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Nonlinear Dynamic Response of Floating Circular Cylinder with Taut Tether

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ABSTRACT

Tethered floating circular cylinder can be regarded as a typical simplified model in offshore engineering. Such structure is the basic component of TLP. Careful investigation on the dynamic response of this type of cylinder may give a hint on some new nonlinear characteristics of TLP, which have been omitted before. Then the nonlinear dynamic analysis of a tethered cylinder is performed in the time domain. Nonlinearities considered in the analysis include geometric nonlinearity induced by coupled finite translational and rotational displacements of the cylinder, nonlinear hydrostatic and inviscid hydrodynamic forces introduced by the effect of instantaneous wet surface, and the velocity squared viscous drag force (also integrated to instantaneous wet surface). Numerical results are presented which illustrate that rotations exert a significant influence on the dynamic motion responses of the tethered cylinder, and should be dealt with as finite variables instead of infinitesimal.

KEY WORDS: Nonlinear response; floating circular cylinder; taut tether; TLP; geometric nonlinearity; finite displacement.

INTRODUCTION

A typical TLP is a floating structure comprising group of cylinders with taut tether, which allows motions of surge, sway, and yaw in the horizontal plane and heave, pitch, and roll in the vertical plane. Some mathematical models have been presented to analyze the dynamic response of TLP. 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. 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.

For many mathematical models, *a priori* assumptions are made explicitly or implicitly, such as translational displacements and angular displacements being kept infinitesimal. Although other models ostensibly claim to have considered arbitrary displacements, actually it may not be the fact. The reason is that, in such models, the method deriving the stiffness matrix is to give an arbitrary displacement just in one direction, keeping all other degrees of freedom restrained. In fact, stiffness matrix obtained by this measure is about the initial static equilibrium position, and can be employed for linear problem. However, for nonlinear problem the stiffness matrix should be derived based on the instantaneous displaced position (i.e. the structure may move in all six degrees of freedom, none of them should be restrained). Furthermore, to deal with problems related to finite rotation angle, the concept of Eulerian angles have to be introduced, which make the stiffness matrix acquired on non-displaced position very questionable.

The foregoing mentioned assumptions make the process of dynamic analysis fairly easy. However, such technique places too severe restriction to include all load cases, especially in some extreme circumstances. It is obvious that precision will be improved if displacements are not restricted to infinitesimal, whereas the problem is whether it deserves to do at the cost of more complicated analysis process. Unfortunately, no open literatures give the comparison thus far up to the authors' knowledge.

If translational and angular displacements are finite quantities instead of infinitesimal, all six degrees of freedom are coupled, restoring force and wave force are displacement dependent. Then many nonlinear terms are introduced. These nonlinearities not only make the mathematical model of dynamics of TLP very complex, but also cause the solving procedure onerous and time-consuming. In order to get the quantitative evidence of the effect of those nonlinearities at rational cost, a simplified TLP-like model is set up. The model is made up of one floating circular cylinder and a taut tether along the axis of cylinder. Buoyancy provided by floating cylinder exceeds its weight, and thus the tether is tightened mooring to the seabed. For this model, nonlinear differential equation is established, and dynamic response due to finite coupled motion is obtained.

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

- The motion of cylinder is finite instead of infinitesimal.
- The cylinder is assumed sufficient slender, i.e. the wave

diffraction effects have been neglected.

- Wave forces are evaluated at the instantaneous displaced position of the cylinder by Morison's equation using Airy's wave theory with free surface effects taken into account.

THEORETICAL DEVELOPMENT

A floating circular cylinder of diameter D with a taut tether located in water of uniform depth is shown in Fig. 1. Four right-hand cartesian coordinate systems are defined in Figs. 1~2. The oxyz is space fixed, global coordinate system, and plane oxy coincides with the undisturbed calm water surface. The positive z-axis is pointing upwards. The OXYZ is also space fixed coordinate system, which has its origin located at the center of gravity (C.G.) of the surface-piercing cylinder. 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 cylinder has zero displacement. Cartesian coordinate systems GX'Y'Z' (Fig. 2) are in parallel with OXYZ, with coordinates of G being X_1, X_2, X_3.

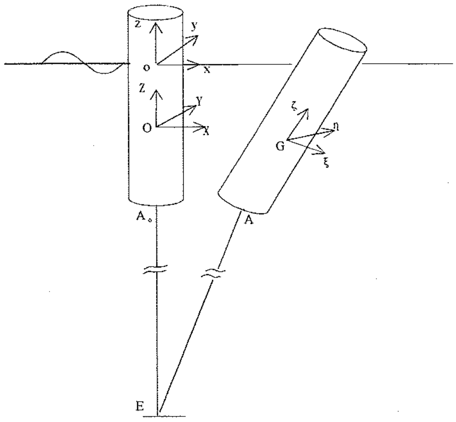

Fig. 1 Three coordinate systems

X_1, X_2, X_3 are translational motions of C.G. along three axes of coordinate system OXYZ. The longitudinal displacement along X is defined as surge, the transverse displacement along Y is sway, and the vertical one along Z is heave. Angular motions are represented in terms of three Eulerian angles X_4, X_5, X_6. Cartesian frame GX'Y'Z' can be rotated into cartesian frame $G\xi\eta\zeta$ by rotating the frame first about its first coordinate axis by angle X_4, then about the new position of the second axis by angle X_5, finally about the resulting position of the third axis by angle X_6. In this paper, X_i (i=1, ... , 6) do not need to be restrained infinitesimal, i.e. X_i can be finite quantities.

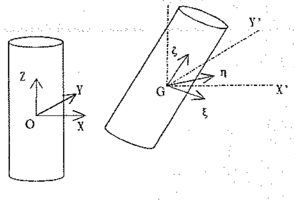

Fig. 2 The coordinate systems defining three Eulerian angles

The transformation of coordinates can be written as follows:

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

where:

$$t_{11} = \cos X_5 \cos X_6 \tag{2}$$

$$t_{12} = -\cos X_5 \sin X_6 \tag{3}$$

$$t_{13} = \sin X_5 \tag{4}$$

$$t_{21} = \sin X_4 \sin X_5 \cos X_6 + \cos X_4 \sin X_6 \tag{5}$$

$$t_{22} = -\sin X_4 \sin X_5 \sin X_6 + \cos X_4 \cos X_6 \tag{6}$$

$$t_{23} = -\sin X_4 \cos X_5 \tag{7}$$

$$t_{31} = -\cos X_4 \sin X_5 \cos X_6 + \sin X_4 \sin X_6 \tag{8}$$

$$t_{32} = \cos X_4 \sin X_5 \sin X_6 + \sin X_4 \cos X_6 \tag{9}$$

$$t_{33} = \cos X_4 \cos X_5 \tag{10}$$

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

$$\begin{pmatrix} M & 0 & 0 & 0 & 0 & 0 \\ 0 & M & 0 & 0 & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & 0 & 0 & I_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_3 \end{pmatrix} \begin{pmatrix} \ddot{X}_1 \\ \ddot{X}_2 \\ \ddot{X}_3 \\ \dot{\omega}_1 \\ \dot{\omega}_2 \\ \dot{\omega}_3 \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 - (I_3 - I_2)\omega_2\omega_3 \\ F_5 - (I_1 - I_3)\omega_3\omega_1 \\ F_6 - (I_2 - I_1)\omega_1\omega_2 \end{pmatrix} \tag{11}$$

in which M is the body mass of cylinder in air, I_i (i=1, 2, 3) are the moments of inertia with respect to the principal axes through C.G. of cylinder, 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

$$\omega_1 = \dot{X}_4 \cos X_5 \cos X_6 + \dot{X}_5 \sin X_6 \tag{12}$$

$$\omega_2 = -\dot{X}_4 \cos X_5 \sin X_6 + \dot{X}_5 \cos X_6 \tag{13}$$

$$\omega_3 = \dot{X}_4 \sin X_5 + \dot{X}_6 \tag{14}$$

Hydrodynamic Force Vector

When the circular cylinder moves to an arbitrary position in waves, the axis of cylinder may be inclined instead of vertically upwards. Then forces acting on the cylinder need to be written in terms of the normal components of fluid acceleration and relative acceleration and velocity vectors between water particle and structural element. Using generalized Morison equation, force vector per unit length of arbitrary oriented cylinder $\vec{f}_n$ is written:

$$\vec{f}_n = \rho \frac{\pi D^2}{4}\dot{\vec{V}}_n + C_a \rho \frac{\pi D^2}{4}\dot{\vec{V}}_{rn} + C_d \frac{\rho D}{2}\left|\vec{V}_{rn}\right|\vec{V}_{rn} \tag{15}$$

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 water particle and structural element normal to inclined cylinder. Water particle kinematics are evaluated in reference frame oxyz employing modified Airy's linear wave theory with stretching method used (Chakrabarti, 1987). The normal acceleration vector $\dot{\vec{V}}_n$ is given as

$$\dot{\vec{V}}_n = \vec{e}_3 \times (\dot{\vec{V}} \times \vec{e}_3) = \dot{v}_{n1}\vec{i} + \dot{v}_{n2}\vec{j} + \dot{v}_{n3}\vec{k} \tag{16}$$

where $\dot{v}_{n1}, \dot{v}_{n2}, \dot{v}_{n3}$ are components of $\dot{\vec{V}}_n$ along three axes of coordinate system OXYZ, respectively, $\dot{\vec{V}}$ is the acceleration vector of water particle, $\vec{e}_3$ is the unit vector along the Cartesian coordinate axis $G\zeta$, i.e. the unit vector along the cylinder axis. By analogy with the Eq. 16, the relative normal velocity vector $\vec{V}_{rn}$ is obtained

$$\vec{V}_{rn} = \vec{e}_3 \times (\vec{V}_r \times \vec{e}_3) \tag{17}$$

where

$$\vec{V}_r = \vec{V} - \vec{V}_s \tag{18}$$

in which $\vec{V}$ is the velocity vector of water particle, $\vec{V}_s$ shown in Fig. 3 is the velocity vector of respective centroid *s* of referred cross section of cylinder, and can be derived from the translational and angular velocities of the whole cylinder, $\vec{V}_G$ and $\vec{\omega}$:

$$\vec{V}_s = \vec{V}_G + \vec{\omega} \times \vec{r}_G \tag{19}$$

where

$$\vec{V}_G = \dot{X}_1\vec{i} + \dot{X}_2\vec{j} + \dot{X}_3\vec{k} \tag{20}$$

$$\vec{\omega} = \omega_1\vec{e}_1 + \omega_2\vec{e}_2 + \omega_3\vec{e}_3 \tag{21}$$

$\vec{i}$, $\vec{j}$, $\vec{k}$, $\vec{e}_1$, $\vec{e}_2$ are unit vectors along the coordinate axes OX, OY, OZ, $G\xi$ and $G\eta$, respectively, $\vec{r}_G$ is position vector with reference to the center of gravity of the cylinder. On the analogy of the derivation of $\vec{V}_{rn}$, the relative normal acceleration vector $\dot{\vec{V}}_{rn}$ is given

$$\dot{\vec{V}}_{rn} = \vec{e}_3 \times (\dot{\vec{V}}_r \times \vec{e}_3) \tag{22}$$

$$\dot{\vec{V}}_r = \dot{\vec{V}} - \dot{\vec{V}}_s \tag{23}$$

$$\dot{\vec{V}}_s = \dot{\vec{V}}_G + \dot{\vec{\omega}} \times \vec{r}_G + \vec{\omega} \times (\vec{\omega} \times \vec{r}_G) \tag{24}$$

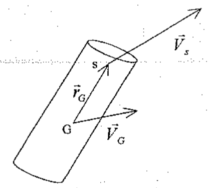

Fig. 3 Velocity vector of cross section

The vectorial resultant $\vec{F}_w$ of hydrodynamic force on the cylinder is obtained by the integral

$$\vec{F}_w = \int_{-h_G}^{-h_G+h_1} \vec{f}_n \, d\zeta \tag{25}$$

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

$$\vec{M}_{Gw} = \int_{-h_G}^{-h_G+h_1} \left(\vec{r}_G \times \vec{f}_n\right) d\zeta \tag{26}$$

Hydrostatic Force Vector

When the floating cylinder moves from equilibrium position to an arbitrary heeled position, the magnitude and geometry of the displaced fluid volume changes. Therefore, the magnitude of buoyancy F_B changes, and the center of buoyancy B is shifted (Fig. 4).

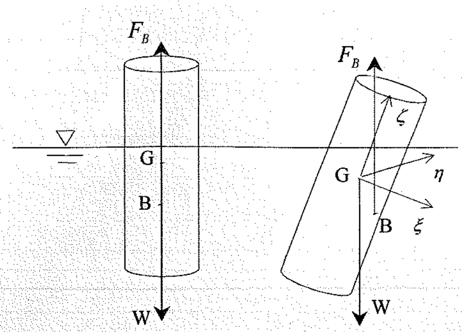

Fig. 4 The changed buoyancy and center of buoyancy

As shown in Fig.5, the changed draught *h*, *H* are obtained:

$$h = h_1 - \frac{r}{t_{33}}\sqrt{t_{31}^2 + t_{32}^2} \tag{27}$$

$$H = h_1 + \frac{r}{t_{33}}\sqrt{t_{31}^2 + t_{32}^2} \tag{28}$$

where r is the radius of cylinder.
The position vector $\vec{r}_{GB}$ of the center of buoyancy B and the buoyancy vector in $G\xi\eta\zeta$ can be given:

$$\vec{r}_{GB} = \xi_B\vec{e}_1 + \eta_B\vec{e}_2 + \zeta_B\vec{e}_3 \tag{29}$$

$$\vec{F_B} = \rho g\pi r^2 h_1\left(t_{31}\vec{e}_1 + t_{32}\vec{e}_2 + t_{33}\vec{e}_3\right) \tag{30}$$

$$\xi_B = -\frac{t_{31}r^2}{4t_{33}h_1} \tag{31}$$

$$\eta_B = -\frac{t_{32}r^2}{4t_{33}h_1} \tag{32}$$

$$\zeta_B = -h_G + \frac{h_1}{2} + \frac{r^2(t_{31}^2 + t_{32}^2)}{8t_{33}^2 h_1} \tag{33}$$

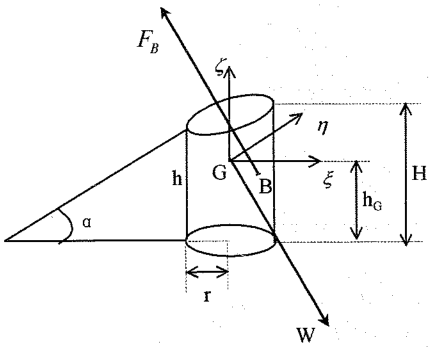

Fig. 5 The changed buoyancy and center of buoyancy in coordinate system $G\xi\eta\zeta$

Then the buoyancy generating moment vector with reference to the principal axes of cylinder is given:

$$\vec{M}_{GB} = \vec{r}_{GB} \times \vec{F}_B \tag{34}$$

Tension Vector in the Tether

When the cylinder moves to an arbitrary position, the coordinates of the top and end of tether (A and E in Fig.1) in OXYZ are $(X_1 - t_{13}h_G, X_2 - t_{23}h_G,\ X_3 - t_{33}h_G)$ and $(0,0,-h_G - L)$. L is the initial length of the tether. Then the vector $\overrightarrow{AE}$ can be given:

$$\overrightarrow{AE} = \left(-X_1 + t_{13}h_G\right)\vec{i} + \left(-X_2 + t_{23}h_G\right)\vec{j} + \left(-h_G - L - X_3 + t_{33}h_G\right)\vec{k} \tag{35}$$

Therefore, vector of tension $\overrightarrow{F_{Ot}}$ in the tether can be obtained as:

$$\overrightarrow{F_{Ot}} = (T_0 + \frac{ES}{L}(L_1 - L)) \cdot \frac{\overrightarrow{AE}}{\left|\overrightarrow{AE}\right|} \tag{36}$$

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

$$\vec{M}_{Gt} = \vec{r}_{GA} \times \vec{F}_{Gt} \tag{37}$$

where $\vec{r}_{GA}$ $(= -h_G\vec{e}_3)$ is the position vector of point A in $G\xi\eta\zeta$, $\overrightarrow{F_{Gt}}$ is the tension vector. The unit vector of $\overrightarrow{F_{Gt}}$ is given below:

$$\frac{\overrightarrow{F_{Gt}}}{\left|\overrightarrow{F_{Gt}}\right|} = \{\left[-X_1t_{11} - X_2t_{21} - (h_G + L + X_3)t_{31}\right]\vec{e}_1 + \left[-X_1t_{12} - X_2t_{22} - (h_G + L + X_3)t_{32}\right]\vec{e}_2 + \left[-X_1t_{13} - X_2t_{23} - (h_G + L + X_3)t_{33} + h_G\right]\vec{e}_3\}/L_1$$

$\overrightarrow{F_{Gt}}$ in Eq. 37 and $\overrightarrow{F_{Ot}}$ in Eq. 36 are the same tension vector. However, the components of the vector are different because the tension vector is referred to two different sets of reference frames determined by the base vectors $\vec{e}_1, \vec{e}_2, \vec{e}_3$ and $\vec{i}, \vec{j}, \vec{k}$.

Total External Force and Moment Vectors Acting on the Cylinder

The total external force vector $\vec{F}$ can be obtained by summing the hydrodynamic force, the hydrostatic force, the tension in the tether, and the weight of cylinder together:

$$\vec{F} = \vec{F}_w + \vec{F}_B + \vec{F}_{Ot} - Mg\vec{k} = F_1\vec{i} + F_2\vec{j} + F_3\vec{k} \tag{38}$$

in which g is the acceleration due to gravity.
The total external moment vector $\vec{M}$ with reference to the principal axes through C.G. of cylinder can be obtained by summing the moments generated by the external forces:

$$\vec{M} = \vec{M}_{Gw} + \vec{M}_{GB} + \vec{M}_{Gt} = F_4\vec{e}_1 + F_5\vec{e}_2 + F_6\vec{e}_3 \tag{39}$$

NUMERICAL STUDY

Numerical Solution of the Equation of Motion in the Time Domain

Up to now, the equations for calculating the external force and moment vectors acting on the cylinder have been acquired as shown in the preceding part of this paper. Such force and moment vectors are response dependent, i.e. F_i (i=1, 2, ... ,6) are functions of X_i (i=1, 2, ... ,6). Therefore, the equations of motion of the cylinder with six degrees of freedom (Eqs. 11~14) are nonlinear and coupled differential

equations.
In the present work, Eqs. 11~14 are solved by using a fourth-order Runge-Kutta numerical time integration procedure with constant time step.

Numerical Results and Discussion

The nonlinear six degrees of freedom motion of the cylinder and the instantaneous length of the tether are calculated by the method proposed in the preceding chapters. Furthermore, in order to investigate the influence of the rotational displacements on the overall motions, two different transformation matrices are adopted. One is the precise transformation matrix as shown in Eqs. 1~10, in which the angles X_4, X_5, X_6 can be finite quantities. The other is an approximate matrix as shown in Eq. 40, where the angles are assumed to be infinitesimal, and the components of the matrix are truncated after the first order small magnitude. The first order transformation matrix is given as:

$$\begin{pmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{pmatrix} = \begin{pmatrix} 1 & -X_6 & X_5 \\ X_6 & 1 & -X_4 \\ -X_5 & X_4 & 1 \end{pmatrix} \tag{40}$$

The primary properties of the circular cylinder with taut tether are shown in Table 1.

Table 1. Primary properties of the cylinder

Description	Value
Mass (kg)	2300000
Tether length L (m)	300
Water depth (m)	335
ES/L (kN/m)	308028
Diameter of cylinder D (m)	16
C.G. above keel h_G (m)	28
r_ξ (m)	17.9
r_η (m)	17.9
r_ζ (m)	5.7

r_ξ, r_η and r_ζ are the radii of gyration about the ξ axis, η axis and ζ axis respectively.
Two wave conditions are considered as shown in Table 2.

Table 2. Two wave conditions considered

Description	Case A	Case B
Wave height (m)	4	6
Wave period (s)	9	9
Wave heading angle (deg.)	45	45

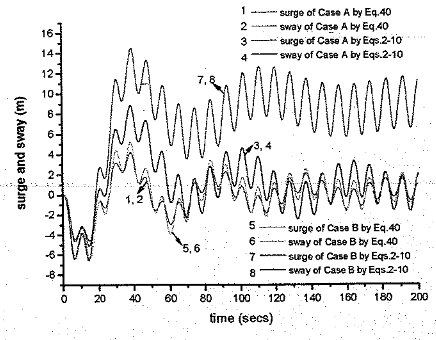

Fig. 6 Transient response of surge and sway

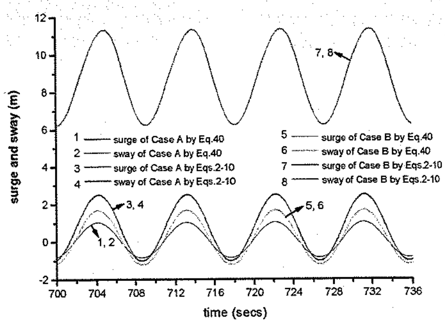

Fig. 7 Steady-state response of surge and sway

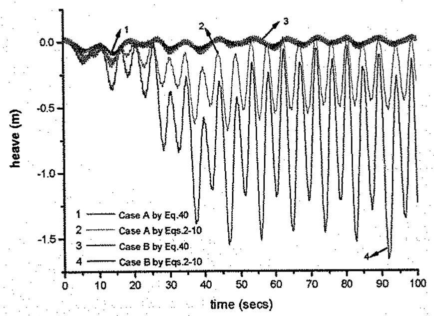

Fig. 8 Transient response of heave

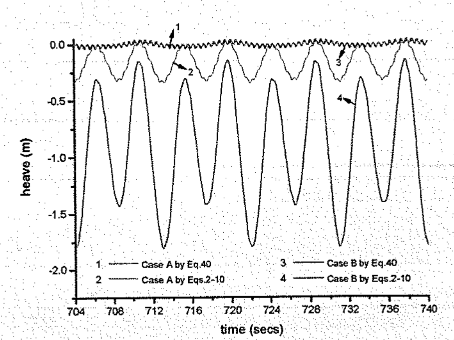

Fig. 9 Steady-state response of heave

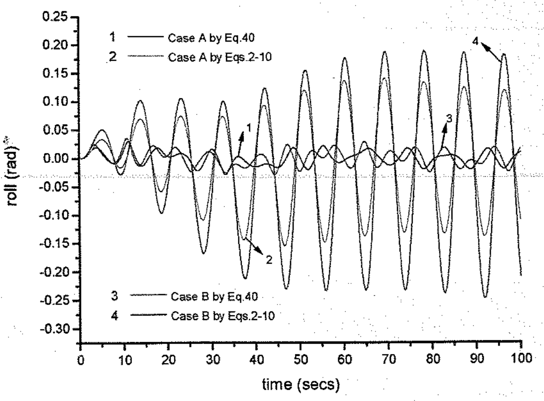

Fig. 10 Transient response of roll

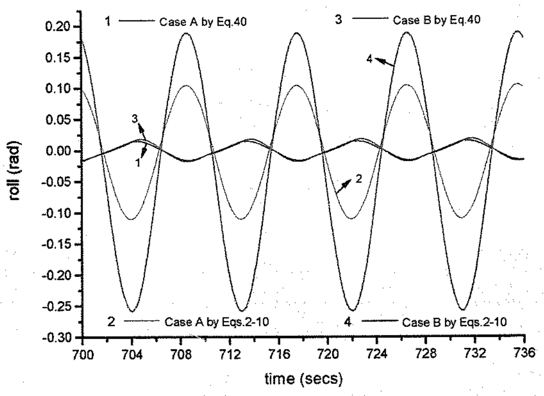

Fig. 11 Steady-state response of roll

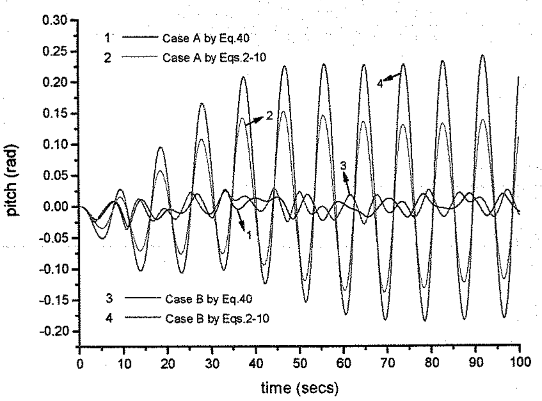

Fig. 12 Transient response of pitch

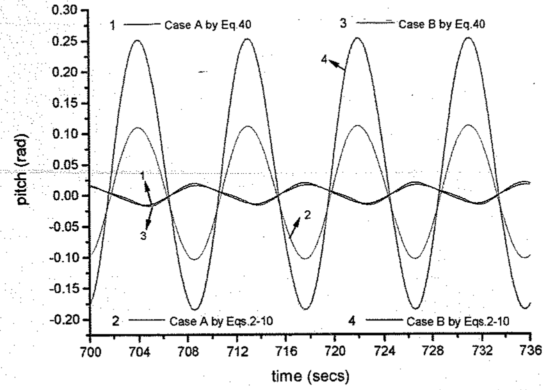

Fig. 13 Steady-state response of pitch

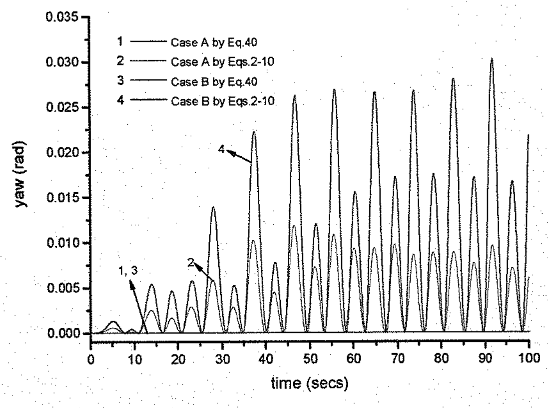

Fig. 14 Transient response of yaw

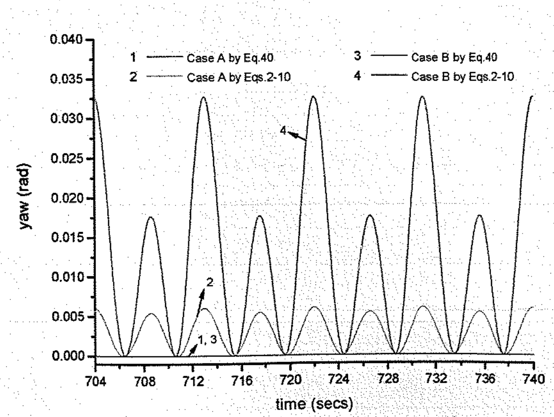

Fig. 15 Steady-state response of yaw

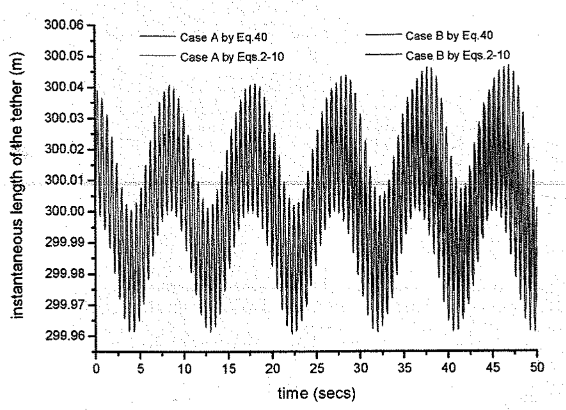

Fig. 16 Transient response of length of tether

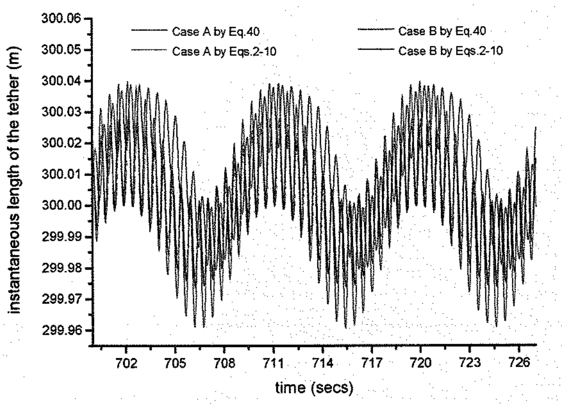

Fig. 17 Steady-state response of length of tether

For two wave conditions (case A and B), the transient and steady-state responses of nonlinear rigid body motion in six degrees of freedom and the instantaneous length of the tether are shown in Figs. 6~17. The surge and sway motions coincide with each other as shown in Figs. 6~7 because the wave heading angle is 45 degree. It is seen from Figs. 10~14 that the maximum values of the angular displacements (roll, pitch and yaw) are less than 15 degree. Even for such magnitude of rotation, the truncation-induced error of the components of the first order transformation matrix (shown in Eq. 40) is small. The differences between the components of the first order transformation matrix in Eq. 40 and that of precise transformation matrix of Eq. 1 (shown in Eqs. 2~10) are about 1% ~ 3%. However, it can be found that, the differences of displacements between two methods (i.e. by using the first order and the precise transformation matrices respectively) are remarkable, and the differences become more distinct as the wave height increases. The difference of respective heave between the two methods is the largest, which can be dozens of times. The differences of surge, sway, roll and pitch between the two methods are also large, which can be multiple folds. For response of yaw, the results obtained by the first order transformation matrix are zeros, while the results by the precise matrix are nonzero. The differences of instantaneous length of the tether are relatively small compared to that of the motions, and the differences also become more distinct when the wave height increases. The two methods are identical except that the transformation matrices are different. Therefore, such large differences of motions must be induced by the infinitesimal rotation assumption. The differences may be attributed to both the complicated nonlinear coupling among six degrees of freedom and the nonlinear wave-structure interactions (i.e. wave loads are response dependent). Consequently, it may be acquired that the rotational displacements should not be assumed infinitesimal when the overall motions are to be computed.

CONCLUSIONS

The nonlinear rigid body motion and instantaneous length of the tether of a floating circular cylinder with a taut tether have been calculated by two methods developed in this paper. One method is based on complete finite displacements assumption (i.e. both translational and rotational displacements are finite), the other assumes that the translations are finite, and the rotations are infinitesimal. As a result of the numerical study, the following conclusions can be drawn:

1. The rotational angles play an important role in the computation of the six degrees of freedom motions of the tethered cylinder, and the rotation should not be assumed infinitesimal.
2. For analogous offshore structures, such as tension leg platform or tethered spar platform, similar problem may be taken into account. Some validations may be needed to perform before any approximation related to rotation is made.

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