were compared with experimental data. Yang and Kim (2010) carried out coupled analysis of hull-tendon-riser for a TLP. The mooring line/riser/tendon system was modeled as elastic rod. It was connected to the hull by linear and rotational springs. The equilibrium equations of hull and mooring line/risers/ tendon system were solved simultaneously.

The existing traditional dealings of analysis pronounce that, the force and displacement of mooring heads and vessel fairleads are iteratively matched at every instant of time marching scheme while solving the equilibrium equations. However, the velocity and acceleration do not reportedly match. Further, the continuity of vessel and mooring is missing. In this process the major contribution of moorings in terms of drag, inertia and damping due to their longer lengths, larger sizes and heavier weights are not fully incorporated. This effect is more pronounced in deep water conditions. Furthermore, the behavior after a long period of wave hitting has not been assessed. The conduct at longer time state on Spar-mooring system may be severe. Hence, the main objective of present study is to idealize the Spar mooring integrated system as a fully/strongly coupled system as well as to study the damping effects on mooring lines and the importance of coupling effect on Spar platform.

For the study here, the fully coupled integrated Spar-mooring line system has been implemented. This essentially means that the large spar cylinder is physically linked with mooring lines at fairleads provided by six nonlinear springs. The mooring lines as an integral part of the system, support the spar at fairlead and pinned at the far end on the seabed. They partly hang and partly lying on the sea bed. Sea bed is modeled as a large flat surface with a provision to simulate mooring contact behavior. The mooring line dynamics takes into account the instantaneous tension fluctuation and damping forces with time-wise variation of other properties. The forces on mooring lines due to in sea state are drag, inertia and damping forces. These forces are active concurrently on Spar hull cylinder. Hence, it is not needed to match the force, displacement, velocity and acceleration at the fairlead location iteratively. The output from such analyses will be platform motions as well as a detailed mooring line response. The commercial finite element code ABAQUS/ AQUA is found to be suitable for the present study. Modeled spar-mooring system has been analyzed in effect of proper environmental loading at regular wave. The structural response behavior in steady state after 3000 and 10000 s of wave hitting have been extracted in the form of surge, heave and pitch motion.

METHODOLOGY

The growth of a non-linear deterministic model for coupled dynamic analysis, involves the formulation of a non-linear stiffness matrix considering mooring line tension fluctuations due to variable buoyancy as well as structural and environmental non-linearities. The model involves selection and solution of wave theory that reasonably represents the water particle kinematics to estimate the drag and inertia for all the six degrees of freedom. The static coupled problem is solved by Newton's method. In order to incorporate high degrees of non-linearities, an iterative time domain numerical integration is required to solve the equation of motion and to obtain the response time histories. The Newmark- β time integration scheme with iterative convergence has been adopted for solving the coupled dynamic model.

The equation of motion describing the Spar-mooring system equilibrium between inertia, damping, restoring and exciting forces can be assembled as follows:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F(t)\} \tag{1}$$

Where, [M], [C], [K] are the total mass, damping and stiffness matrices respectively of the Spar-mooring system. The 6 degrees of freedom (DOF) structural displacements are represented by {X} and the dot denotes differentiation with respect to time. The total Spar-mooring mass matrix of the system consists of structural mass and added mass components. The structural mass of the Spar-mooring system is made up of elemental consistent mass matrices of the moorings and lumped mass properties of the rigid Spar hull. The lumped mass properties are assumed to be concentrated at the CG of Spar hull. The added mass of the structure occurs due to the water surrounding the entire structure. Considering the oscillation of the free surface, this effect of variable submergence is simulated as per Wheeler's approach.

The total stiffness matrix element [K] consists of two parts, the elastic stiffness matrix [K_E] and the geometrical stiffness matrix [K_G]. The overall damping to the system is being offered by structural and hydrodynamic damping. The major damping is induced due to the hydrodynamic effects. It may be obtained if the structure velocity term in the Morison equation is transferred from the force vector on right hand side to the damping term on the left hand side in the governing equation of motion. The structural damping is simulated by Rayleigh damping.

The investigation of Spar platform considering actual physical coupling between the rigid vertical floating hull and mooring lines is possible using the finite element method. In actual field problems hydrodynamic loads due to wave and currents act simultaneously on Spar platform and mooring lines. In finite element model, the entire structure with acts as a continuum. This model can handle all non-linearities, loading and boundary conditions. The commercial finite element code ABAQUS/ AQUA has been utilized for the present analysis. The other reason to use ABAQUS is that its module AQUA appropriately models an off-shore environment. It is capable of simulating the hydrodynamic loading due to wave.

The equation of motion (Equation 1) has been solved using the above finite element code. It has the capability of modeling slender and rigid bodies with realistic boundary conditions, including fluid inertia and viscous drag (Jameel, 2008). The mooring lines are modeled as three dimensional tensioned beam elements. It includes the non-linearities due to low strain large deformation and fluctuating pretension. Hybrid beam element is used to model the mooring lines. It is hybrid because it employs the mixed formulation involving six displacements and axial tension as nodal degrees of freedom. The axial tension maintains the catenary shape of the mooring line. The hybrid beam element is selected for easy convergence, linear or non linear truss elements can also be considered with associated limitations. The beam element under consideration experiences the wave forces due to Morison's equation. The self weight and axial tension are duly incorporated. The 12×12 consistent elemental mass matrix consists of the structural mass and the added mass and respective mass moments of inertia. The force vector consists of the concentrated forces fx, fy and fz and the corresponding moments m_x , m_y and m_z at each node. The three dimensional stiffness matrix in ABAQUS is capable of including geometric stiffness matrix with elastic stiffness matrix. $[K_G]$ models the large deformation associated with mooring configuration. Instantaneous stiffness matrix with varying axial tension in the modified geometry takes into account the associated non-linearity. The structural damping is simulated by Rayleigh model. Hydrodynamic damping is dominant in case of oscillating slender member surrounded by water. As mentioned above, ABAQUS with module AQUA is fully capable of modelling the above mentioned forces in the integrated finite element model.

The Spar hull is modeled as an assemblage of rigid beam elements connecting its center of gravity, riser reaction points and mooring line fair leads. The radii of gyration and the cylinder mass are defined at C.G. The rigid Spar platform has been connected to the elastic mooring lines by means of six springs (Three each for translation and rotation, respectively). The stiffnesses of translation springs are very high, where as the stiffnesses of rotational springs are very low simulating a hinge connection.

RESULTS AND DISCUSSION

Floating structure like spar platform has been chosen allowing coupling of spar-mooring in ocean wave in 1018 m deep water is chosen. Sea-states are represented by two parameters, "H_s" (significant wave height) and "T_z" (zero up crossing period). Values of "H_s" and "T_z" used in numerical study is 6 m 14 s. These sea-states adequately cover the conditions of significant dynamic excitation for steady. The mechanical and geotechnical properties of the Spar mooring system under study are given in Table 1 and Table 2 with Table 2 demonstrating the hydrodynamic characteristics of sea environment. Mooring tensions are assumed to be equally distributed in all the four mooring lines. The Spar hull is expected to behave like a rigid body. When the wave forces act on the entire structure, participation of mooring lines in the overall response is well depicted. The variable boundary condition due to mooring anchor point are appropriately incorporated. Due to the ideal modeling, the solution is having difficulty in convergence. Responses of Spar and mooring lines under regular wave are extracted at 1000 and 6000 s, respectively of wave hitting.

Through the time domain analysis using step-by-step integration procedure, the response time histories are obtained for sufficient length of time so that the response attains their steady state. The analysis of Spar-mooring system for deep water condition has been performed up to a long length of 7000 s. This time limit is clearly more than 6000 s of wave hitting. To understand the mooring damping and coupling effect, two sets of responses are obtained. The responses in terms of surge, heave, pitch and mooring line tension are plotted between 1000 to 2000 s and 6000 to 7000 s respectively. The statistical characteristics of the Spar responses are also determined taking these time lengths of 1000~2000 s and 6000~7000 s duration. Detail evaluation obviously explains the Spar-mooring system responses due to coupled analysis after approximately 1000 and 6000 s, respectively of storm.

Response of Spar platform due to wave after 3000 and 10000 s of storm

This coupled form of structural modeling is the idealized in proper. It copes with effect of due to mooring lines in a consistent manner. It gives true behavior of spar-mooring system. This approach yields dynamic equilibrium between the forces acting on the spar and the mooring line at every time station. The computational efforts required for the coupled analysis considering a complete model including all mooring lines are substantial. The ability for more accurate prediction of platform motions by coupled analysis approach may consequently contribute to a smaller and less expensive mooring-riser system and hence a lighter Spar platform through a reduction in payload requirements.

The results are shown in Figures 1-20 (Figures 1-4 for surge, Figures 5-8 for heave, Figures 9-12 for pitch and Figures 13-20 for mooring line tension). Both the time series and power spectral density are presented through these figures. Statistical analysis in terms of maxima, minima, mean and standard deviation have also been exposed in Tables 3 and 4 for 1000 and 6000 s of wave hitting respectively.

Surge response

The time series of surge response after 3000 s of wave hitting at the deck level is shown in Figure 1. The peak of surge response ranges from +16.194 m to -13.658 m (Table 3). The nature of surge at the deck level is predominantly periodic as shown in Figure 1. This is why a single dominant peak occurs in surge response at

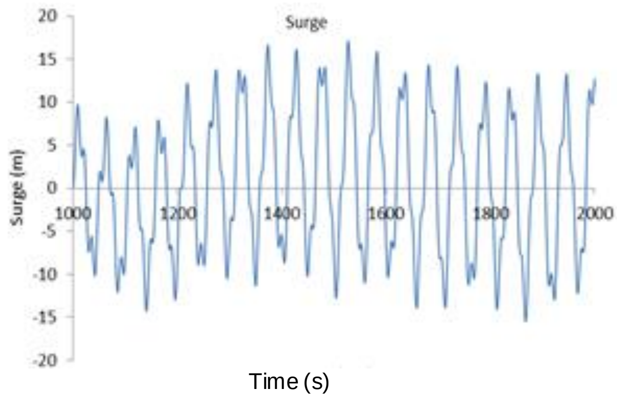

Figure 1. Surge time series after 1000 s of wave hitting

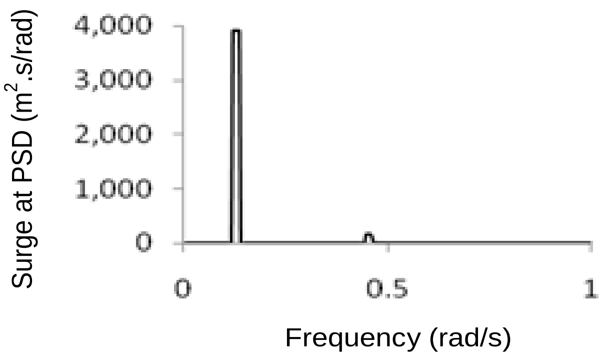

Figure 2. Surge response at PSD after 3000 s of wave hitting.

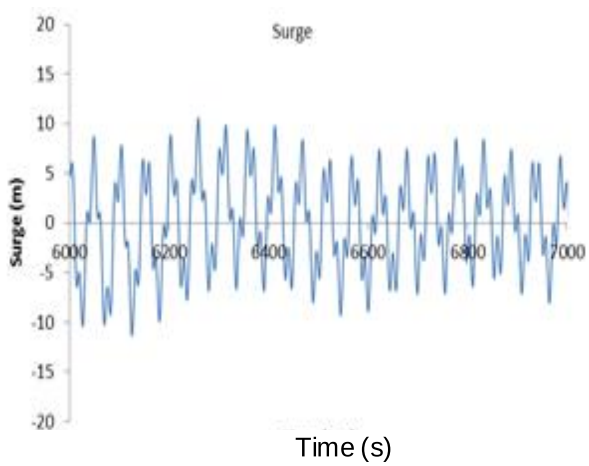

Figure 3. Surge time series after 6000 s of wave hitting.

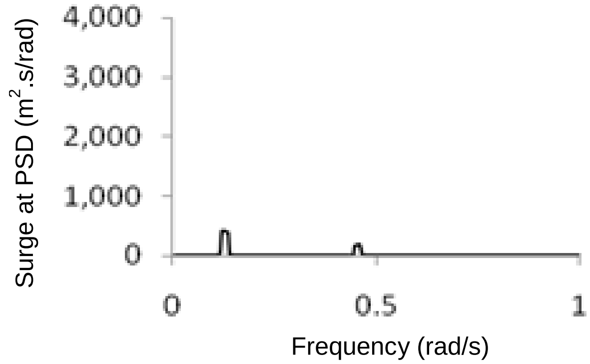

Figure 4. Surge response at PSD after 10000 s of wave hitting.

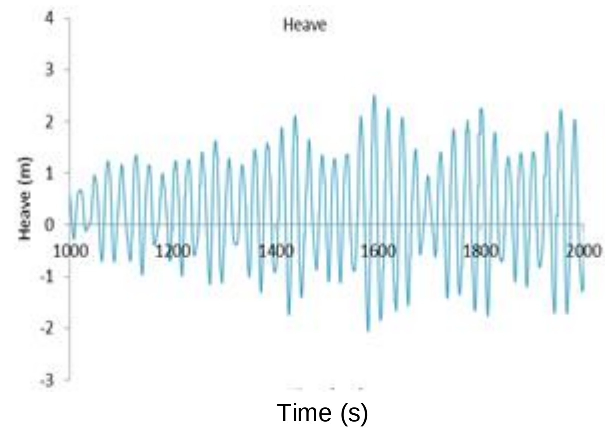

Figure 5. Heave time series after 1000 s of wave hitting.

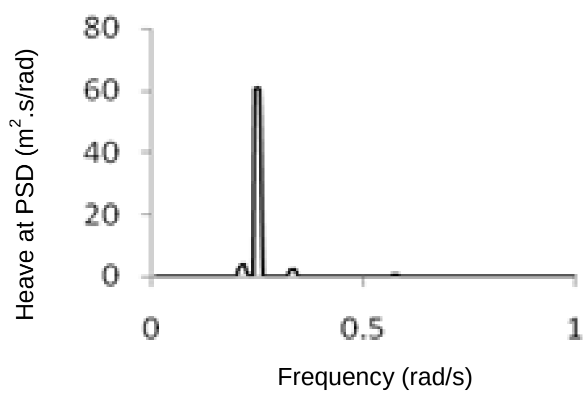

Figure 6. Heave response at PSD after 3000 s of wave hitting.

pitching frequency (Figure 2). The pitch motion (Figure 9) occurs simultaneously with surge and attracts significant wave energy close to the pitch frequency. Surge response requires huge energy input because of large inertia and hence do not get excited. However, pitching motion occurring with surge gets excited easily. The surge response at the deck level is mainly dominated by the pitching motion of the hull with insignificant excitation of surge mode. It is mainly due to coupling of surge and pitch. The power spectral density as shown in Figure 2 shows the participation of two frequencies. The small oscillation of the harmonic response occurs at a frequency of 0.452 rad/s. This is because of the natural

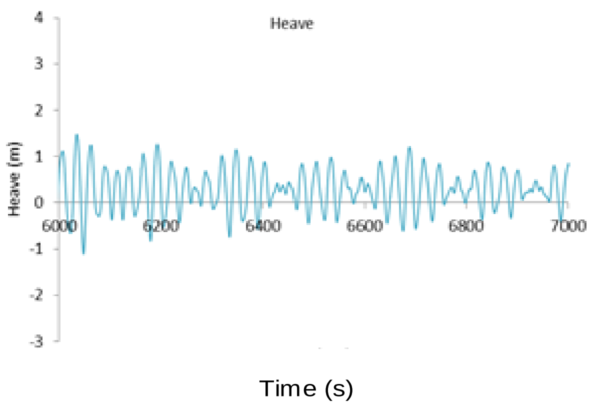

Figure 7. Heave time series after 6000 s of wave hitting.

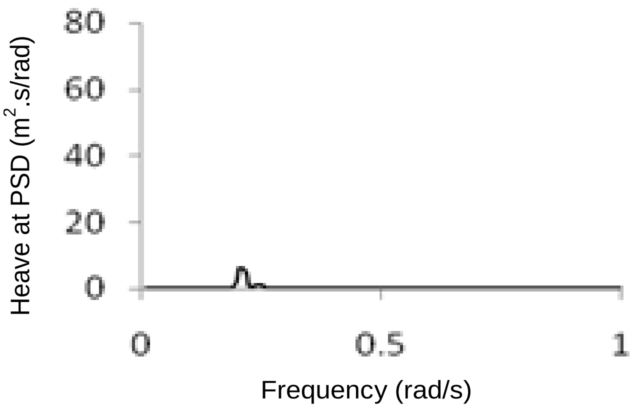

Figure 8. Heave response at PSD after 10000 s of wave hitting.

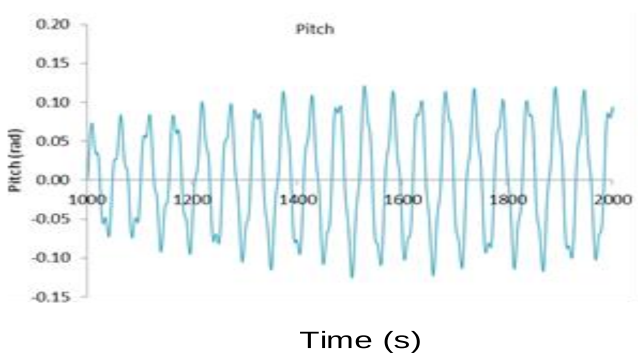

Figure 9. Pitch time series after 1000 s of wave hitting.

frequency. There is not at all evidence of any significant participation of other frequencies. Effect of non-linearity is not very strong on surge response.

The time series of surge after 6000 s of storm is showing a typical regular behavior as shown in Figure 3. The platform oscillates in regular fashion with maximum and minimum value of 9.583 and -10.260 m. The mean

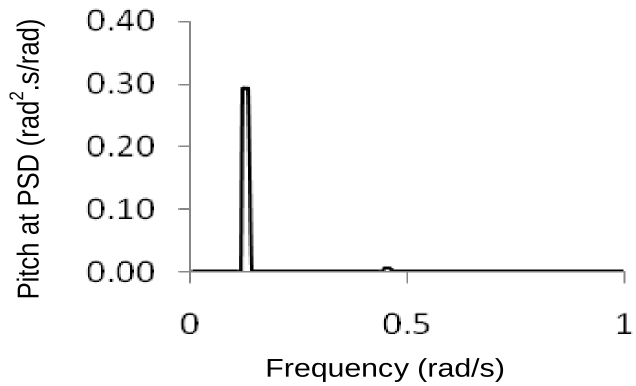

Figure 10. Pitch response at PSD after 3000 s of wave hitting.

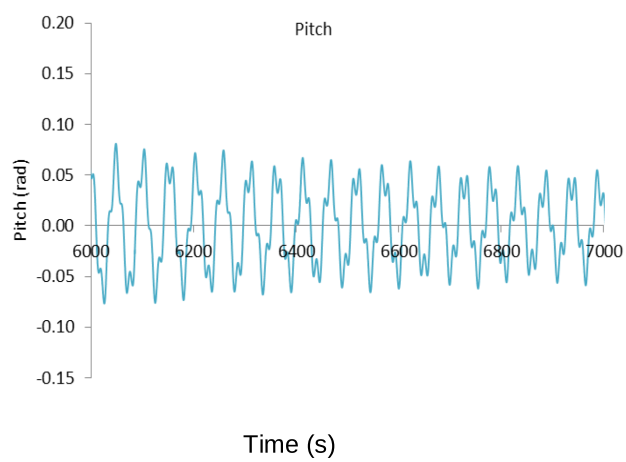

Figure 11. Pitch time series after 6000 s of wave hitting.

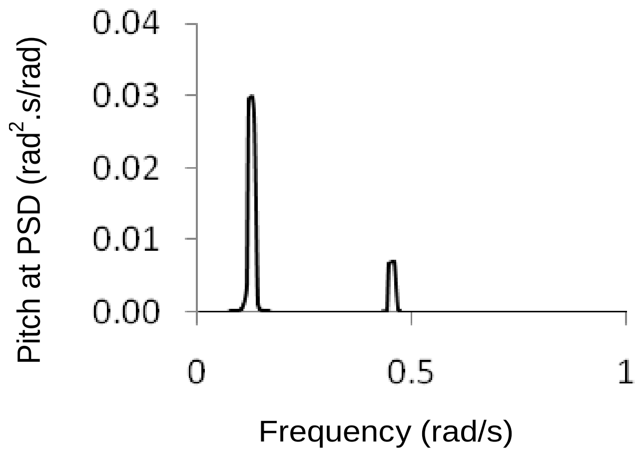

Figure 12. Pitch response at PSD after 10000 s of wave hitting.

value of surge is given by 0.457 m whereas the standard deviation of this distribution is found to be 5.561. On comparison of statistics with the surge response in

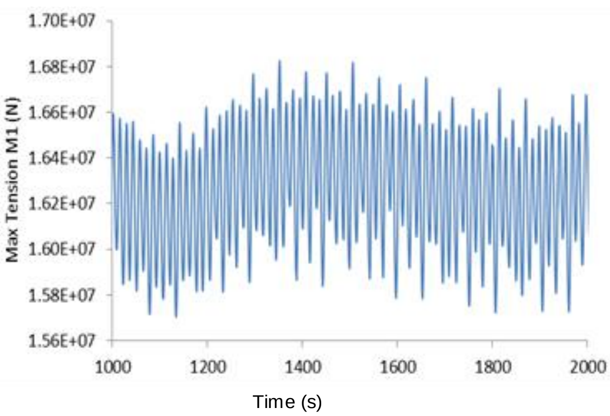

Figure 13. Maximum tension time series of Mooring line 1 after 1000 s of wave hitting.

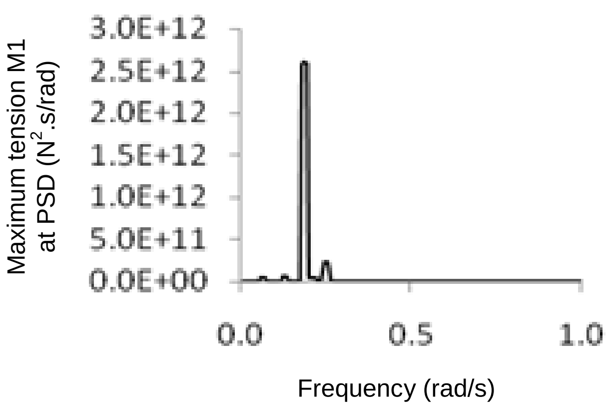

Figure 14. Maximum tension at Mooring line 1 at PSD after 3000 s of wave hitting.

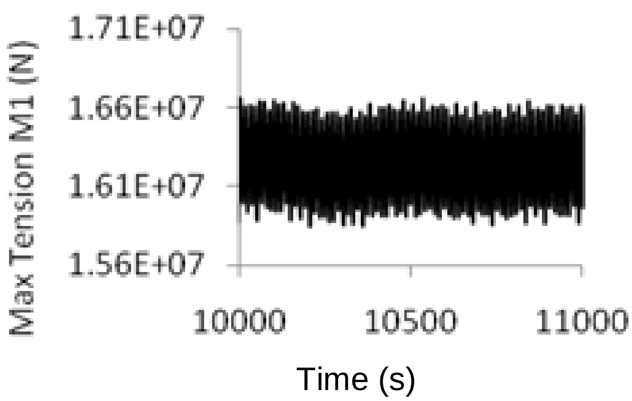

Figure 15. Maximum tension time series of Mooring line 1 after 10000 s of wave hitting.

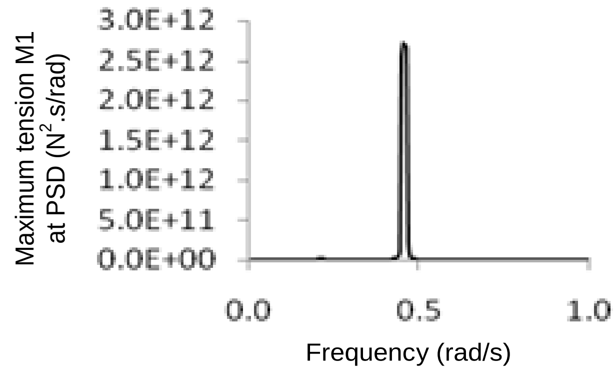

Figure 16. Maximum tension at Mooring line 1 at PSD after 10000 s of wave hitting.

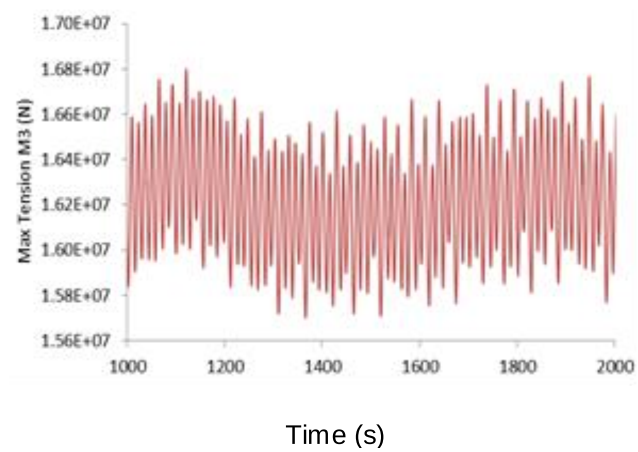

Figure 17. Maximum tension time series of Mooring line 3 after 1000 s of wave hitting.

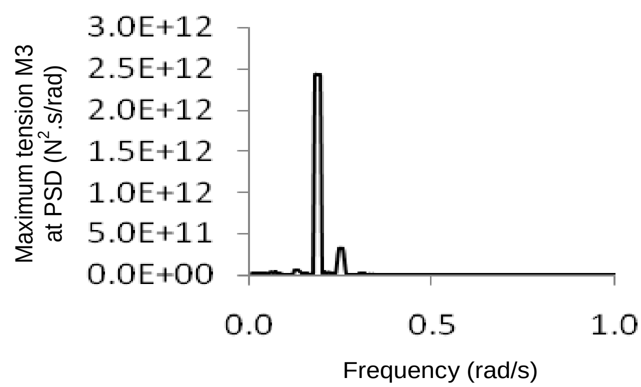

Figure 18. Maximum tension at Mooring line 3 at PSD after 3000 s of wave hitting.

regular wave (Table 4), the above trend is established. The surge time series power spectral density (PSD) at 6000 s plus time state shows two distinct peaks (Figure 4) at 0.133 rad/s and 0.464 rad/s. These peaks correspond to natural frequencies of surge and pitch respectively. The coupled stiffness matrix of the Spar mooring system significantly changes when the Spar hull undergoes a static off-set at time state 10000 s. The

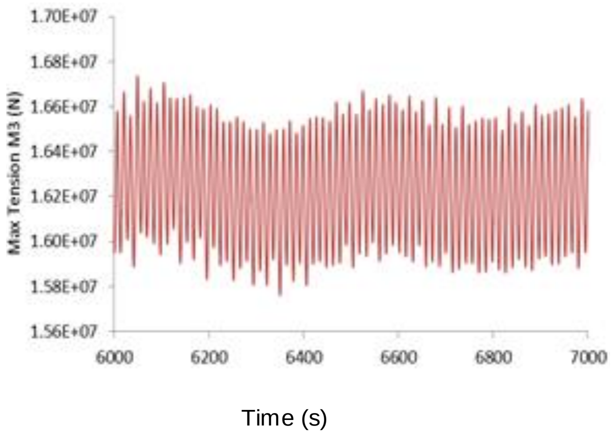

Figure 19. Maximum tension time series of Mooring line 3 after 6000 s of wave hitting.

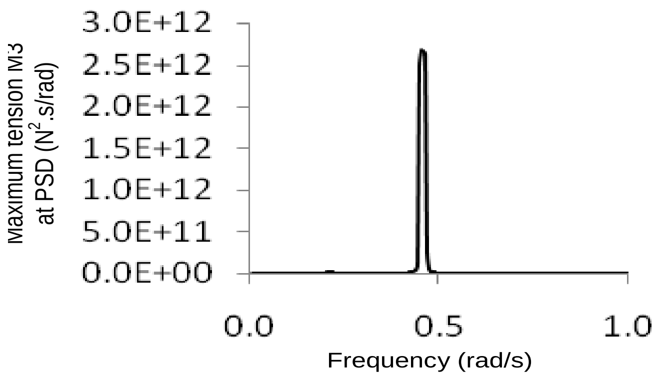

Figure 20. Maximum tension at Mooring line 3 at PSD after 10000 s of wave hitting.

forces in the mooring lines and their geometry changes appreciably. It is because mooring lines become taut, when the system oscillates about the static off-set position. This is the reason why nonlinearities and regularity is more appreciable.

Heave response

The heave response directly influences the mooring tensions and other operations. The heave responses under regular wave are shown in Figure 5. The time series shows the cluster of reversals occurring at varying time intervals. The phenomenon shows the regularity in the behavior. The statistical Table 3 shows the maximum and minimum responses as 2.365 m and – 1.968 m, while the mean value is 0.373. The heave response fluctuates about the mean position oscillating from smaller to larger amplitudes and repeating the same trend onwards all through the time series as shown in the Figure 5. The fluctuations gradually increase from narrow to broad by 30%. Reaching the peak, it gradually reduces by 30%.

PSD of heave response shows a prominent peak at 0.247 rad/s which is close to the natural frequency of heave while other peaks (Figure 6) have very small energy content. Such peaks may, however, attract more energy at some other sea state occurring in that region. The response is periodic in nature with superimposed ripples. The local fluctuations near the peaks in the time series have small participation in the response. It is clearly identified that after 10000 s of wave striking the maximum heave response in presence of regular wave reduces by approximately 50%. It is because of the static off-set of the hull and mooring behavior. The heave time series in Figure 7 shows the beating phenomenon. The PSD in Figure 8 shows a solitary peak at natural frequency of heave. But the peak is drastically reduced up to more than 15 times causing a very low magnitude.

Pitch response

Figure 9 shows the pitch response after 3000 sec. time period. The time series shows regular fluctuations ranging from $\pm$0.11 rad. and reducing to small ordinates of $\pm$0.08 rad. at time station 1050 s. It takes the energy and further increases to $\pm$ 0.11 rad. The statistical Table 3 that shows the maximum positive and negative pitch values of +0.117 and -0.115 rad. The mean value is almost zero and the standard deviation is 0.074 rad. The mean value of zero shows its regular oscillations about the mean position. The significant value of pitch response leads to a significant surge at deck level. It is coupled with the surge of rigid hull which otherwise is of small magnitude but gets enhanced due to pitch input. This is why the surge time series at deck level shows maximum peak at pitch frequency (Figure 2). Like surge response pitch time series also shows the similar behavior. The periodic response oscillates at frequency of 0.168 rad/s about the mean position (Figure 10). It is the wave frequency response as the pitch drives its force from the wave. The frequency of 0.435 rad/s is quite close to the natural frequency of pitch response. However, the participation at low frequency is very small.

The pitch response at time state 10000 s plus gets significantly modified in comparison to the case with 3000 s wave hitting. Figure 11 shows the pitch time series under regular wave after 10000 s of storm. Pitching motion is regularly distributed about the mean position. Maximum and minimum values of pitch responses are reduced 3 times in comparison to the case with 3000 s time state. The reason is the damping of pitching motion due to regular wave on Spar and mooring system. However, the regularity is more sever here. The PSD of pitch time series as shown in Figure 12 confirms the regular behavior. The first peak occurs at 0.126 rad/s which is close to the pitch natural frequency while the another peak occurs at 0.458 rad/s which is the dominant wave loading. The energy content of PSD is however,

Table 1. Mechanical and geometrical properties of spar and moorings.

Sea-bed size		**5000 × 5000 m^2**
Spar (Classic JIP Spar)	Length	213.044 m
	Diameter	40.54 m
	Draft	198.12 m
	Mass	2.515276E8 kg
	Mooring point	106.62 m
	No. of nodes	17
	No. of elements	16
	Type of element	Rigid beam element
Water Depth		1018 m
Mooring	No. of moorings	4
	Stiffness (EA)	1.50E9 N
	Length	2000.0 m
	Mass	1100 Kg/m
	Mooring line pre-tension	1.625E7 N
	No. of nodes	101
	Element type	Hybrid beam element

Table 2. Hydrodynamic properties.

Spar	Drag coefficient : 0.6
	Inertia coefficient: 2.0
	Added mass coefficient : 1.0
Mooring line	Drag coefficient : 1.0
	Inertia coefficient : 2.2
	Added mass coefficient: 1.2

Table 3. Statistical response of Spar-mooring system (After 3000 s wave hitting)

H_s =6 m; T_z =14 s	Max	Min	Mean	Standard deviation
Surge (m)	16.683	-14.490	1.059	9.526
Heave (m)	2.365	-1.968	0.373	1.223
Pitch (rad.)	0.117	-0.115	0.0001	0.081
Tension Mooring line 1 (N)	1.683E+07	1.577E+07	1.641E+07	2.723E+05
Tension Mooring line 3 (N)	1.681E+07	1.574E+07	1.635E+07	2.524E+05

Table 4. Statistical response of Spar-mooring system (After 10000 s wave hitting).

H_s =6 m; T_z =14 s	Max	Min	Mean	Standard deviation
Surge (m)	9.583	-10.260	0.457	5.561
Heave (m)	1.326	-0.955	0.297	0.965
Pitch (rad.)	0.072	-0.067	0.0000	0.046
Tension Mooring line 1 (N)	1.673E+07	1.584E+07	1.638E+07	2.482E+05
Tension Mooring line 3 (N)	1.671E+07	1.581E+07	1.636E+07	2.413E+05

significantly small in comparison to that at 3000 s time state (Figure 10). The reduction ranges to 10 times. It is mainly due to the damping of the pitch motion.

Mooring line tension response

The response of mooring lines plays an important role in the coupled dynamic analysis of the Spar platform. Mooring lines are physically linked with the Spar hull at the fairlead and pinned at the seabed in the finite element model. The regular wave loads simultaneously act on the hull and mooring lines. The analysis of this structure yields the coupled response in true sense.

The designed pretension in each mooring line of the present problem is 1.625E+07 N (Table 1). Mooring line 1 shows the regular behavior of tension after 3000 s of storm (Figure 13). The PSD of the tension time histories are shown in Figure 14. There are several peaks shown but the maxima occur approximately at 0.18 rad/s which is close to the natural frequency of heave. It is expected that heave will significantly influence the mooring tension response. A small peak also occurs, exciting the low frequency surge response. Surge response also causes increase in tension. Other peaks occur at 0.229 to 0.281 rad/s are small, but may get excited under other sea states. The statistics shows the maximum and minimum values as 1.683E+07 N and 1.577E+07 N respectively in mooring line 1. The tension time series of mooring line 3 (Figure 17) is also regular in nature. It is important from fatigue view point. However, there is slight fluctuations in magnitude. The PSD of time series shows a governed peak at 0.17 rad/s (Figure 18) which is close to the heave natural frequency.

Mooring line 1 and 3 are positioned in the direction of wave propagation. Mooring line 1 experiences the maximum tension to support surge in the forward direction, while mooring line 3 slackens resulting in the reduction of pretension. Figure 13 and 17 show the tension fluctuations when mooring line 1 stretches and mooring line 3 slackens due to surge response. Tension fluctuation is of complex periodic nature showing minor ripples near the peaks. For both of these, mooring lines at the regular wave periodic behavior is governed. The major peak frequency as shown in PSD matches with the same.

The slack mooring line 3 remains in catenary shape with the reduction in tension. Figure 17 shows the major peak at the wave frequency. The response also shows a large low frequency peak (0.260 rad/s) close to the natural period of surge as shown in Figure 18. On this low frequency fluctuation a periodic oscillation at the frequency close to the wave frequency is superimposed. The low frequency response in mooring line 1 and 3 is important as it attract significant energy. Wave frequency response too is quite substantial and should duly be considered. There are very small peaks at several other frequencies whose magnitude is negligible. However, the presence of such peaks shows the tendency of excitation due to changes in mooring line characteristics and forcing behavior. The non-linear behavior may also lead to sub and super harmonic resonance. While designing the mooring lines this behavior should not be ignored.

The coupled Spar mooring system changes slightly when 10000 s plus time state with waves is considered. It is expected more in case of huge time duration when mooring line is affected with damping. Maximum tension time series in mooring line 1 is shown in Figure 15. Regular oscillations are taking place about the mean value of 1.638E+07 N. The maximum and minimum values of tensions are 1.673E+07 N and 1.584E+07 N, which are less than those at 1000 s time state. Fluctuations of the time series is also less in case of 6000 s of storm. The PSD (Figure 16) shows clearly a prominent single peak at 0.469 rad/s that is quite different from the 3000 s time state condition as earlier. This natural frequency is significantly shifted; changed to 2.5 times than that at 3000 sec. wave hitting. The participation of heave in mooring tension is significantly small as compared to that with 3000 s time state condition (Figure 19). It is because the damping effect is active in heave motion. The surge is also contributing in response but with a small magnitude. The time series of mooring line 3 under regular wave shows a damped response of regular nature. The statistics for mooring line 3 shows the maxima, minima and mean of1.671E+07 N, 1.581E+07 N, and 1.636E+07 N respectively (Table 4). Whereas, for the case of wave at 1000 s plus time state, the maxima, minima and mean are 1.681E+07 N, 1.574E+07 N and 1.635E+07 N respectively as shown in Table 3. The response is damped out with no further increment because of lateral position of mooring line 3. Figure 20 indicates similar pattern of power spectral density for mooring line 3 like the case of mooring line 1.

The tension time series of mooring line 3 under regular wave at 10000 s plus time state shows the mean value smaller than the pretension. Likewise, the maximum and minimum values are also smaller in comparison to that in case of response at 3000 sec. wave hitting. This behavior is expected because of slacking of mooring line 3 at 10000 s time state.

Conclusions

In the present finite element model, the entire structure acts as a continuum. This model can handle all non-linearities, loading and boundary conditions. The computational efforts required for coupled system analysis considers a complete model including structural coupling of all mooring lines. These are substantial and should therefore mainly be considered as a tool for final verification purposes. The Spar response gets significantly modified and mean position of oscillations gets shifted after longer time of wave hitting. For the range of steady state sea (Hs = 6 m, Tz = 14 s) at 1018 m deep, the surge, heave and pitch responses are predominantly excited respectively. However, the low frequency and wave frequency responses may simultaneously occur due to synchronizing sea states. The energy contents of PSDs of surge, heave and pitch responses at 6000 s wave hitting are significantly and drastically reduced as compared to that with 1000 s of storm case. It is mainly due to the damping of mooring line in the integrated coupled Spar mooring system. The pitch response is quite sensitive to the hitting time of wave. After 1000 s of wave hitting natural frequency, response is predominant while after 6000 s of storm condition it is reduced a lot. But the wave frequency increases slightly in case of 6000 s of wave hitting. Mooring tensions are slightly influenced by the time duration involved while this effect of minute reduction is due to damping phenomena.

Significant qualitative and quantitative changes in the dynamic responses are observed for the time passing after wave hitting. Hence, a wide range of time duration with respective probabilities of occurrences should be considered for the final design recommendation.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the management of Civil Engineering Department of University of Malaya (UM), for their constant support and the grant PS054/2010B and RG093-10AET provided to fund the research work.

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