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Nonlinear Dynamic Response of Tension Leg Platform

Xiaohui Zeng[a], *Yang Liu*[a], *Xiaopeng Shen*[a b], *Yingxiang Wu*[a]
[a]Division of Engineering Sciences, Institute of Mechanics, Chinese Academy of Sciences
Beijing, China
[b]CNOOC Research Center
Beijing, China

ABSTRACT

Tension Leg Platform (TLP) is a typical compliant offshore structure for oil exploitation in deep water. Most of the existing mathematical models for analyzing the dynamic response of TLP are based on explicit or implicit assumptions that displacements (translations and rotations) are small magnitude. Herein a theoretical method for analyzing the nonlinear dynamic behavior of TLP with finite displacement is developed, in which multifold nonlinearities are taken into account, i.e. finite displacement, coupling of the six degrees of freedom, instantaneous position, instantaneous wet surface, free surface effects and viscous drag force. Using this theoretical model, we perform the numerical analysis of dynamic response of a representative TLP. The comparison between the degenerative linear solution of the proposed nonlinear model and the published one shows good agreements. Furthermore, numerical results are presented which illustrate that nonlinearities exert a distinct influence on the dynamic responses of the TLP.

KEY WORDS: Tension leg platform (TLP); nonlinear dynamic response; finite displacement; geometric nonlinearity; behavior; wave loads; numerical simulation.

INTRODUCTION

The oil and gas resource in land and inshore continental shelf gradually decrease. In view of this situation, petroleum industries take great interest in deep water exploration and development.

Tension Leg Platform (TLP) is a typical compliant floating working station for oil exploitation in deep sea. It consists of hull, taut tendons and foundations, which allows motions of surge, sway, and yaw in the horizontal plane and heave, pitch, and roll in the vertical plane. The dynamic response of TLP is a question of common interest for offshore scientists and engineers, and there are many research works published. Williams and Rangappa (1994) developed an approximate semi-analytical technique to calculate hydrodynamic loads and added mass and damping coefficients for idealized TLP consisting of arrays of circular cylinder. Yilmaz (1998) presented an exact analytical method to solve the diffraction and radiation problems of a group of cylinders, taking account of the interaction between the cylinders. Yilmaz, Incecik and Barltrop (2001) calculated free surface elevations for an array of four cylinders. Ahmad (1996) conducted response analysis considering viscous hydrodynamic force, variable added mass and large excursion. In addition, Ahmad, Islam and Ali (1997) investigate TLP' s sensitivity to dynamic effects of the wind. Chandrasekaran and Jain (2002a, b) proposed a triangular configuration TLP, and developed a method to analyze the dynamic behavior of triangular and square TLP. Furthermore, they performed numerical studies to compare the dynamic responses of a triangular TLP with that of a square TLP.

Up to the author's knowledge, the existing investigations on TLP mostly make *a priori* assumptions explicitly or implicitly that the translational displacements and angular displacements being kept small magnitude. Therefore, the finite motions and accordingly aroused other nonlinear factors are not taken into account. In fact, in severe sea state or ultimate adverse operation state such as one or more tension legs being broken, the displacements of TLP may be large quantities and should not be taken for small magnitudes. Even though the small magnitudes are kept to two or three orders, it is deficient for such terrible situation. Very few investigations ostensibly claim to have considered arbitrary displacements. However, it may not be the fact. The reason is that, when they deduce the stiffness matrix, arbitrary displacement is given just in one direction while keeping all other degrees of freedom restrained. In nature, stiffness matrix obtained by such technique is with respect to the initial static equilibrium position. This technique can only be employed for linear problem. For nonlinear problem, the stiffness matrix should be deduced with reference to the instantaneous displaced position (i.e. the structure may move in all six degrees of freedom, none of them should be restrained).

The aforementioned assumptions make the process of dynamic analysis of TLP fairly easy. However, such technique places too severe restriction to include all load cases, especially in some extreme circumstances. It is obvious that the method can be modified to adapt for more general operation state if we abandon the assumptions. Finite displacements are visible nonlinearities. In addition, there are more concomitant nonlinear factors induced by finite displacements. For example, the six degrees of freedom are coupled; the hydrodynamic forces on TLP are response dependent (i.e. wave forces are functions of the instantaneous position, velocity, acceleration and wet surface of TLP). Although considering all the nonlinearities makes the problem very complex, it is worthwhile according to our analysis. We have investigated the dynamic response of a floating circular cylinder with a taut tether taking account of all the nonlinearities above-mentioned (Zeng, Shen and Wu, 2005). It is shown that these nonlinear factors exert a significant influence on the dynamic responses of the tethered cylinder.

Whereas the reason we interpret above, this paper investigates the nonlinear dynamic response of a typical TLP. The nonlinearities include finite displacements, coupling of the six degrees of freedom, instantaneous position, instantaneous wet surface, free surface effects and viscous drag force.

In this paper, the major assumptions are made as followings:

- The motion of cylinder is finite instead of small.
- The cylinder is assumed sufficient slender, and then the wave diffraction effects have been neglected.
- Wave forces are evaluated at the instantaneous displaced position of the cylinder by Morison's equation.
- The free surface effects are taken into account.

THEORETICAL DEVELOPMENT

A typical TLP consisting of four columns and pontoons is shown in Figs. 1(a)(c)(d). Three right-hand Cartesian coordinate systems oxyz、OXYZ、$G\xi\eta\zeta$ are defined in Fig. 1(b). The oxyz is space fixed coordinate system, plane oxy coincides with the undisturbed calm water surface, and the positive z-axis is pointing upwards. This coordinate system is used to define wave. The OXYZ is also space fixed coordinate system, which has its origin located at the center of gravity (C.G.) of the undisturbed TLP. Three axes of coordinate system OXYZ are in parallel with those of oxyz. The $G\xi\eta\zeta$ is body fixed coordinate system, which coincides with the OXYZ when the TLP has zero displacement. The motions of TLP are denoted by the displacements X_1, X_2, X_3, X_4, X_5 and X_6 of $G\xi\eta\zeta$ with respect to OXYZ. X_1, X_2, X_3 are the coordinates of G in OXYZ, which denote the translation of TLP. The longitudinal displacement X_1 is defined as surge, the transverse displacement X_2 is sway, and the vertical one X_3 along Z is heave. Angular motions are represented in terms of three Eulerian angles X_4, X_5, X_6 of $G\xi\eta\zeta$ with reference to OXYZ. In this paper, X_1, X_2, X_3, X_4, X_5 and X_6 are finite magnitude instead of infinitesimal.

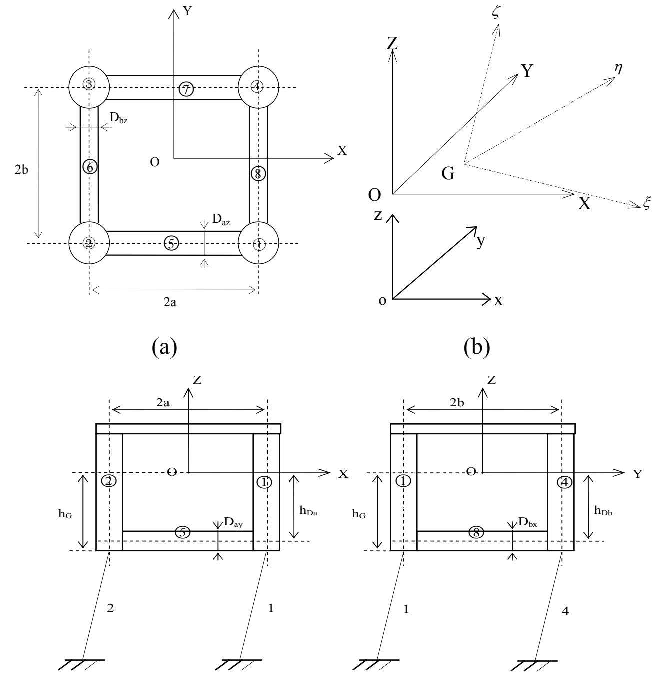
The transformation of coordinates can be written as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} + \begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} \begin{pmatrix} \xi \\ \eta \\ \zeta \end{pmatrix} \tag{1a}$$

Where

$$\begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} =$$

$$\begin{pmatrix} \cos X_5 \cos X_6 & -\cos X_5 \sin X_6 & \sin X_5 \\ \sin X_4 \sin X_5 \cos X_6 + \cos X_4 \sin X_6 & -\sin X_4 \sin X_5 \sin X_6 + \cos X_4 \cos X_6 & -\sin X_4 \cos X_5 \\ -\cos X_4 \sin X_5 \cos X_6 + \sin X_4 \sin X_6 & \cos X_4 \sin X_5 \sin X_6 + \sin X_4 \cos X_6 & \cos X_4 \cos X_5 \end{pmatrix} \tag{1b}$$



(a) (b)

(c) (d)

(a)(c)(d) View of TLP (b) The coordinate systems

Fig. 1 Sketch of TLP and the coordinate systems

If the angles are assumed to be infinitesimal, and the components of the matrix are truncated after the first order small magnitude, Eq. 1b can be linearized as:

$$\begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} = \begin{pmatrix} 1 & -X_6 & X_5 \\ X_6 & 1 & -X_4 \\ -X_5 & X_4 & 1 \end{pmatrix} \tag{1c}$$

Generally, the existing method employs Eq. 1c to analyze the overall dynamic response of TLP. It can be found that Eq. 1b differs from Eq. 1c in many ways. The latter is the approximation of the former. In addition, the latter ignores some terms related to coupling among various degrees of freedom. As the rotations are finite magnitude, such approximation will obviously induce comparative errors. Even if the rotation is small, those coupled terms may evoke considerable effect in view of the small damping and the near-resonance state.

In this paper, we study the situation of finite displacements with the exact transformation matrix (Eq. 1b) being used. Thus the interactions between degrees of freedom can be retained, and the precision of numerical calculation can be improved.

By using Newton's second law; we can obtain the equations of six components X_i of TLP's motions as:

$$\begin{pmatrix} M & 0 & 0 & 0 & 0 & 0 \\ 0 & M & 0 & 0 & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & 0 & 0 & I_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_3 \end{pmatrix} \begin{pmatrix} \ddot{X}_1 \\ \ddot{X}_2 \\ \ddot{X}_3 \\ \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \end{pmatrix} = \begin{pmatrix} F_1(X_i, \dot{X}_i, \ddot{X}_i) \\ F_2(X_i, \dot{X}_i, \ddot{X}_i) \\ F_3(X_i, \dot{X}_i, \ddot{X}_i) \\ F_4(X_i, \dot{X}_i, \ddot{X}_i) - (I_3 - I_2)\omega_2\omega_3 \\ F_5(X_i, \dot{X}_i, \ddot{X}_i) - (I_1 - I_3)\omega_3\omega_1 \\ F_6(X_i, \dot{X}_i, \ddot{X}_i) - (I_2 - I_1)\omega_1\omega_2 \end{pmatrix} \tag{2}$$

in which M is the body mass of TLP in air, I_i (i=1, 2, 3) are the moments of inertia with respect to the principal axes through C.G.; F_i are the components of external force (i=1, 2, 3) and moment (i=4, 5, 6) vectors, respectively; ω_i (i=1, 2, 3) are the components of angular velocity, dot over variable means time derivative. Angular velocities are given by:

$$\omega_1 = \dot{X}_4 \cos X_5 \cos X_6 + \dot{X}_5 \sin X_6 \tag{3}$$

$$\omega_2 = -\dot{X}_4 \cos X_5 \sin X_6 + \dot{X}_5 \cos X_6 \tag{4}$$

$$\omega_3 = \dot{X}_4 \sin X_5 + \dot{X}_6 \tag{5}$$

The external forces and moments in the right hand of Eq. 2 are coupled with the instantaneous response of TLP, which is different from the case with small motion. Then we will derive the formulae for them. From among the process of derivation, we can see that external forces and moments are assuredly coupled with the instantaneous position, velocity and acceleration of TLP. They are nonlinear functions of the response.

External Forces and Moments Vectors Acting on TLP

TLP endures tension of tendons, hydrodynamic and hydrostatic forces acting on columns and pontoons and the self gravities. After doing vector sums of those forces, we can obtain the principal vector $\vec{F}$ of external forces acting on TLP:

$$\vec{F} = \vec{F}_w + \vec{F}_B + \vec{F}_t - Mg\vec{k} = F_1\vec{i} + F_2\vec{j} + F_3\vec{k} \tag{6}$$

where $\vec{i}$, $\vec{j}$, $\vec{k}$ are base vectors of system OXYZ; g is the acceleration due to gravity. Similarly, we can get the resultant moment $\vec{M}$ by summing external moment vectors together:

$$\vec{M} = \vec{M}_{Gw} + \vec{M}_{GB} + \vec{M}_{Gt} = F_4\vec{e}_1 + F_5\vec{e}_2 + F_6\vec{e}_3 \tag{7}$$

where $\vec{e}_1$, $\vec{e}_2$, $\vec{e}_3$ are base vectors of system $G\xi\eta\zeta$. As said before, F_i (i=1,2,⋯,6) are nonlinear functions of the response of TLP. As long as the formulae for calculating F_i are obtained, we can perform evaluation of Eq. 2. The detailed formulae are given below.

Hydrodynamic Forces Vectors

When the TLP moves to an arbitrary position in waves, the axis of its component cylinders may be inclined instead of pointing to their original vertical or horizontal directions. Then forces acting on the cylinder need to be written in terms of the normal components of fluid acceleration, relative acceleration and velocity vectors between water particle and structural element. The relative acceleration and velocity vectors are functions of the response of TLP, and the fluid accelerations are calculated at the displaced position of TLP. Then one can easily see that the forces and responses are coupled.

In this paper, we present the formulae for calculation of hydrodynamic forces acting on column 1. The formulae for hydrodynamic forces on other columns and pontoons are similar. Using modified Morison equation (see e.g. Clauss, Lehmann, and Ostergaard, 1992), force vector per unit length of arbitrary oriented cylinder $\vec{f}_n$ is written as:

$$\vec{f}_n = \rho\frac{\pi D^2}{4}\dot{\vec{V}}_n + C_a\rho\frac{\pi D^2}{4}\dot{\vec{V}}_{rn} + C_d\frac{\rho D}{2}\left|\vec{V}_{rn}\right|\vec{V}_{rn} \tag{8}$$

In which ρ is mass density of water, C_a is added mass coefficient, C_d is drag coefficient, $\dot{\vec{V}}_n$ is acceleration vector of water particle normal to inclined cylinder, $\dot{\vec{V}}_{rn}$ and $\vec{V}_{rn}$ are relative acceleration and velocity vectors between the water particle and structural element normal to inclined column. The normal acceleration vector $\dot{\vec{V}}_n$ is given as

$$\dot{\vec{V}}_n = \vec{e}_3 \times (\dot{\vec{V}} \times \vec{e}_3) \tag{9}$$

$\dot{\vec{V}}$ is the fluid acceleration vector of water particle at the instantaneous position of column 1, which is evaluated in reference frame oxyz employing modified Airy's linear wave theory with stretching method Chakrabarti (1987) used. The position of TLP always changes, and then the accelerations of fluid particle used to calculate wave forces also alter along with TLP. $\vec{e}_3$ is the unit vector along the Cartesian coordinate axis $G\zeta$, and it is the function of displacements of TLP. Therefore, it is obvious that $\dot{\vec{V}}_n$ is nonlinear function of the displacements X_i :

$$\dot{\vec{V}}_n = \dot{\vec{V}}_n(X_i) \quad \text{(i=1, 2, ⋯, 6)} \tag{10}$$

Similarly, relative velocity and acceleration vectors ($\vec{V}_{rn}$ and $\dot{\vec{V}}_{rn}$) between the water particle and structural element normal to inclined column 1 can be given as:

$$\vec{V}_{rn} = \vec{V}_{rn}(X_i, \dot{X}_i) = \vec{e}_3 \times (\vec{V}_r \times \vec{e}_3) \qquad \text{(i=1,2,⋯,6)} \tag{11}$$

$$\dot{\vec{V}}_{rn} = \dot{\vec{V}}_{rn}(X_i, \dot{X}_j, \ddot{X}_i) = \vec{e}_3 \times (\dot{\vec{V}}_r \times \vec{e}_3) \quad \text{(i=1,2,⋯,6; j=4,5,6)} \tag{12}$$

in which, $\vec{V}_r = \vec{V} - \vec{V}_s$, $\dot{\vec{V}}_r = \dot{\vec{V}} - \dot{\vec{V}}_s$, $\vec{V}$ is the velocity vector of water particle, $\vec{V}_s$ is the the velocity vector of arbitrary point on the axis of column 1. By analogy with that of $\dot{\vec{V}}_n$, one can see that $\vec{V}_{rn}$ is nonlinear function of the displacement X_i and velocity $\dot{X}_i$ of TLP, and $\dot{\vec{V}}_{rn}$ is nonlinear function of the displacement X_i , the velocity $\dot{X}_i$ and the acceleration $\ddot{X}_i$ of TLP.

As $\dot{\vec{V}}_n$, $\dot{\vec{V}}_{rn}$, $\vec{V}_{rn}$ are all nonlinear functions of the dynamic responses of TLP, the wave force vector (Eq. 8) $\vec{f}_n = \vec{f}_n(X_i, \dot{X}_i, \ddot{X}_i)$ is also nonlinear function of the responses of TLP. Hence the wave loads on TLP are coupled with the dynamic responses. Therefore, we can see that such nonlinear situation differs obviously from that of the linear one.

Integrating along the column, we can obtain the hydrodynamic force vector acting on the whole column (column 1)

$$\vec{F}_{w1} = \vec{F}_{w1}(X_i, \dot{X}_i, \ddot{X}_i) = \int_{-h_G}^{-h_G+h_1} \vec{f}_{n1}\, d\zeta \tag{13}$$

where h_G is the distance between C.G. and the bottom of cylinder, and h_1 is the distance along centerline of column 1 from the bottom of column to the instantaneous wetted surface at any time. $\vec{f}_{n1}$ is $\vec{f}_n$ on column 1. The moment vector $\vec{M}_{Gw}$ with reference to the principal axes of TLP generated by hydrodynamic force is given as follows:

$$\vec{M}_{Gw1} = \int_{-h_G}^{-h_G+h_1} \left(\vec{r}_G \times \vec{f}_{n1}\right) d\zeta = \vec{M}_{Gw1}(X_i, \dot{X}_i, \ddot{X}_i) \qquad (14)$$

Hydrostatic Force Vectors

As the buoyancy $\overrightarrow{F_B}$ is always perpendicular to still water surface, the hydrostatic force on TLP is only in the heave direction. The magnitude of buoyancy is

$$\left|\overrightarrow{F_B}\right| = \rho g \pi R^2 \cdot (h_1 + h_2 + h_3 + h_4) + \rho g D_{ay} D_{az} \cdot 4a + \rho g D_{bx} D_{bz} \cdot 4b \quad (15)$$

where $D_{ay}, D_{az}, D_{bx}, D_{bz}, a, b$ are shown in Fig.1. In this paper, h_i （i=1,2,3,4）are always altering and evaluated at the instantaneous position of TLP. Therefore h_i are nonlinear functions of displacements and wave elevation, i.e. $h_i = h_i(X_i)$. While for the situation of linear case, h_i is evaluated at the still position and independent of the wave elevation.

When TLP rotates, the center of buoyancy will depart from the symmetry axis. Consequently the buoyancy will generate moment with reference to the C.G. The buoyancy and buoyancy generating moment vectors on column 1 are given below, and those on the other columns and pontoons can be obtained similarly.

The magnitude of buoyancy on column 1 is $F_{B1}(X_i) = \rho g \pi r^2 h_1$, pointing upward perpendicular to the still water surface. r is the radius of column. The coordinates of shifted center of buoyancy in $G\xi\eta\zeta$ are (B_x, B_y, B_z):

$$B_x = -\frac{r^2}{4h_1}\frac{t_{31}}{t_{33}} + a$$

$$B_y = -\frac{r^2}{4h_1}\frac{t_{32}}{t_{33}} - b$$

$$B_z = \frac{h_1}{2} + \frac{r^2}{8h_1}\frac{t_{31}^2 + t_{32}^2}{t_{33}^2} - h_G$$

The moment vector induced by buoyancy on column 1 is

$$\vec{M}_{GB1} = \vec{r}_{GB} \times \vec{F}_{B1} = \vec{M}_{GB1}(X_i) \qquad (16)$$

where $\vec{r}_{GB}$ is the position vector of center of buoyancy with respect to C.G. It is obvious that $\vec{F}_{B1}(X_i)$ and $\vec{M}_{GB1}(X_i)$ are both nonlinear functions of displacements.

Tension Vectors of the Tendon

The existing method for deriving the tension of tendon is only suitable for linear case because the stiffness matrix is derived with respect to the initial still equilibrium position. Hence the stiffness matrix is constant matrix and the tension is linear function of the displacements of TLP. Whereas the stiffness matrix should be derived with reference to the instantaneous position as the finite displacements are taken into account, i.e. the stiffness matrix is function of the displacements and all of the six degrees of freedom should be simultaneously considered. In this paper, we express the tension in terms of the displacements of six degree of freedoms instead of by stiffness matrix. It will induce the coupling among the six degrees of freedom which is apparently another type of nonlinearity.

We also illustrate the deriving of related formulae by tendon 1. Point A is at the bottom of column 1, point B is fixed at the seabed. When TLP moves to arbitrary position, the coordinates of points A and B are (A_X, A_Y, A_Z) and (B_X, B_Y, B_Z), respectively, where

$$(A_X, A_Y, A_Z)^T = \begin{pmatrix} X_1 + t_{11}a - t_{12}b - t_{13}h_G \\ X_2 + t_{21}a - t_{22}b - t_{23}h_G \\ X_3 + t_{31}a - t_{32}b - t_{33}h_G \end{pmatrix} \qquad (B_X, B_Y, B_Z)^T = \begin{pmatrix} a \\ -b \\ (h_G + L) \end{pmatrix}$$

L is the initial length of the tendon. Then the tension vector of tendon 1 can be given as

$$\overrightarrow{F_{t1}} = (T_0 + \frac{ES}{L}(L_1 - L)) \cdot \frac{\overrightarrow{AB}}{\left|\overrightarrow{AB}\right|} = \overrightarrow{F_{t1}}(X_i) \qquad (17)$$

in which T_0 is the initial pretension in the tendon, E is Young's Modulus, S is the cross-sectional area of the tendon, L_1 ($= \left|\overrightarrow{AB}\right|$) is the instantaneous length of the tendon. Moreover, the moment vector $\vec{M}_{Gt}$ with reference to the C.G. induced by tension is given as follows:

$$\vec{M}_{Gt} = \vec{r}_{GA} \times \vec{F}_{Gt} = \vec{M}_{Gt}(X_i) \qquad (18)$$

where $\vec{r}_{GA}$ is the position vector of point A with respect to C.G. $\vec{F}_{t1}(X_i)$, $\vec{M}_{Gt1}(X_i)$ are both nonlinear functions of the displacements. Similarly, the tension and moment vectors of the other three tendons can also be obtained.

In the upper several sections, we have given formulae for calculating the forces and moments acting on column 1. The formulae for other columns and pontoons are similar and easy to acquire so long as the respective position vectors and direction vectors of the referred structures are substituted. Summing the forces and moments vectors on all columns and pontoons, we can obtain the overall external forces and moments. Now, we can begin to solve Eq. 2.

NUMERICAL SOLUTION OF THE MOTION EQUATIONS OF TLP

Now that the external forces and moments are all nonlinear functions of the responses of TLP on condition that the displacements are finite, the motion equations (Eq. 2) of TLP are coupled nonlinear differential equations which can hardly be solved analytically. In this paper, we solve Eq. 2 by using a fourth-order Runge-Kutta numerical time integration procedure with constant time step. To verify the proposed method in this paper and the computer program, we calculated the dynamic responses of a typical TLP (ISSC TLP) using our program. The primary properties of ISSC TLP are shown in Table 1.

Table 1. Primary properties of ISSC TLP (Taylor and Jefferys, 1986)

Description	Value
Spacing between column centres (m)	86.25
Column radius (m)	8.44
Pontoon width (m)	7.5
Pontoon height (m)	10.5
Draft (m)	35.0
Displacement (kg)	54.5×10^6
Mass (kg)	40.5×10^6
Length of tendons (m)	415.0
Roll moment of inertia (kg m^2)	82.37×10^9
Pitch moment of inertia (kg m^2)	82.37×10^9
Yaw moment of inertia (kg m^2)	98.07×10^9
Vertical position of C.G. above keel (m)	38.0

The RAOs of ISSC TLP under the circumstances of 1st order small displacements are computed, which is the degenerative case of the finite displacements. The displacements RAOs of the TLP in directions of surge, sway and yaw in regular waves with heading angle being 22.5 degrees are compared with the existing solution and shown in Figs. 2~4. It can be easily found that our degenerative linear solution coincide with that of the existing one (Taylor and Jefferys, 1986).

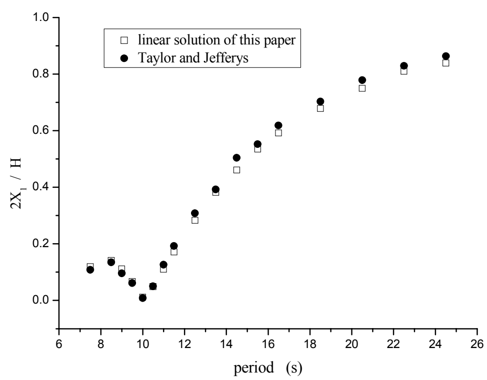


Fig. 2 RAO of surge

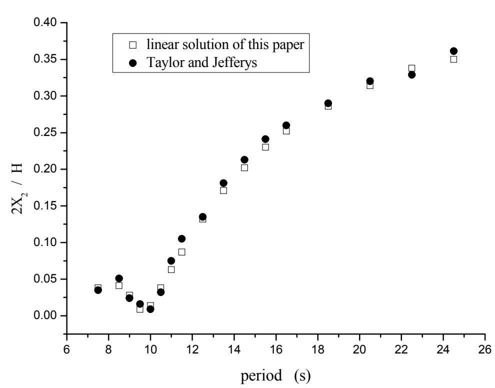


Fig. 3 RAO of sway

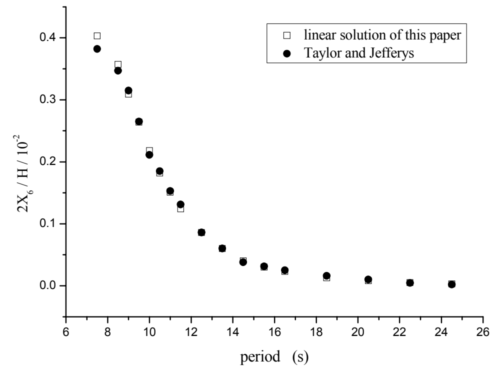


Fig. 4 RAO of yaw

Then the dynamic responses of ISSC TLP taking account of multifold nonlinearities induced by finite displacements are computed, and compared with that of linear case. The linear and nonlinear solutions of the steady state responses of ISSC TLP in regular waves are shown in Figs. 5~10. The wave heading angle is 22.5 degrees, the wave period is 8 seconds, and the wave heights are 8 and 11 meters respectively. It can be found that nonlinearities exert a distinct influence on the dynamic responses of TLP, and the differences between linear and nonlinear solutions become more distinct as the wave height increases. The linear solutions of surge, sway and yaw have nearly zero net excursions, whereas the nonlinear solutions reveal obvious net excursions. The amplitude differences between those two type solutions of surge and sway are about 20%~67%, and the differences of yaw are about 4%~7%. The phase of nonlinear solutions of heave is shifted from that of linear one by about 180 degrees, and the amplitude differences are about 70%. The differences between the linear and nonlinear solutions of roll and pitch are very large, which can be multiple times. In addition, the presence of high-frequency components in the nonlinear solutions of roll and pitch is apparent. The foregoing differences between linear and nonlinear solutions may be attributed to both the complicated nonlinear coupling among six degrees of freedom and the loads-responses interactions induced by finite displacements. The net excursion (drift), high-frequency components, amplitude differences and phase shifts therein mentioned are typical consequences induced by nonlinear terms (e.g. the quadratic, cubic and high order terms introduced by finite displacements) in the governing equations.

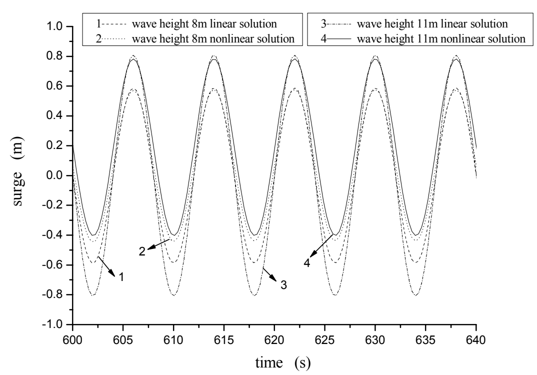


Fig. 5 Steady-state response of surge

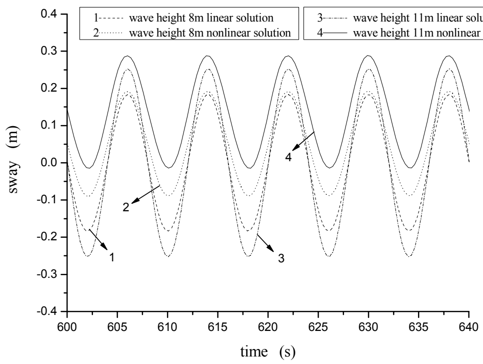


Fig. 6 Steady-state response of sway

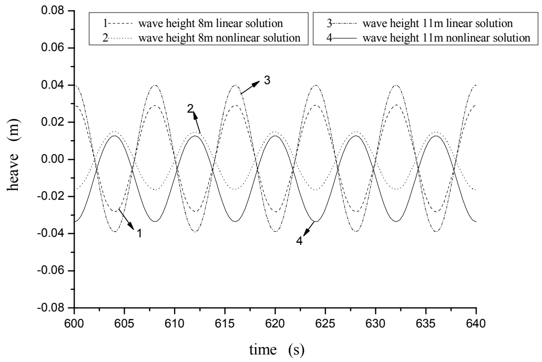


Fig. 7 Steady-state response of heave

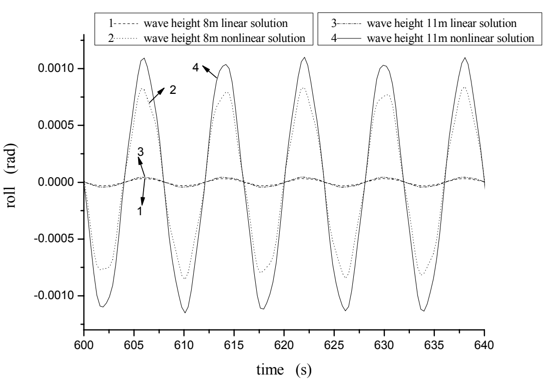


Fig. 8 Steady-state response of roll

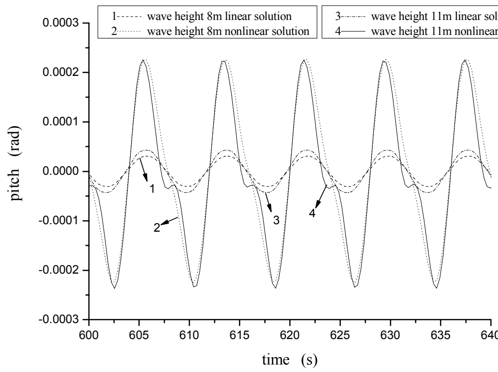


Fig. 9 Steady-state response of pitch

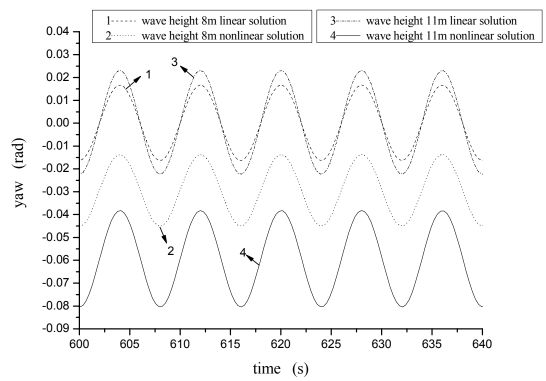


Fig. 10 Steady-state response of yaw

CONCLUSIONS

The dynamic responses of TLP with finite displacements are investigated in this paper. Several nonlinearities induced by finite displacements are taken into account. The differences between nonlinear and linear cases are clarified. Then a method for computing dynamic responses of TLP considering multifold nonlinearities is proposed. The nonlinear factors include finite displacement, coupling of the six degrees of freedom, instantaneous position, instantaneous wet surface, free surface effects and viscous drag force. The formulae are given, and a computer program for numerical analysis is developed.

To verify the proposed method, a degenerative linear case for ISSC TLP is computed and compared with the published one, which shows good agreements. Moreover, the comparison between the nonlinear and linear cases shows distinct differences. It reveals that nonlinear factors play an important role in the dynamic response of TLP. Therefore, it is suggested that the nonlinearities deserve a serious thought. Some validations may be needed to perform before any approximation related to nonlinear factors referred in this paper is made.

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