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Comprehensive study on the results of tension leg platform responses in random sea

TABESHPOUR M.R.[1], GOLAFSHANI A.A.[1], SEIF M.S.[2]
([1]*Department of Civil Engineering, Sharif University of Technology, P.O.Box 11365-9313, Tehran, Iran*)
([2]*Department of Mechanical Engineering, Sharif University of Technology, P.O.Box 11365-9313, Tehran, Iran*)
E-mail: tabesh_mreza@yahoo.com; golali@sharif.edu; seif@sharif.edu
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Abstract: Compliant offshore structures are used for oil exploitation in deep water. Tension leg platform (TLP) is a suitable type for very deep water. The nonlinear dynamic response of TLP under random sea wave load is necessary for determining the maximum deformations and stresses. Accurate and reliable responses are needed for optimum design and control of the structure. In this paper nonlinear dynamic analysis of TLP is carried out in both time and frequency domains. The time history of random wave is generated based on Pierson-Moskowitz spectrum and acts on the structure in arbitrary direction. The hydrodynamic forces are calculated using the modified Morison equation according to Airy's linear wave theory. The power spectral densities (PSDs) of displacements, velocities and accelerations are calculated from nonlinear responses. The focus of the paper is on the comprehensive interpretation of the responses of the structure related to wave excitation and structural characteristics. As an example a case study is investigated and numerical results are discussed.

Key words: Tension leg platform (TLP), Ocean wave, Stochastic, Nonlinear
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INTRODUCTION

There is obvious demand for oil exploitation in deep water. Increasing water depth will make the environment more severe and so some innovative structures are required for economic production of gas and petroleum in deep water. An engineering idea is the minimization of the structure resistance to environmental loads by making the structure flexible. This structural flexibility causes nonlinearity in the structural stiffness matrix because of large deformations. Wave loading on ocean structures is complex. As they must be compliant, these structures must be designed dynamically. And as they are exposed to nonlinearly varying loads, their analysis is highly complex. Simplified design methods are required for practical considerations and for these simplifications, good comprehension of the structural behavior is required.

Because the buoyancy of the tension leg platform (TLP) exceeds its weight, the vertical equilibrium of the platform requires taut moorings connecting the upper structure to the seabed. Fig.1 shows different components of the TLP made up of vertical and horizontal elements on the upper structure and vertical tendons connecting the structure to a foundation on the seabed. The extra buoyancy over the platform weight ensures that the tendons are always kept in tension. As mentioned, the TLP is essentially a semi-submersible vessel moored to the sea floor by a number of pretensioned tendons connected at the sea floor to a template piled in place. It is significant to note that unlike the case of normal pile foundations, the piles here experience tension rather than compression. The structure is sized by adjusting tendon tension and platform buoyancy so that requirements on surge, sway, and yaw periods and "set-down", are satisfied. Set-down, the change in water line location on the buoyancy chambers as the platform moves to maximum surge and sway, must not be so large as to permit waves to strike the deck structure. The natural periods of the structure in surge, away and yaw must be greater than the wave periods of significant energy. The heave, roll and pitch natural periods, on the other hand, being much shorter, must be less than the significant wave energy periods. Further, amplitudes of motion must be sufficiently small to prevent flexural yielding of the drilling risers which connect the platform to the subsea completion template. The cost curves for offshore structures will rise more rapidly than the TLP in deep-water reservoirs, because for a TLP, only the cost of the mooring system and its installation increases as the water depth increases.

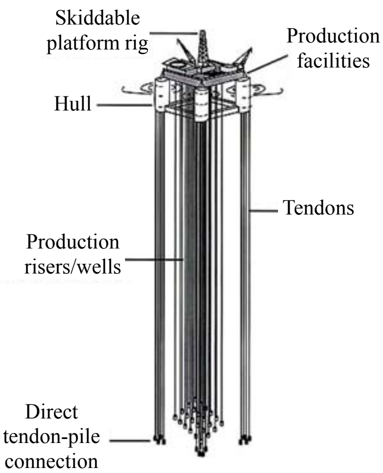

Fig.1 Configuration and components of tension leg platform (Source: the Internet)

Several studies were carried out to gain understanding of the TLP structural behavior and determine the effect of several parameters on the dynamic response and average life time of the structure in recent two decades (Faltinsen *et al*., 1982; Teigen, 1983; Jain, 1997; Siddiqui and Ahmad, 2001).

Tein *et al*.(1981) presented an integrated motion and structural analysis method for TLP's and used the potential theory for hydrodynamic load generation. The effect of viscous damping was introduced based on model test data.

Angelides *et al*.(1982) considered the influence of hull geometry, force coefficients, water depth, pre-tension and tendon stiffness on the TLP's dynamic responses and modelled TLP's floating part as a rigid body with six degrees of freedom. The tendons were represented by linear axial springs. Wave forces were evaluated using a modified Morison equation on the displaced position of the structure considering the effect of the free sea surface variation.

Morgan and Malaeb (1983) investigated the dynamic response of TLPs using a deterministic analysis based on coupled nonlinear stiffness coefficients and closed-form inertia and drag-forcing functions using the Morison equation. The time histories of motions were presented for regular wave excitations. The nonlinear effects considered in the analysis were stiffness nonlinearity arising from coupling of various degrees of freedom, large structural displacements and hydrodynamic drag force nonlinearity arising from the square of the velocity terms. It was reported that stiffness coupling could significantly affect the structure behavior and that the strongest coupling was found to exist between heave and surge or sway.

Ahmad (1996) investigated the coupled response of a TLP to random waves characterized by a long-crested sea surface spectrum. The response analysis was based on a simulation, which duly considered various nonlinear effects, such as relative velocity squared drag force, variable added mass due to variable submergence with the passage of waves and nonlinearity due to large excursion. It also accounted for variable tension in tethers due to variable submergence, variable buoyancy and vertical wave forces. The power spectral density function (PSDF) of the coupled heave and tether tension showed the energy distribution with respect to frequencies and proved to be an important informative tool for the preliminary design under the long-crested sea state. Variable submergence was found to be a major source of nonlinearity enhancing the surge and heave responses, which in turn introduced tether tension fluctuations.

Chandrasekaran and Jain (2002a; 2002b) investigated the structural response behavior of the triangular TLP under several random sea wave loads and current loads in both time and frequency domains. They study the effect of coupling of stiffness coefficients in the stiffness matrix and the effect of variable submergence of the structure, due to varying water surface, on the structural response of the triangular TLP.

The effect of added mass fluctuation on the heave response of the TLP was investigated by using perturbation method both for discrete and continuous models (Tabeshpour *et al*., 2004). An analytical heave vibration of TLP with radiation and scattering effects for undamped systems was presented in (Tabeshpour *et al*., 2005). The effect of structural and radiation damping on the response of the structure was not considered so that the amplitude of the heave motion was over estimated.

The modified Euler method presented here is a simple numerical procedure which can be effectively used for analyzing the dynamic response of structures in the time domain and had been shown to be conditionally stable (Hahn, 1991), and its application showed that it is efficient and easy to use, that it can be used to obtain accurate solutions to a wide variety of structural dynamics problems, and that simplicity is one of its distinguishing features.

Because the modified Euler method is conditionally stable, it may be inefficient for the analysis by direct integration of the response of a multi-degree-of-freedom system with a very short highest natural period of vibration. However, the method is explicit, and is particularly suited for the analysis of non-linear systems. The modified Euler method has been successfully used for analyzing the dynamic response of wave-excited offshore structures (Sanghvi, 1990).

A computer program SNATELP is developed in this work for stochastic and nonlinear dynamic analysis capable of solving large displacement problem dynamically in the time domain. The transformed responses in the frequency domain can also be calculated. The solution procedure formulated uses the stiffness method in global coordinate reference frame. The modified Euler method is used for the numerical integration in time domain.

WAVE FORCES

The problem of suitable representation of the wave environment or more precisely the wave loading is a problem of prime concern. Once the wave environment is evaluated, wave loading on the structure may be computed based on suitable theory. In this work the water particle position η is determined according to Airy's linear wave theory:

$$\eta(x,t) = A\cos(kx - \omega t), \tag{1}$$

where A is the amplitude of the wave, k is the wave number, ω is the wave frequency and x is the horizontal distance from the origin.

In order to incorporate the effect of variable submergence which is an important aspect of hydrodynamic loading on TLP, Chakarbarti's approach will be adopted in which instantaneous sea surface elevation is taken as the still water level (or water depth). The fluctuating free surface effect can be significant when the wave height cannot be ignored compared to the water depth. Chakarbarti suggested the following form of the water particle velocity $\dot{u}$:

$$\dot{u} = A\omega\cos(kx - \omega t)\frac{\cosh(kz)}{\sinh(d+\eta)}, \tag{2}$$

where η is the instantaneous water surface elevation and is given by Eq.(1). The water particle acceleration is also modified.

In stochastic modelling, sea waves are commonly characterized by their PSDFs. Water particle kinematics at different location on the structure are considered to be derived processes which need not be specified in addition to the sea surface elevation. As various physical processes are involved in the generation of waves, a random wave is regarded as a superposition of an infinite number of independent waves with different wave heights, wave periods, and arbitrary phase angles. In the present simulation procedure, waves are assumed to be stationary, homogeneous and ergodic in the statistical sense. By considering the random process as a linear superposition of a large number of independent waves, its distribution becomes Gaussian. Depending on the fetch conditions, several analytical expressions exist for approximating the sea surface elevation spectrum (i.e. its PSDF). A well-known spectrum model for ocean waves is Peirson-Moskowitz (P-M) model. The modified P-M spectrum model is assumed to adequately represent the sea state and is given by:

$$S_{\eta\eta}(\omega) = \frac{H_s^2 T_z}{8\pi^2}\left(\frac{T_z\omega}{2\pi}\right)^{-5}\exp\left[-\frac{1}{\pi}\left(\frac{T_z\omega}{2\pi}\right)^{-4}\right], \tag{3}$$

where H_s is the significant wave height in m, T_z is zero up crossing period in s and ω is the angular frequency. Fig.2 shows the normalized curve of the spectrum.

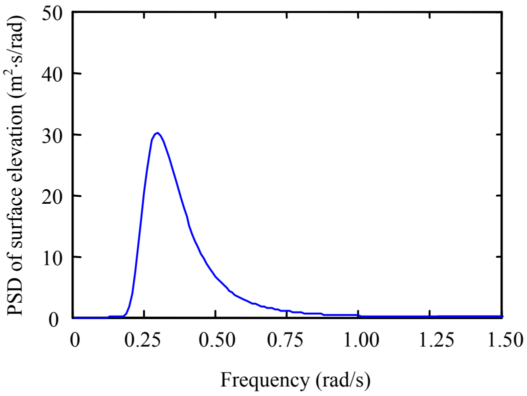

Fig.2 Wave spectrum

Linearized small-amplitude wave theory allows the summation of velocity potential, wave elevation, and water particle kinematics of the individual regular wave to form a random wave made up of a number of components. The generated synthetic random wave is considered to be adequately represented by a summation of linear harmonic regular waves. The series representation of sea surface elevation is given by the equation

$$\eta(x,t) = \lim \sum_{i=1}^{N} A_i \cos(k_i x - \omega_i t + \phi_i), \tag{4}$$

$$A_i = \sqrt{2S_{\eta\eta}(\omega_i)\Delta\omega_i}, \tag{5}$$

where A_i is the amplitude of the ith component wave, k_i is the wave number of the ith component wave, ω_i is the wave frequency of the ith component wave, ϕ is the phase angle of the ith component wave, and varies from 0 to 2π, x is the horizontal distance from the origin and $S_{\eta\eta}(\omega)$ is the one-sided sea surface elevation PSDF. Based on these studies, the asymptotic approach to the Gaussian distribution is found to be slow for a number of component waves over about 75. The time interval Δt is set to satisfy the condition $\Delta t \le 2\pi/(5\omega_{max})$. Keeping in view the natural period of the structure, the value of Δt is chosen as 0.5 s, which is much smaller than required. The length of the simulated wave record is controlled so that about 4096 data points are generated in one run. For the random wave, when the response is to be found by simulation, the total period of simulated loading of 2048 s is chosen which gives 4096 (i.e. 2^{12}) data points. A typical random sea surface elevation is shown in Fig.3.

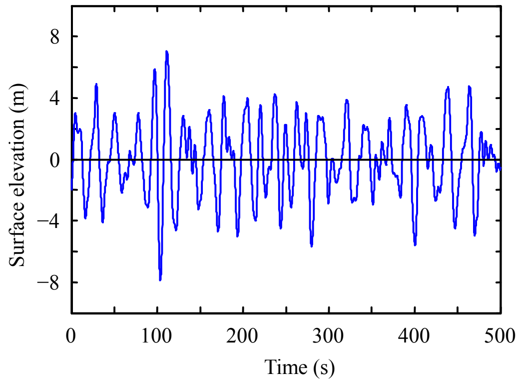

Fig.3 Random elevation of surface wave

Once the sea surface elevation time history $\eta(x,t)$ is known from Eq.(4), the time histories of the water particle velocity and acceleration are computed by wave superposition, according to Airy's linear wave theory. The horizontal water particle velocity $\dot{u}(x,t)$ and the vertical water particle velocity $\dot{v}(x,t)$ are given as:

$$\dot{u}(x,t) = \sum_{i=1}^{N} A_i\omega_i \cos(k_i x - \omega_i t + \phi_i)\frac{\cosh(k_i z)}{\sinh[k_i(d+\eta)]}, \tag{6}$$

$$\dot{v}(x,t) = \sum_{i=1}^{N} A_i\omega_i \sin(k_i x - \omega_i t + \phi_i)\frac{\sinh(k_i z)}{\sinh[k_i(d+\eta)]}. \tag{7}$$

The horizontal water particle acceleration $\ddot{u}(x,t)$ and the vertical water particle acceleration $\ddot{v}(x,t)$ are given as:

$$\ddot{u}(x,t) = \sum_{i=1}^{N} A_i\omega_i^2 \sin(k_i x - \omega_i t + \phi_i)\frac{\cosh(k_i z)}{\sinh[k_i(d+\eta)]}, \tag{8}$$

$$\ddot{v}(x,t) = \sum_{i=1}^{N} A_i\omega_i^2 \cos(k_i x - \omega_i t + \phi_i)\frac{\sinh(k_i z)}{\sinh[k_i(d+\eta)]}, \tag{9}$$

where k_i is the ith component wave number, y is the vertical distance at which the wave kinematics is calculated, d is the water depth, η is the sea surface elevation, which is equal to $\eta(x,t)$ given by Eq.(4). The wave forces acting on the cylindrical member of the TLP structure are obtained by using modified

Morison's equation, which takes relative velocity and acceleration between the structure and water particles into account. While calculating the wave forces, water particle kinematics for each member are determined with respect to the average value across the diameter of the member. The integration of the elemental forces acting on the pontoons and columns is performed numerically by dividing the cylinder into small elements. The instantaneous total hydrodynamic force is determined at each time station with the assigned values of the structural displacements, velocities and accelerations.

In order to carry out probabilistic work on the wave height, the knowledge of the wave height distribution is of great importance since various valuable information can be derived from this distribution. It has been found that wave heights of an irregular sea follow a Rayleigh distribution (Chandrasekaran and Jain, 2002b).

EQUATION OF MOTION

The equation of motion of triangular TLP under a regular wave is given as:

$$\boldsymbol{M}\ddot{\boldsymbol{X}} + \boldsymbol{C}\dot{\boldsymbol{X}} + \boldsymbol{K}\boldsymbol{X} = \boldsymbol{F}(t), \tag{10}$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ are the matrices of mass, damping and stiffness respectively, $\boldsymbol{X}$, $\dot{\boldsymbol{X}}$ and $\ddot{\boldsymbol{X}}$ are the structural displacement, velocity, and acceleration vector respectively and $\boldsymbol{F}(t)$ is the excitation force vector.

Mass matrix, *M*

Structural mass is assumed to be lumped at each degree of freedom. Hence, it is diagonal in nature and is constant. The added mass, M_{a}, due to the water surrounding the structural members and arising from the modified Morrison equation is considered up to the mean sea level (MSL) only. The fluctuating component of added mass due to the variable submergence of the structure in water is considered in the force vector depending upon whether the sea surface elevation is above (or below) the MSL. The mass matrix of TLP is

$$\begin{array}{c} \left|\begin{array}{cccccc} \text{Surge} & \text{Sway} & \text{Heave} & \text{Roll} & \text{Pitch} & \text{Yaw} \end{array}\right| \\ \boldsymbol{M} = \begin{bmatrix} M'_{\mathrm{SS}} & 0 & 0 & 0 & 0 & 0 \\ 0 & M'_{\mathrm{WW}} & 0 & 0 & 0 & 0 \\ 0 & 0 & M'_{\mathrm{HH}} & 0 & 0 & 0 \\ M_{\mathrm{aRS}} & M_{\mathrm{aRW}} & M_{\mathrm{aRH}} & M_{\mathrm{RR}} & 0 & 0 \\ M_{\mathrm{aPS}} & M_{\mathrm{aPW}} & M_{\mathrm{aPH}} & 0 & M_{\mathrm{PP}} & 0 \\ 0 & 0 & 0 & 0 & 0 & M_{\mathrm{YY}} \end{bmatrix} \end{array}, \tag{11}$$

where $M_{\mathrm{SS}}=M_{\mathrm{WW}}=M_{\mathrm{HH}}=M$ and $M'_{\mathrm{SS}} = M_{\mathrm{SS}} + M_{\mathrm{aSS}}$ and $M'_{\mathrm{WW}} = M_{\mathrm{WW}} + M_{\mathrm{aWW}}$ and $M'_{\mathrm{HH}} = M_{\mathrm{HH}} + M_{\mathrm{aHH}}$. $\boldsymbol{M}$ is the total mass of the entire structure. M_{RR}, M_{PP} and M_{YY} are the total mass moment of inertia about the x, y and z axes respectively. $M_{\mathrm{RR}} = Mr_x^2$, $M_{\mathrm{PP}} = Mr_y^2$, $M_{\mathrm{YY}} = Mr_z^2$, r_x, r_y, r_z are the radii of gyration about the x, y, z axes respectively. The added mass terms are:

$$\mathrm{d}M_{\mathrm{aSS}} = \mathrm{d}M_{\mathrm{aWW}} = \mathrm{d}M_{\mathrm{aHH}} = 0.25\pi D^2 (C_m - 1)\rho\,\mathrm{d}l, \tag{12}$$

$$M_{\mathrm{aSS}} = \int_{\text{length}} \mathrm{d}M_{\mathrm{aSS}}. \tag{13}$$

M_{aRS}, M_{aRW} and M_{aRH} are the added mass moment of inertia in the roll degree of freedom due to hydrodynamic force in the surge, sway and heave directions, respectively. M_{aPS}, M_{aPW} and M_{aPH} are the added mass moment of inertia in the pitch degree of freedom due to hydrodynamic force in the surge, sway and heave directions, respectively. The presence of off-diagonal terms in the mass matrix indicates a contribution in the added mass due to the hydrodynamic loading. The loading will be attracted only in the surge, heave and pitch degrees of freedom due to the unidirectional wave acting in the surge direction on a symmetric configuration of the platform about the x and z axes).

Damping matrix, *C*

Assuming $\boldsymbol{C}$ to be proportional to $\boldsymbol{K}$ and $\boldsymbol{M}$, the elements of $\boldsymbol{C}$ are determined by the equation given below, using the orthogonal properties of $\boldsymbol{M}$ and $\boldsymbol{K}$:

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K}, \tag{14}$$

α and β are constants. This matrix is calculated based on the initial values of $\boldsymbol{K}$ and $\boldsymbol{M}$ only.

Stiffness matrix, *K*

The coefficients, K_{AB}, of the stiffness matrix of the triangular TLP are derived as the reaction in the degree of freedom A due to unit displacement in the degree of freedom B, keeping all other degrees of freedom restrained. The coefficients of the stiffness matrix have nonlinear terms due to the cosine, sine, square root and squared terms of the displacements. Furthermore, the tendon tension changes due to the motion of the TLP in different degrees of freedom makes the stiffness matrix response-dependent. The stiffness matrix $\boldsymbol{K}$ of a TLP is:

$$\begin{array}{c} \left|\begin{matrix}\text{Surge} & \text{Sway} & \text{Heave} & \text{Roll} & \text{Pitch} & \text{Yaw}\end{matrix}\right| \\ \boldsymbol{K}=\begin{bmatrix} K_{\mathrm{SS}} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{\mathrm{WW}} & 0 & 0 & 0 & 0 \\ K_{\mathrm{HS}} & K_{\mathrm{HW}} & K_{\mathrm{HH}} & K_{\mathrm{HR}} & K_{\mathrm{HP}} & K_{\mathrm{HY}} \\ 0 & K_{\mathrm{RW}} & 0 & K_{\mathrm{RR}} & 0 & 0 \\ K_{\mathrm{PS}} & 0 & 0 & 0 & K_{\mathrm{PP}} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{\mathrm{YY}} \end{bmatrix}. \end{array} \quad (15)$$

In the stiffness matrix the presence of off-diagonal terms reflects the coupling effect between the various degrees of freedom and the coefficients depend on the change in the tension of the tendons, which affects the buoyancy of the system. Hence, $\boldsymbol{K}$ is not constant for all time instants but the coefficients are replaced by a new value computed at each time instant depending upon the response value at that time instant. The stiffness matrix of the four-legged square TLP is taken as suggested by Morgan and Malaeb (1983). The stiffness matrix shows: (1) the presence of off-diagonal terms, which reflects the coupling effect between the various degrees of freedom; (2) that the coefficients depend on the change in the tension of the tethers affecting the buoyancy of the system. Hence, the matrix is response-dependent.

Hydrodynamic force vector, *F*(*t*)

Water particle kinematics are evaluated using Airy's linear wave theory. This description assumes the wave form whose wave height, H, is small in comparison to its wave length, L, and water depth, d. Knowing the water particle kinematics, the hydrodynamic force vector is calculated in each degree of freedom. According to Morison's equation, the intensity of wave force per unit length on the structure is given as:

$$\begin{aligned} f(x,y,t) &= 0.5\rho_{\mathrm{w}} C_{\mathrm{d}} D(\dot{u}-\dot{x}+\dot{u}_{\mathrm{c}})\,|\,\dot{u}-\dot{x}+\dot{u}_{\mathrm{c}}\,| \\ &\quad + 0.25\pi D^2 \rho_{\mathrm{w}} C_{\mathrm{m}} \ddot{u} \pm 0.25\pi D^2 (C_{\mathrm{m}}-1)\rho_{\mathrm{w}} \ddot{x}, \end{aligned} \quad (16)$$

where $\dot{u}_{\mathrm{c}}$ is the current velocity, $\dot{u}$ is the horizontal water particle velocity, $\dot{x}$ is the horizontal structural velocity, D is the column diameter, $\ddot{x}$ is the horizontal structural acceleration, and $\ddot{u}$ is the horizontal water particle acceleration. The last term in Eq.(16) is the added mass term where a positive sign is used when the water surface is below the MSL and a negative sign is used when the water surface is above the MSL. The contribution of added mass up to the MSL will already be considered along with structural mass.

SOLUTION OF MOTION EQUATION

In the time domain approach, the equations of motion of the system are solved by a step-by-step numerical integration technique over a sufficiently long time interval. Also, as previously pointed out, time domain equations of motion are usually highly nonlinear from both hydrodynamic and structural viewpoints. There are several methods to solve the equation of motion in time domain. Among them the modified Euler method (MEM) is simple to use and suitable for response-dependent problems.

The MEM presented herein is a simple numerical procedure which can be effectively used for analysis of the dynamic response of structures in the time domain. Applications of any numerical method for the analysis of the dynamics of the dynamic response of structures must be made with due consideration of its limitations, among which those related to the accuracy and stability of the method are particularly important. The applications of the MEM made herein show that it is efficient and easy to use, and that it can be employed to obtain accurate solutions to a wide variety of structural dynamics problems. Simplicity is one of the distinguishing features of the method. Because the MEM is conditionally stable, it may be inefficient for the analysis by direct integration of the response of a multi-degree-of-freedom system with a very short highest natural period of vibration. However, the method is explicit, and is particularly suited for the analysis of non-linear systems. The MEM has been successfully used in the analysis of the dynamic response of wave-excited offshore structures (Sanghvi, 1990). The inherent simplicity of the method has also led to successful applications of it.

Let x_n and $\dot{x}_n$ be the known displacement and velocity, respectively, of the system at time t_n. This time is expressed in terms of a non-negative integer number, n, and a time step, Δt, as $t_n=n\Delta t$. By application of the MEM, the displacement and velocity of the system, x_{n+1} and $\dot{x}_{n+1}$, at time $t_{n+1}=(n+1)\Delta t$, are evaluated as follows:

$$\dot{x}_{n+1} = \dot{x}_n + \ddot{x}_n \Delta t, \tag{17}$$

$$x_{n+1} = x_n + \dot{x}_{n+1} \Delta t. \tag{18}$$

With the values of x_{n+1} and $\dot{x}_{n+1}$ available, the procedure defined by Eqs.(17) and (18) may be repeated to compute the response of the system for subsequent discrete times larger than t_{n+1}. These computations can be carried out accurately by a proper implementation of the MEM.

NUMERICAL STUDY

A TLP in 700 m deep water has been chosen for the numerical study. The characteristics of the TLP under study are: Diameter of Columns, D_c=18 m; Diameter of Pontoon, D=12 m; Pre-tension, T_0= 0.55×10^5 KN; Length=90 m; Tether tensions are assumed to be equally distributed in all the four tethers. TLP structure is assumed to behave like a rigid body. The stiffness matrix developed takes into account large deformations and other nonlinearities like tether tension, etc. The angle of attack of long crested sea is 0 and H_s=10 m, T_z=15 s. The angle of incident wave with x direction is 30°. Eigenvalue analysis results in the following periods are as follows:

Surge: 78.7 s (0.08 rad/s); Sway: 78.7 s (0.08 rad/s); Heave: 2.0 s (3.14 rad/s); Roll: 1.8 s (3.49 rad/s); Pitch: 1.8 s (3.49 rad/s); and Yaw: 74.2 s (0.085 rad/s).

A computer program STATELP has been developed using MATLAB, for nonlinear dynamic and spectral analysis as well as reliability assessment based on first order reliability method (FORM) and Monte-Carlo simulation.

Fig.2 shows the spectrum of sea-state for H_s=10 m and T_z=15 s. Based on the mentioned formulation, random surface elevation was derived. A typical generated wave is shown in Fig.3.

Fig.4 shows the power spectral density (PSD) of generated wave. The smooth spectrum is approximately the average of the non-smoothed PSD. It is seen that the maximum input energy occurs in the range of 0.25~0.40 rad/s.

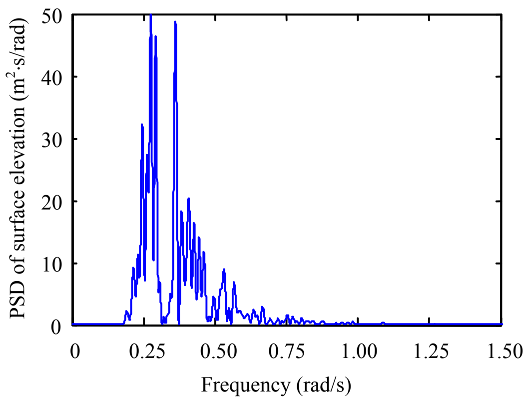

Fig.4 PSD of surface wave

Then nonlinear dynamic analysis was carried out to achieve useful results. Displacement of various degrees of freedom is illustrated in Fig.5 showing the low and high frequency components of motions illustrating the wave and structural period. Approximately seven cycles of surge motion last 500 s. It means that every global cycle occurred in time equal to surge period (78.7 s). Similar result is seen for sway, roll, pitch and yaw motions.

It is clear that each surge cycle has two peaks in heave degree of freedom because of the peak response in heave at the end of surge motion both in the right and left hand side of the structure. Therefore a surge cycle is expected to have 14 peaks in 500 s.

The effect of the high frequency component is seen in all motions especially in roll and pitch degrees of freedom. In order to evaluate the high frequency component a short duration of motion is shown in Fig.6. A smooth motion that occurred in 15 s (T_z) is seen in surge, sway, heave and yaw motions. Because of coupling between heave and surge, heave motion is affected by the frequency of the surge degree

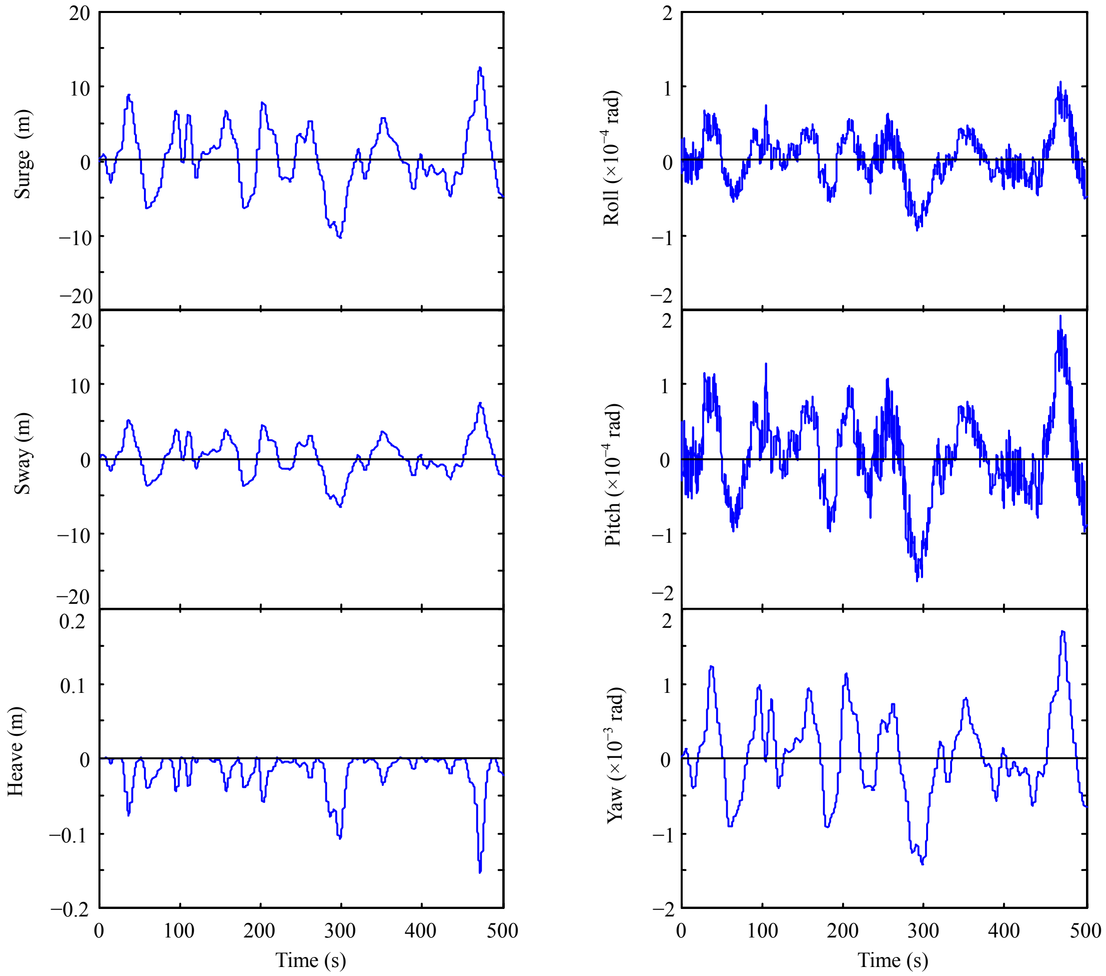

Fig.5 Time history of displacements in 500 s

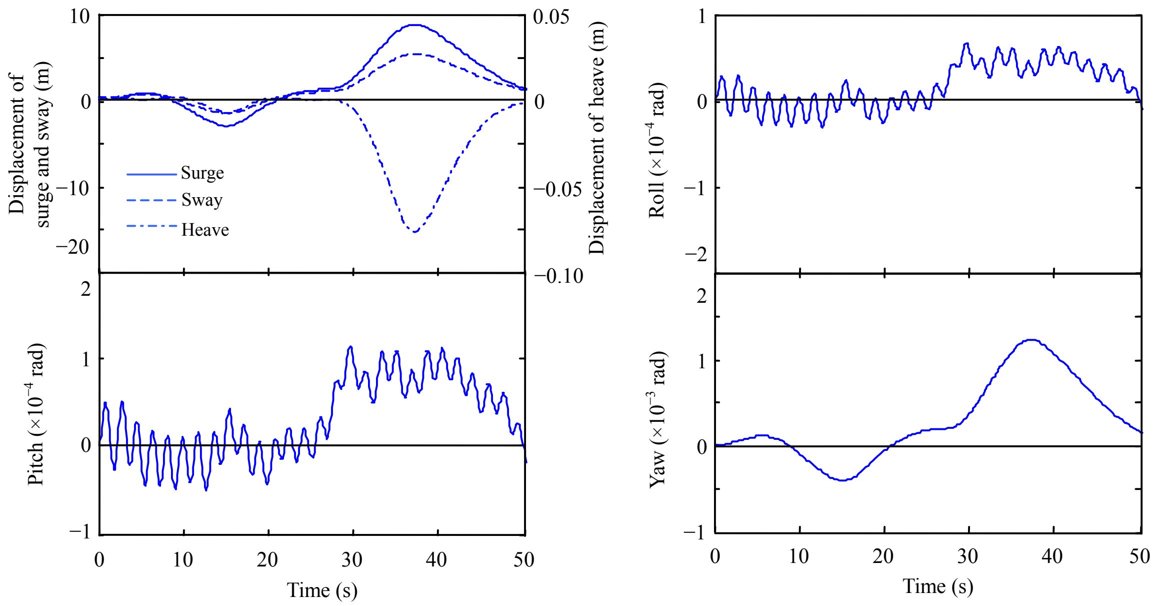

Fig.6 Time history of displacements in 50 s

of freedom. But in roll and pitch the period of the high frequency component is equal to 1.8 s (roll and pitch period). Also it is seen that yaw rotation is more than that of pitch and roll, because of no restriction in the yaw degree of freedom.

An important parameter for desired serviceability is acceleration. This parameter is shown in Fig.7. The importance of acceleration goes back to the human and equipment sensitivity to vertical acceleration. Heave, roll and pitch accelerations are important for studying and investigating the serviceability and performance of the system. A phenomenon similar to beating is clear in roll and pitch accelerations. The period of beating is equal to the structural period of surge and sway (78.7 s). Such phenomenon is not seen in yaw motion because the period of yaw is very long (74.2 s).

For evaluating the effect of the high frequency component, a short duration of motion is shown in Fig.8. A smooth motion that occurred in 15 s (T_z) is seen in surge, sway and yaw motions. The period of the high frequency component in heave degree of freedom is equal to 2 s (heave period) and for roll and pitch motion the period of acceleration is equal to 1.8 s (roll and pitch period).

In order to get a deeper view on the energy of motion one can use PSD diagrams of various degrees of freedom (Fig.9). The significant amplitude of surge and sway motion occured in the neighborhood of 0.8 rad/s (related to surge and sway period equal to 78.7 s). Similar results are seen for other degrees of freedom because of coupling with surge and sway. There is a clear peak in frequency equal to 0.42 rad/s related to T_z.

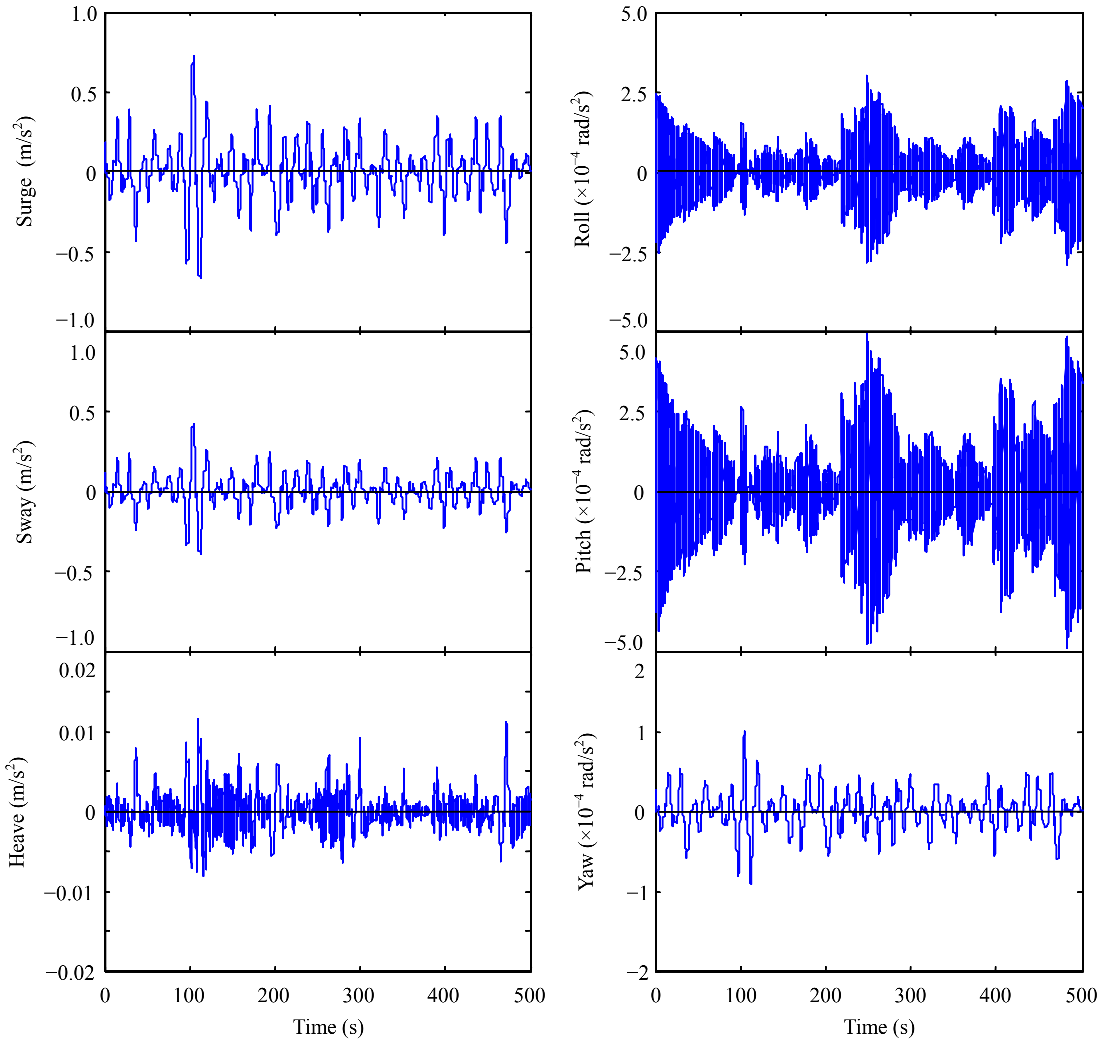

Fig.7 Time history of acceleration in 500 s

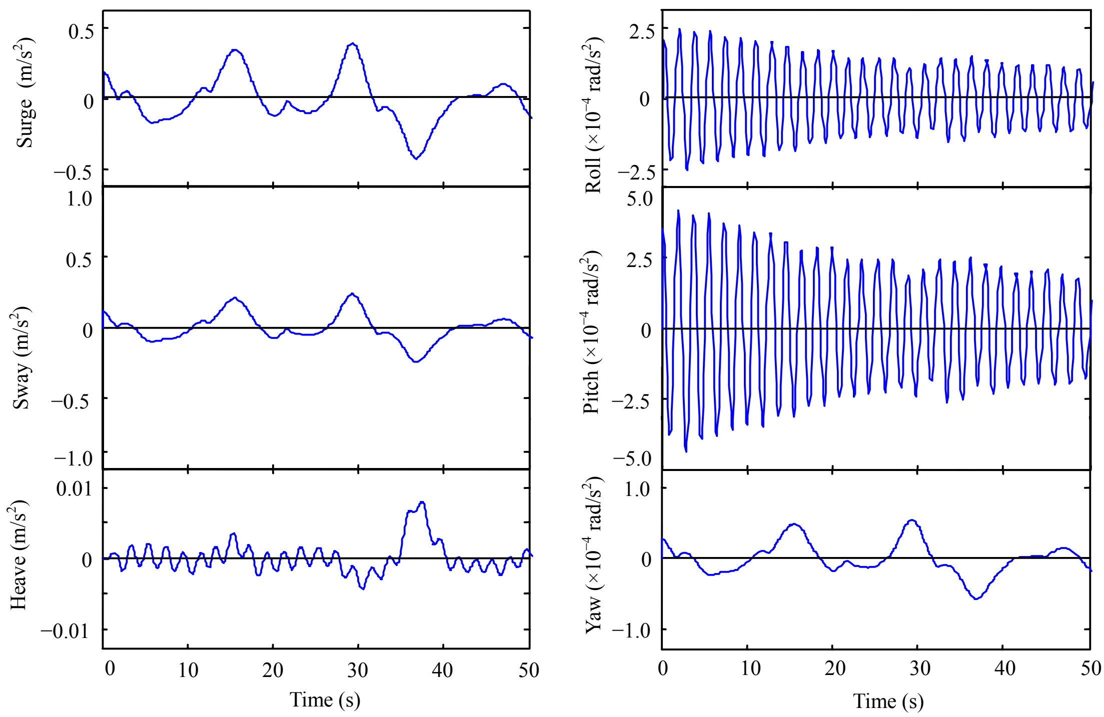

Fig.8 Time history of acceleration in 50 s

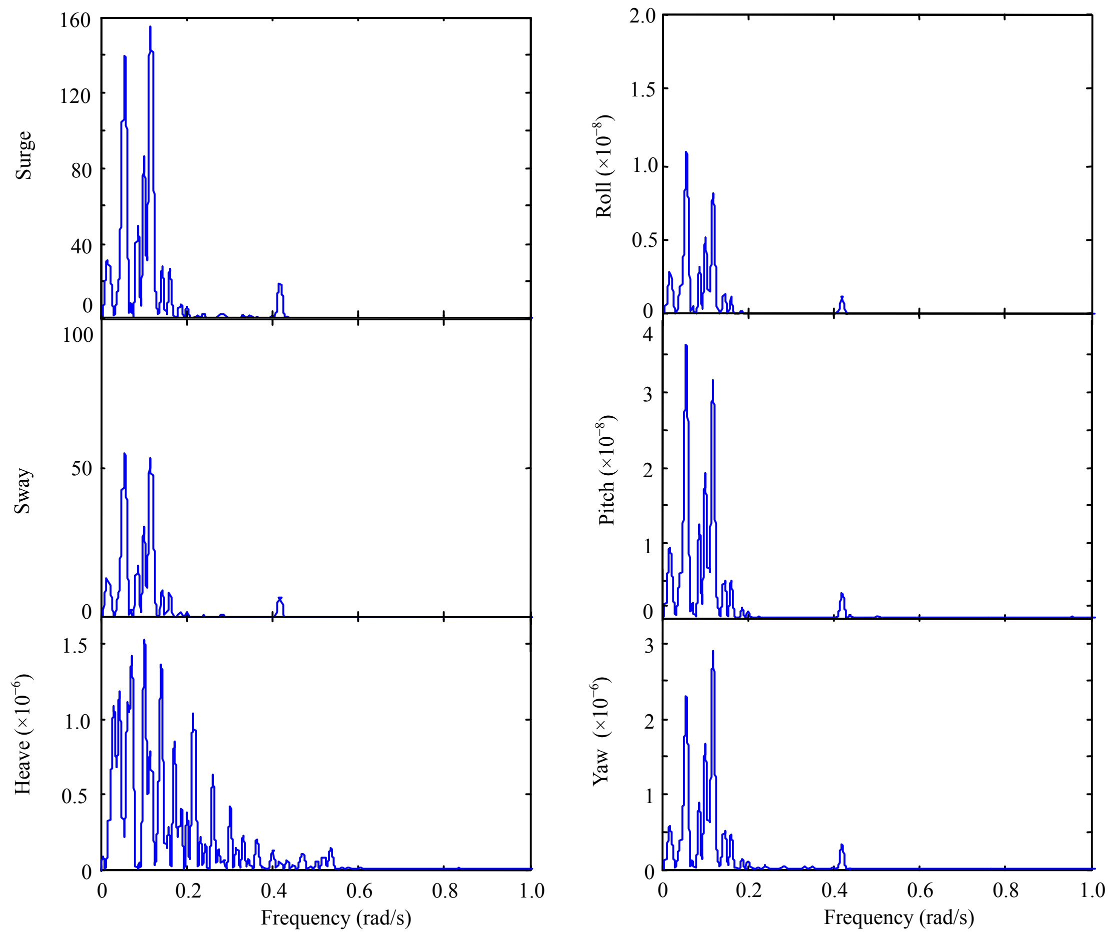

Fig.9 PSD of displacements

PSDs of accelerations are shown in Fig.10. The significant peaks of surge, sway, heave and yaw accelerations occurred in the neighborhood of 0.42 rad/s. But for roll and pitch accelerations the maximum energy is in the neighborhood of frequency equal to 3.49 rad/s (roll and pitch frequency).

Instability is an important point for TLP. The phase plane is used for discussion on nonlinear instabilities. Phase plane gives a conceptual view of dynamic behavior of the structure. The phase plane of all degrees of freedom is illustrated in Fig.11. The path of the system can be followed from initial conditions based on initial values for displacements or velocities. It is observed that the behavior of the structure is periodic and stable.

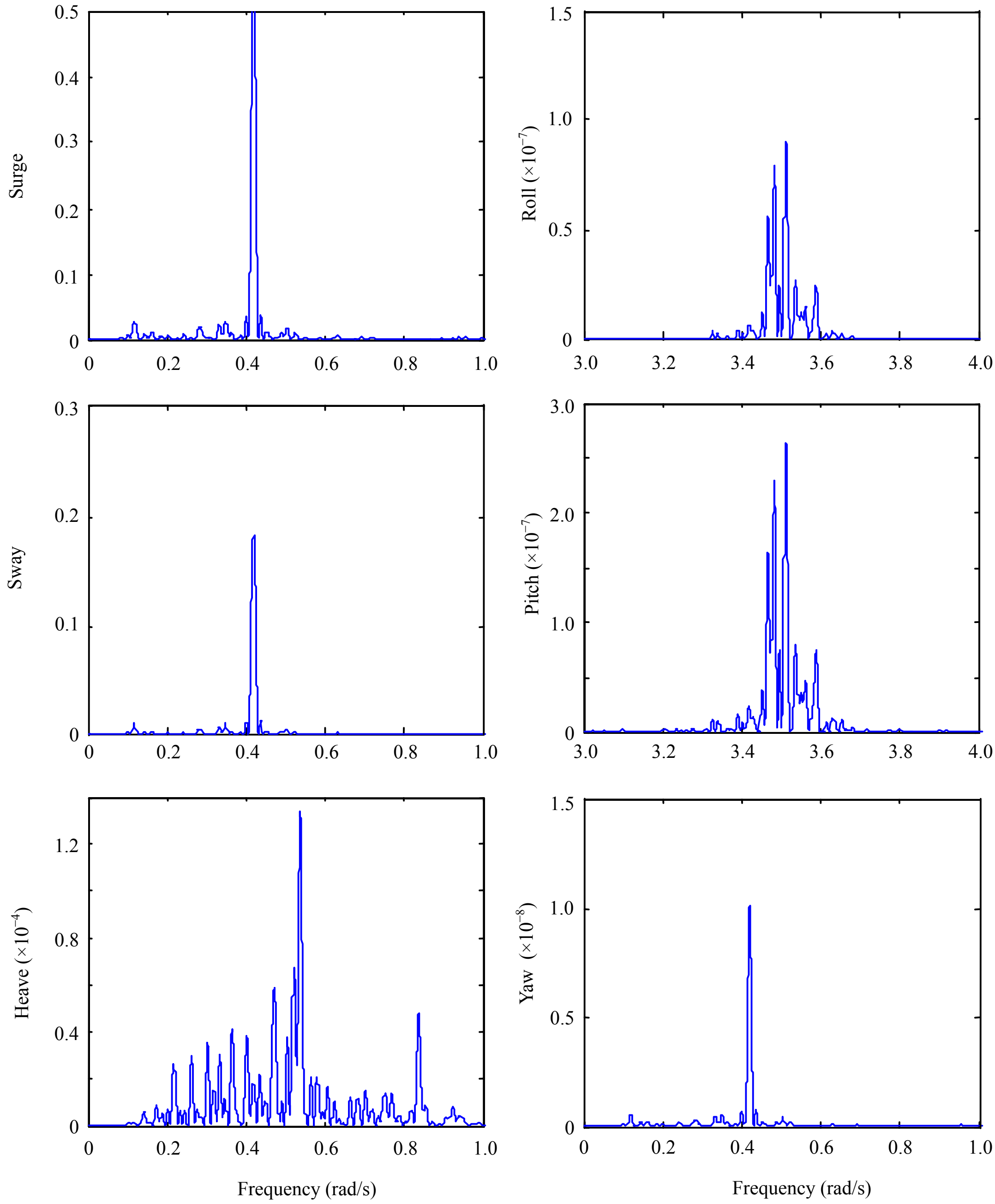

Fig.10 PSD of accelerations

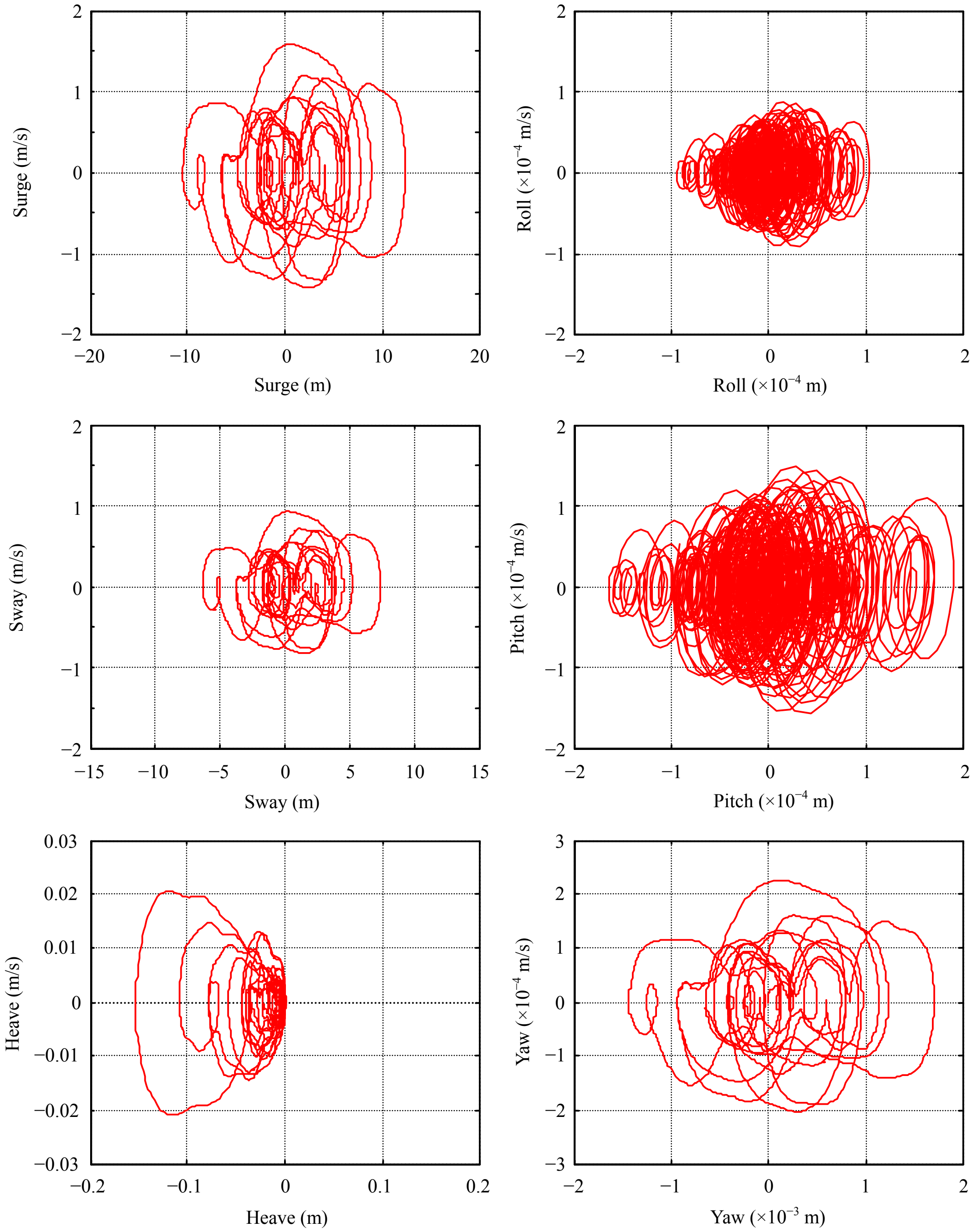

Fig.11 Phase planes

CONCLUSION

The nonlinear dynamic response of TLP under random sea wave loads was investigated. Analyses were carried out in both time and frequency domains. The time history of random wave is generated based on Pierson-Moskowitz spectrum and it acts on the structure in arbitrary direction. The hydrodynamic forces are calculated using the modified Morison equation according to Airy's linear wave theory. This kind of analysis is necessary for checking the response of a designed TLP under environmental loads.

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