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Investigation on the Dynamic Responses of a Truss Spar Platform for Different Mooring Line Groups

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Abstract: The dynamic responses of any floating platform are dependent on the mass, stiffness and damping characteristics of the body as well as mooring system. Therefore, it is very essential to study the effect of individual contributions to the system that can finally help to economise their cost. This paper focuses on the effect of mooring stiffness on the responses of a truss spar platform, obtained by different grouping of lines. The study is part of our present researches on mooring systems which include the effect of line pretension, diameter and azimuth angles. The platform is modelled as a rigid body with three degrees-of-freedom and its motions are analyzed in time-domain using the implicit Newmark Beta technique. The mooring lines restoring force-excursion relationship is evaluated using a quasi-static approach. It is observed that the mooring system with lines arranged in less number of groups exhibits better performance in terms of the restoring forces as well as mean position of platform. However, the dynamic motions of platform remain unaffected for different line groups.

Keywords: mooring system; mooring lines, spar platform; motion responses; Newmark Beta method; Morison equation; quasi-static approach; dynamic responses

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1 Introduction

In recent years, the initiative to exploit oil and gas reserves in deep waters has led to the innovation of various platforms suitable for these water depths. Considering different types of platforms with respect to cost, time and ease of installation the floating platforms are best suitable and economically feasible for deep waters. The spar platforms are among the largest offshore platforms in use for deep waters. Mooring lines are used to keep them stationed in ocean environments and constitute around 20%–30% of the overall project cost. Thus, it is essential to find the performance of different mooring line groups on the dynamic responses of platform, which can provide guidance in selecting the best possible grouping without compromising on its performance.

Truss spar among the three different types of spar platforms available has a shallower draft and is considered as a more economical design (Kim *et al*., 2001). For a typical deep water offshore platform such as spar platform, the ratio of structure dimension to characteristic design wavelength is usually small. Hence, using this slender body approximation, it may be assumed that the wave field is virtually undisturbed by structure and the Morison equation is adequate to calculate wave exciting forces (Cao, 1996).

Morison equation when combined with accurate prediction of wave particle kinematics can give reliable prediction of platform responses for all wave frequencies (Cao, 1996). As the wave heights in deep waters of Malaysia are usually small compared to the wave length and water depth, the linear airy wave theory (LAWT) can be used to predict the incident wave kinematics which is considered as most useful of all the wave theories (Chakrabarti, 1987).

Placement of several mooring lines around the platform provides the principal resistance to horizontal displacements induced by the environmental loading (Smith and MacFarlane, 2001). There is a need to incorporate the dynamic considerations in analysis/design procedure for the deep water mooring systems but the quasi-static approach has been proven to be a proper design tool for the mooring systems and can be considered a better choice in the first approach as it is almost certain to achieve convergence. If desired, further analysis may then be carried out using the output of the static analysis as initial conditions for the dynamic analysis (Mavrakos *et al*., 1996; Smith and MacFarlane, 2001; Pascoal *et al*., 2005, 2006).

Many researches were conducted using the analysis of mooring lines and dynamic responses of spar platforms. Nevertheless, no studies were conducted on the performance of truss spar platform with different mooring line groups. This paper shall contribute to fill this gap in literature which indeed aids the industry to decide on the mooring configuration for a given truss spar platform especially in the preliminary design stage.

The study also includes developing two MATLAB codes to compute mooring restoring forces and dynamic responses of truss spar platforms. These two numerical codes have been validated with experimental measurements from literature and used for the study. In the present numerical study, a unidirectional regular wave model is used to compute the incident wave kinematics by LAWT and

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modified Morison equation is used to compute the water wave forces on platform. The dynamic responses of platform are computed in time-domain using implicit Newmark Beta technique as its accuracy and numerical stability are high in solving nonlinear differential equation (Argyris and Mlejnek, 1991).

2 Governing equations

Linear airy wave theory is based on the assumption that the wave height is small compared to the wave length or water depth. This assumption allows the free surface boundary conditions to be linearized by dropping wave height terms, which are beyond the first order. Also, it is satisfied at the mean water level (MWL) rather than at the oscillating free surface.

The governing equations for waves and its kinematics are summarized below based on LAWT. Assuming H as wave height, k as wave number, $+x$ as the direction of wave propagation, c as wave velocity, t as the time and substituting $\theta=k(x-ct)$, the wave profile η is given as:

$$\eta=\frac{H}{2}\cos(\theta) \tag{1}$$

The wave and current forces formulated using the modified Morison equation (relative velocity model) are composed of two components: inertia and drag. The incremental force f on a small segment ds of the platform, e.g. cylindrical hard tank having diameter D is given as:

$$f=C_m A_I \dot{u}-C_A A_I \ddot{x}+C_D A_D\left|u-\dot{x}\right|(u-\dot{x}) \tag{2}$$

$$A_I=\rho A_s (\text{here, } A_s=\frac{\pi}{4}D^2) \text{ and } A_D=\frac{1}{2}\rho D \tag{3}$$

where C_m, C_A and C_D are inertia, added mass and drag coefficient, $\dot{u}$ is the local water-particle acceleration, u is the instantaneous water-particle velocity including current velocity, $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the cylinder, respectively.

In general, the global responses of a rigid structure have six degrees-of-freedom. The structural response of the truss spar platform is a dynamic problem. The wave incident forces in the equations of motion are derived from modified Morison equation described above, while the stiffness, mass and damping matrices are obtained from the usual concepts of structural analysis. Since the equations describe the instantaneous structural response, this dynamic problem can be tagged as a time domain problem.

In practical situations, waves are always accompanied by current and wind. The study in this paper is concerned with only unidirectional waves, steady current and wind forces. In the case of unidirectional incident waves, only surge, heave and pitch motions are significant and the out-of-plane motions i.e. sway, roll and yaw due to the transverse forces such as Vortex Induced Vibration (VIV) are neglected (Cao, 1996).

In this study, the truss spar platform is modelled as a rigid structure with three degrees-of-freedom. It is supported by an anchor system consisting of spread mooring lines. Mooring lines are modelled as springs and their contribution to the inertia, damping and excitation forces is neglected, thus leading to an uncoupled analysis.

The force on the spar platform is the resultant of a number of components including the excitation forces due to wave, hydrostatic pressure, restoring forces due to mooring lines and damping from drag on the structure. The equations for rigid-body motion are derived by applying the conditions of equilibrium in the horizontal and vertical directions and rotation about the Centre of Gravity (CG). They can be most conveniently represented in matrix form in terms of stiffness, mass and damping matrices and force vector. The centroidal displacements in the x-y plane (termed as surge x_G, heave y_G and pitch γ) are given by the equilibrium equations relating the structural motion to the resultant of excitation forces, added forces and spring resistance. As spar is a rigid body, it does not have internal stiffness of its own and derives its static resistance from support-systems (moorings) and hydrostatic stiffness.

Let $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{K}$, and $\boldsymbol{F}$ be the structural mass, damping, stiffness and resultant force matrices, respectively; $\ddot{\boldsymbol{X}},\dot{\boldsymbol{X}}$ and $\boldsymbol{X}$ be the structure acceleration, velocity and displacement matrix, then the equilibrium equation is:

$$\boldsymbol{M}\ddot{\boldsymbol{X}}+\boldsymbol{C}\dot{\boldsymbol{X}}+\boldsymbol{K}\boldsymbol{X}=\boldsymbol{F} \tag{4}$$

a) Mass matrix: The mass matrix denoted in Eq. (4) is given as $\boldsymbol{M}=\boldsymbol{M}_0+\boldsymbol{M}_a$. Here $\boldsymbol{M}_0$ is the structural mass matrix consisting of the inertial terms of the structure itself. $\boldsymbol{M}_a$ is the hydrodynamic or added mass matrix which depends on the fluid domain around the structure.

In Morison equation, the added mass matrix is derived from the relative acceleration term corresponding to the inertia force. As such, it is assumed constant in this study. Let m and I_{Gz} be the physical mass and centroidal mass moment of inertia about z-axis of the platform, y_{CG} as centroid distance from the still water level, l as wet length of the platform and substituting $k_m=C_A A_I$, the total mass matrix (heave plates added mass not inclusive) is given as:

$$\boldsymbol{M}=\begin{bmatrix} m+k_m l & 0 & k_m l(-y_{CG}-l/2) \\ 0 & m & 0 \\ k_m l(-y_{CG}-l/2) & 0 & I_{GZ}+\left(k_m l^3/12\right) \end{bmatrix} \tag{5}$$

b) Damping matrix: The damping matrix involves much greater uncertainties than mass and stiffness matrix (Anam, 2000). Damping sources can be identified as structural, radiation, wave drift and mooring lines. Here, only structural damping is considered while the drag term remains in force vector. The damping matrix (heave plates damping not inclusive) is given as:

$$\boldsymbol{C}=\begin{bmatrix} 2\zeta_x\omega_{nx}m & 0 & 0 \\ 0 & 2\zeta_y\omega_{ny}m & 0 \\ 0 & 0 & 2\zeta_z\omega_{nz}I_{Gz} \end{bmatrix} \tag{6}$$

in which, ζ is the damping ratio in the specified direction of motion and ω_n is the natural frequency of the system in the specified degree of freedom. In the present work, the damping ratios and natural frequencies are obtained from the free-decay test.

c) Stiffness matrix: The stiffness matrix includes two components–mooring lines restoring stiffness and hydrostatic stiffness of the platform.

The mooring lines, which are represented here by linear/nonlinear massless springs attached at the platform fairleads, are the only source of stiffness in the direction of surge motion. The horizontal mooring stiffness k_x can be treated as a constant for small displacements of the platform but when the displacements are large, k_x becomes nonlinear and is determined based on a surge static offset test. The hydrostatic buoyancy force provides the heave restoring force. Let δ be the distance between the Centre of Gravity (CG) and fairleads, y_{CB} is the distance of Centre of Buoyancy (CB) from the still water level, then the total stiffness matrix is given as:

$$\boldsymbol{K} = \begin{bmatrix} k_x & 0 & -k_x\delta \\ 0 & \rho g A_s & 0 \\ -k_x\delta & 0 & -k_x\delta^2 + \rho g A_s D\left(y_{CG} - y_{CB}\right) \end{bmatrix} \tag{7}$$

Since k_x is a function of platform displacement, the solution process involves updating the total stiffness matrix for each time step of the analysis.

d) Force Matrix: The contribution to force vector $\boldsymbol{F}$ is from incident waves, current, wind and heave plates that greatly increase the heave added mass and viscous damping (Lu *et al*., 2003). Therefore, the force matrix is:

$$\boldsymbol{F} = \begin{bmatrix} F_{ex} \\ F_{ey} \\ M_{ez} \end{bmatrix} + \begin{bmatrix} F_w \\ 0 \\ F_w c_w \end{bmatrix} - \begin{bmatrix} 0 \\ \rho \dfrac{\partial U}{\partial t} L^3 C_{Ah} + \dfrac{1}{2}\rho U|U| L^2 C_{Dh} \\ 0 \end{bmatrix} \tag{8}$$

in which, F_{ex} and F_{ey} are the exciting forces due to wave and current forces in the specified direction, M_{ez} is the exiting moment due to wave and current (formulated as $y_{CG}F_{ex}$), F_w is the wind force on the platform, c_w is the distance from the CG to the effective centre of wind pressure, C_{Ah} and C_{Dh} are the added mass and drag coefficient for the heave plates, $\partial U/\partial t$ and U represent the acceleration and relative velocity perpendicular to the plate, respectively.

3 Numerical modelling

3.1 Quasi-static analysis of the mooring lines

The nonlinear relationship between the restoring force and horizontal excursion of a mooring line usually requires an iterative solution. The key assumptions made for the analysis of mooring lines are: a) components of the mooring line move very slowly so that the drag forces on the line can be treated as negligible; b) change in the line geometry is insignificant and thereby, in the line force due to direct fluid loading caused from the waves; c) the clump weight segment is inextensible; and d) only horizontal excursion of the line is considered.

Using equation of a catenary for the evaluation of force-excursion relationship of the mooring line, the analysis has been carried out for the mooring line with disturbed clump weight according to the procedure steps mentioned in Agarwal and Jain (2003); incorporating the two conditions stated for lifting-off of the clump weight. The behaviour of the mooring system i.e. the resultant horizontal force H, for an excursion δ can be computed using the Eq. (9).

$$H(\delta) = \sum_{j=1,p} H_j(\delta_j)\cos(\pi - \theta_j) \tag{9}$$

where p–Total number of mooring lines; θ_j – Angle between the j^{th} mooring line and the direction of excursion; δ_j – Excursion for the j^{th} mooring line; $H_j(\delta_j)$–Associated horizontal force with $\delta_j=\delta\cos(\pi\text{-}\theta_j)$.

3.2 Implicit Newmark Beta technique

The equation of motion for computing dynamic responses of the platform is solved using the implicit Newmark Beta integration technique (Newmark variances involve average accelerations procedure i.e. β=1/4 and γ=1/2).

Let $\boldsymbol{M}$, $\boldsymbol{C}$, $\boldsymbol{R}(\boldsymbol{r}, \boldsymbol{t})$, $\boldsymbol{r}(\boldsymbol{t})$, $\boldsymbol{R}_e$ denote structural mass matrix, damping matrix, external force vector, displacement vector and restoring force vector where non-linear stiffness is considered in an integration form ($\boldsymbol{K}_t$ being the tangential stiffness matrix):

$$\boldsymbol{R}_e I = \int_0^r \boldsymbol{K}_t \mathrm{d}r \tag{10}$$

Argyris and Mlejnek (1991) show the flowchart of the implicit Newmark Beta procedure applied to nonlinear dynamic analyses. Once the procedure is started, the dynamic equilibrium can be checked by testing the dynamic-out-of-balance force $R_u(r_k)$. If the unbalanced force is less than prescribed error, the equilibrium is attained and the procedure advances to the next time-step.

To avoid unrealistic initial force impact on the structure, a cosine smoothing function is used to supress the transient effect as given below:

$$\mathrm{SF} = \frac{1}{2}\left[1 - \cos\left(\frac{\pi t}{T_{\mathrm{tr}}}\right)\right] \tag{11}$$

in which T_{tr} is the smoothing time period. As long as T_{tr} is large enough, the numerical results are not sensitive to the choice of T_{tr} (Ramos and Zhang, 1996).

4 Validation of numerical predictions

4.1 Validation of numerical predictions

To compute restoring forces in mooring lines, the quasi-static approach is adopted for the analysis and a MATLAB code named *QSAML* was developed. The numerical code is validated with experiment tests by comparing the mooring stiffness curve obtained for the MARLIN truss spar mooring configuration (Ran, 2000).

The material properties such as: wet weight, effective modulus, breaking loads and lengths of the various components of mooring lines used for MARLIN truss spar platform are as given in (Ran, 2000).

4.2 Dynamic responses of the truss spar platform

A MATLAB code named DATSpar was developed to compute the dynamic responses of the truss spar platform subjected to unidirectional regular waves, steady current and wind loads. The validation of DATSpar is performed using the truss spar platform details given in Technip document (2005).

The amplitude of the platform responses computed are normalised with respect to the amplitude of the wave. Obtaining the response-amplitude operator (RAO) for a wide range of wave frequencies can allow transfer of the exciting waves into responses of the platform (Chakrabarti, 1987).

$$\text{Response} = (\text{RAO}) \times \eta \tag{12}$$

To determine the surge, heave and pitch RAOs, various unidirectional waves (wave periods: 4 s to 22 s) combined with current (1.34 m/s) and wind loads (237 kN) were chosen for the prototype to cover a range of operational sea states and large storms as well as capture any phenomenon not properly modelled in the numerical model.

5 Mooring lines groups used for the study

After validating QSAML and DATSpar, the two codes are used to study the dynamic responses of the truss spar platform for different mooring line groups.

A floating platform having the fairleads at a height of 941.832 m from the sea bed is considered. Two different mooring line groups are considered for the study as shown in Table 1 (*Note:* I×J - 'I' denotes number of mooring line groups & 'J' denotes number of lines in each group). They are chosen in regards to the present scenario of floating platforms containing mooring lines more commonly in three or four groups with three to four lines in each group.

As the present day floating platforms are usually installed with nearly symmetric azimuth angles, the mooring lines are arranged symmetrically and analysed for their restoring forces in two cases: (a) with one mooring line group in wave heading and (b) without any mooring line group in wave heading.

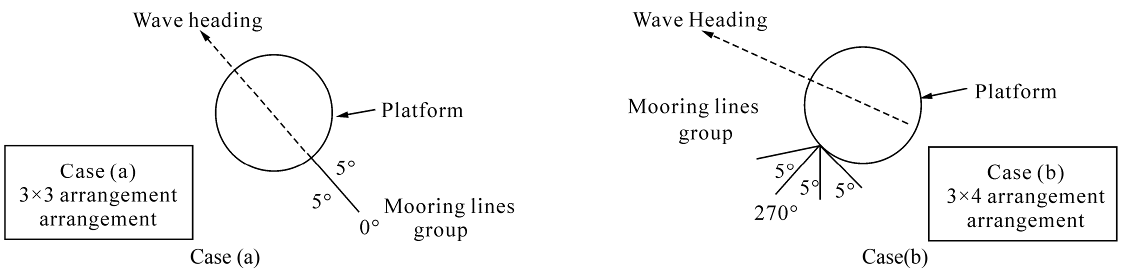

Fig. 1 Platform with three and four mooring lines groups

Table 1 Mooring lines groups used for the study

S. No.	Grouping Scheme	Legend	Azimuth angle for one mooring line in each group	Remarks
1	3×3	Case (a);Case (b)	0°, 120°, 240°; 30°, 150°, 270°	All the other lines in each group differ by −5° and +5° for three lines group and −5°, +5°, +10°, or four lines group; as depicted in Fig. 1
2	3×4			
3	4×3	Case (a);Case (b)	0°, 90°, 180°, 270°; 30°, 120°, 210°, 300°	
4	4×4			

6 Results and Discussions

6.1 Mooring line

6.1.1 Validation of QSAML

Fig. 2 shows the results obtained from numerical code, QSAML and experiments tests for mooring system used for validation. The experimental tests were performed on a 1:61 scale truss spar model by Amooc in Offshore Technology Research Centre wave tank at Texas A&M University (Ran, 2000).

The difference in the results can be attributed to change in the mooring line set up between the prototype and experimental model. The prototype is considered with nine mooring lines, and the experimental model with only with five mooring lines, which otherwise can be concluded that there is a good agreement between the numerical and experimental results.

Practically, the platform excursions are not permitted beyond 30 m. Hence, the deviation of the numerical predictions from the experimental measurements in Fig. 2 for excursions beyond 30 m can be ignored, considering only the portion of curve within 30m for the numerical study.

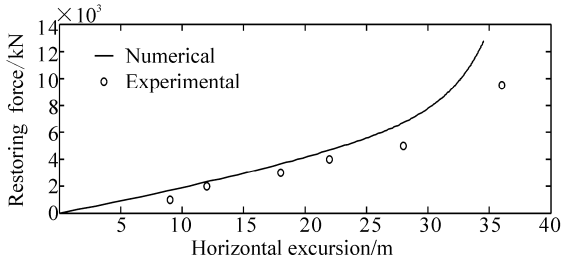

Fig. 2 Validation of numerical predictions with experimental measurements–QSAML

6.1.2 Effect of mooring lines groups on the restoring force

From Figs. 3 and 4 it can be inferred that the mooring systems having one line group in wave heading exhibit better restoring performance. The difference in the mooring restoring forces for case (a) and (b), increases with relatively large excursions.

The difference in restoring forces between 3×3 and 4×3 as well as 3×4 and 4×4 mooring arrangements for case (a) and 3×4 and 4×3 arrangements for case (b) is insignificant. For case (a), the maximum difference in the restoring forces between 3×3 and 4×3 arrangements is 1380 kN and 3×4 and 4×4 arrangements is 1376 kN. For case (b), the maximum difference between 3×4 and 4×3 arrangements is 80 kN.

In general, it can be concluded that the restoring performance of the mooring system is not greatly enhanced by increasing the line groups from three to four for case (a) but vice-versa for case (b).

Comparing the mooring restoring performances for 3×4 and 4×3 arrangements, which have same number of lines, it can be observed that in case (a), the arrangement with three groups exhibited a better performance. However, in case (b), the two arrangements exhibited nearly same performance.

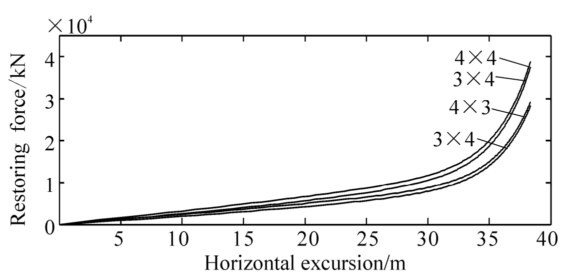

Fig. 3 Mooring restoring force-excursion relationship for all the groups: case (a)

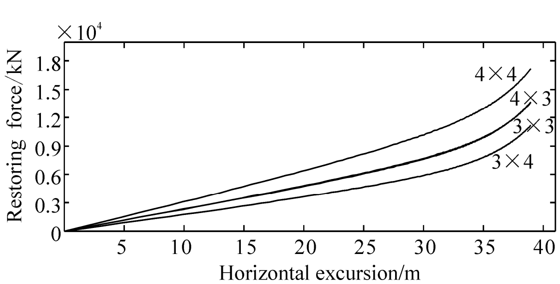

Fig. 4 Mooring restoring force-excursion relationship for all the groups: case (b)

6.2 Responses of the truss spar platform

6.2.1 Validation of DATSpar

To validate the developed code DATSpar, a scaled truss spar model was built for a platform for Malaysia and the experimental studies were carried out at the FORCE Technology basin (Technip document, 2005). A 1:60 scale was chosen with the goals of allowing adequate precision for measurements of small quantities, while fitting within the limitation of the model basin's wave generation capabilities. The full-scale mooring system has ten lines arranged in four groups. Hence, four mooring lines consisting of springs were used in which one mooring line of the model represented the stiffness of each group in the prototype.

Figs. 5, 6 and 7 present the comparison of numerical predictions from DATSpar and experimental measurements. In general, it can be concluded that there has been a good agreement between both the results. The variation in heave RAOs can be attributed to ignoring the effect of risers in this developed code while considered along with strakes in the model tests.

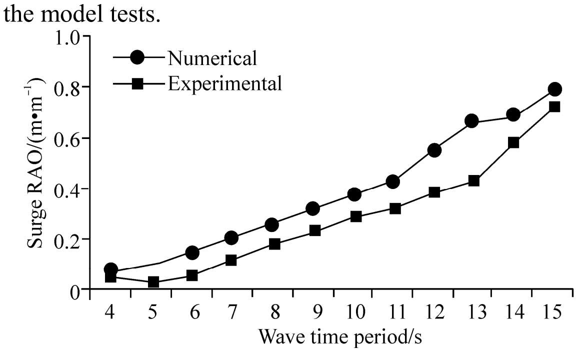

Fig. 5 Comparison of surge RAO: numerical predictions vs experimental measurements–DATSpar

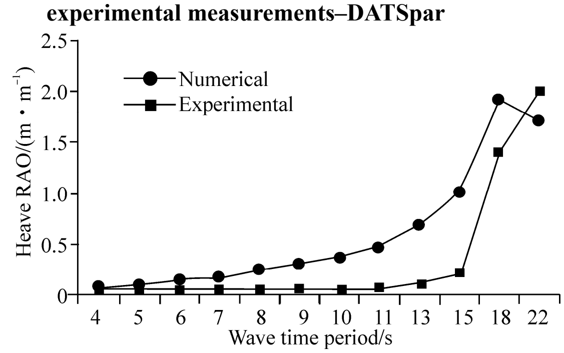

Fig. 6 Comparison of heave RAO: numerical predictions vs experimental measurements–DATSpar

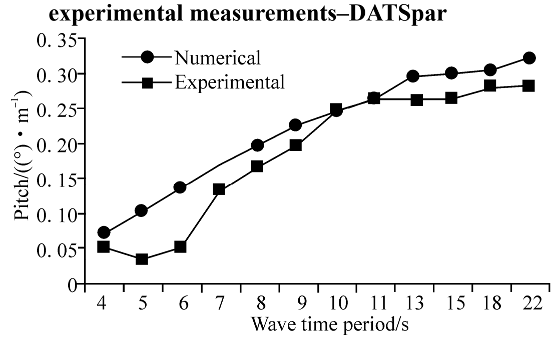

Fig. 7 Comparison of pitch RAO: numerical predictions vs experimental measurements–DATSpar

6.2.2 Effect of mooring lines groups on the responses of the platform

6.2.2.1 Effect on RAOs

Fig. 8 shows the variation in the motions of the platform about its mean position with change in the mooring lines group for case (a) and a similar trend was depicted for case (b) study. It can be observed that the effect of the mooring groupings (case (a) and (b)) on the responses of the platform is insignificant for surge as well as pitch motions and absolutely no effect on the heave motions.

However, the effect of the mooring groups on the surge and pitch motions is found to be more prominent at relatively low wave frequencies. In case (a), the highest percentage of variation in the surge and pitch RAOs is found to be 1.54% and 1.10%, respectively, between 3×3 and 3×4 mooring arrangements. Likewise in case (b), the highest percentage of variation in the surge and pitch RAOs is found to be 2.16% and 2.17% respectively, between 3×3 and 3×4 mooring arrangements. The low variation observed can be attributed to the insignificant change in the mooring restoring force as the line is shifted away from the wave heading.

6.2.2.2 Effect on the mean position

Fig. 9 shows the mean positions of the platform for all the mooring lines groups in case (a) and (b). In general, it can be observed that the mean position attained by the mooring system having one line group in wave heading is relatively lower. This can be attributed to the relatively high restoring force provided by the mooring system in case (a) compared case (b). Comparing all the mooring line groups in each case, it can also be observed that the variation in the mean position of the platform is nearly same for 3×4 and 4×3 arrangements. The highest variation is between 3×3 and 3×4 mooring systems in each case (a) and (b).

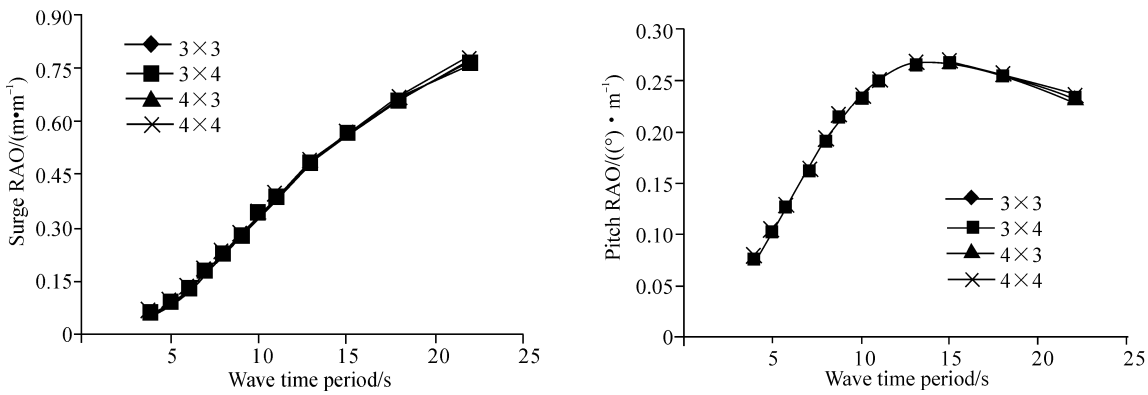

Fig. 8 Surge and pitch RAOs of the platform for all the mooring line groups: Case (a)
(*Note:* Similar RAOs trend has been observed for case (b) study)

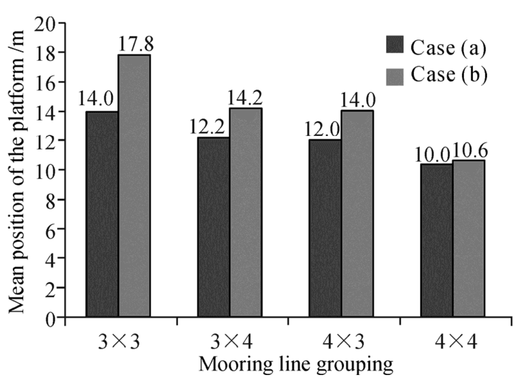

Fig. 9 Mean position of the platform for all the mooring line groups: Case (a) and (b)

7 Conclusions

The main findings from the study conducted are – the variation in responses (RAOs) of the truss spar platform is insignificant for different mooring line groups, but comparatively prominent effect is observed for relatively low wave frequencies. However, the mean position attained by the platform is significantly affected.

The other conclusions can be drawn based on the study conducted:

(a) The mooring systems having a line group in wave heading exhibit better restoring performance.

(b) The restoring performance is not greatly enhanced by increasing the line groups for mooring systems having line group in wave heading, but vice-versa when not having line group in wave heading.

(c) For mooring system having same number of lines and also a line group in wave heading, the arrangement with less number of groups exhibits a better restoring performance.

(d) Similarly, for the mooring system having same number of lines but not having a line group in wave heading exhibit nearly same restoring performance irrespective of the number of groups.

(e) The highest variation in surge and pitch RAOs is found between the mooring systems with less number of line groups.

(f) The variation in initial offsets attained by the platform with mooring systems having same number of lines but different groups is nearly negligible.

Based on the above conclusions, it is recommended to use mooring systems having one line group in wave heading and preferably all mooring lines in less number of groups (for example, arranging twelve mooring lines in 3×4 arrangement amongst 3×4 and 4×3). This is necessary to obtain an optimum mooring configuration with respect to its cost in addition to the dynamic responses of platform.

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