Truss Spar Platform Motions for Combined Wave, Current and Wind Forces

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Abstract—**Truss spar platform is the second development concept that replaces the cylindrical lower section of a classic spar with an open truss structure that includes heave plates. In this paper, the dynamic responses of the Marlin truss spar in regular waves, current and wind are presented. A MATLAB code named TRSPAR was developed for the dynamic analysis of the structure. The structure was modeled as a rigid body with three degrees of freedom. The hyperbolic extrapolation and the extended Morison equation for an inclined cylinder were used for simulating the sea state and for determining the dynamic force vector. Time domain integration using Newmark Beta method was employed. The simulated results show insignificant effect of current and wind on the responses. However, these forces cause significant increase in the surge mean offset.**

Keywords- truss spar; dynamic analysis; time domain; hydrodynamic responses; rigid body

INTRODUCTION

The challenging deepwater environment makes the traditional fixed offshore structures unsuitable. Therefore, alternative innovative platform concepts such as spar, have been developed. The Spar is the latest among this new generation of compliant offshore structures, and it has been used for drilling, production and storage of oil in deepwater [1-3]. The development of spar concept can be categorized into three generations known as classic spar, truss spar and cell spar. The classic spar comprises of a large uniform circular cylinder with a long draft. This configuration allows the installation of rigid risers with dry trees, as the heave and pitch responses are small. Truss spar consists of a large volume of hard tank in the upper part and a lower soft tank. These tanks are separated by a truss portion, which reduces the hull construction costs by 20% to 40% [4]. Moreover, truss section is relatively transparent to the ambient current, resulting in significantly less surge offset and mooring requirements. Cell spars excel compared to the first two generations by saving the construction period, attained by parallel fabrication of the cylinder shell components. Experimental studies on deep draft columns show that multiple cells forming a column can be less subjected to vortices since the spacing between them allows interstitial flow of water through their spaces [5-7].

The research interest on spars has been developed recently and within a short time, quite a number of studies have been conducted on the dynamic responses of spars numerically as well as experimentally. Analytical or numerical approaches can be used to calculate the dynamic response of spars. The most direct approach is the analysis in the time domain, where a wave elevation time series is used as input and the resulting structural responses are calculated numerically. In the structural analysis, it is common practice to treat the mooring lines and risers as springs. This neglects the inertia of the mooring system, as well as the additional drag force that may increase the damping of the total structure.

A MATLAB program named 'TRSPAR' was developed to determine the dynamic responses of truss spar platforms. Time domain integration using Newmark Beta method was employed and the platform was modeled as a rigid body with three degrees of freedom restrained by mooring lines affecting the stiffness values. Hyperbolic extrapolation and modified Morison equation were used for simulating the sea state and for determining the dynamic force vector. Added mass and damping were derived from hydrodynamic considerations.

NUMERICAL PROCEDURE

In consideration of the incident waves that are long crested and advancing in the *x*-direction, a spar is approximated by a rigid body of three degrees of freedom (surge, heave and pitch), and it derives its static resistance from support systems (mooring lines, risers) and hydrostatic stiffness.

Two coordinate systems are employed in the analysis (see Fig.1), the space fixed coordinate system oxz and two dimensional local coordinate $G\zeta\eta$ which is fixed on the body with the origin at its center of gravity (CG). B is the center of buoyancy and F denotes fairlead.

The dynamic equations of the surge-heave-pitch motions of the spar are:

$$\{M\}\left[\frac{\partial^2 x_G}{\partial t^2}\right] + \{C\}\left[\frac{\partial x_G}{\partial t}\right] + \{K\}\left[x_G\right] = \left[F(t)\right] \quad (1)$$

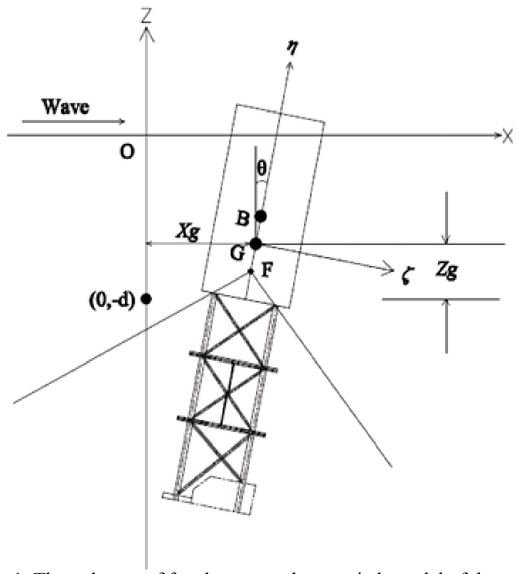


Figure.1. Three degree of freedom surge-heave-pitch model of the spar

where $\{M\}$ is made up of body mass and added mass components as given in Eq. 2 and $\left[\frac{\partial^2 x_G}{\partial t^2}\right]$ is the structural acceleration vector. The resultant force can be defined as

$$\{M\}\left[\frac{\partial^2 x_G}{\partial t^2}\right] = \left\{ \underbrace{\begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix}}_{Mass\ matrix} + \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}}_{Added\ mass\ matrix} \right\} \begin{bmatrix} \frac{\partial^2 x_G}{\partial t^2} \\ \frac{\partial^2 z_G}{\partial t^2} \\ \frac{\partial^2 \vartheta}{\partial t^2} \end{bmatrix} \quad (2)$$

where *m*, *I* and ϑ denote body mass, mass moment of inertia about the y-axis and the pitch angle respectively. The added mass is determined by integrating the added mass from the bottom of the structure/member to the instantaneous surface elevation. The computations of added-mass forces and moments are as follows:

$$\begin{aligned}
m_{11} &= \int_{n_b}^{n_t} \rho\, C_m\ A.\partial n\ \cos\vartheta\ \cos\vartheta \\
m_{12} = m_{21} &= -\int_{n_b}^{n_t} \rho\, C_m\ A.\partial n\ \sin\vartheta\ \cos\vartheta \\
m_{13} = m_{31} &= \int_{n_b}^{n_t} \rho\, C_m\ A\, n.\partial n \cos\vartheta \\
m_{22} &= \int_{n_b}^{n_t} \rho\, C_m\ A.\partial n \sin\vartheta \sin\vartheta \\
m_{23} = m_{32} &= -\int_{n_b}^{n_t} \rho\, C_m\ A\, n.\partial n \sin\vartheta \\
m_{33} &= \int_{n_b}^{n_t} \rho\, C_m\ A\, n^2.\partial n
\end{aligned} \quad (3)$$

$\{C\}\left[\frac{\partial x_G}{\partial t}\right]$ is the structure damping matrix multiply by the body velocity vector in the considered degrees of freedom. The resultant force can be defined as

$$\{C\}\left[\frac{\partial x_G}{\partial t}\right] = \begin{bmatrix} c_{11} & 0 & 0 \\ 0 & c_{22} & 0 \\ 0 & 0 & c_{33} \end{bmatrix} \begin{bmatrix} \frac{\partial x_G}{\partial t} \\ \frac{\partial z_G}{\partial t} \\ \frac{\partial \vartheta}{\partial t} \end{bmatrix} \quad (4)$$

The computations of the structure damping elements are as follows:

$$\begin{aligned}
c_{11} &= 2\,\xi_s\ \omega_{ns}\ m \\
c_{22} &= 2\,\xi_h\ \omega_{nh}\ m \\
c_{33} &= 2\,\xi_p\ \omega_{np}\ I
\end{aligned} \quad (5)$$

where the subscripts *s*, *h* and *p* stand for surge, heave and pitch respectively, ξ 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.

Heave plates greatly increase the heave added mass and viscous damping as follows:

$$F = \frac{1}{2}\rho U\left|U\right| L^2 C_D + \rho \frac{\partial U}{\partial t} L^3 C_A \tag{6}$$

where C_D and C_A are drag and added mass coefficients for the heave plates respectively. U and $\frac{\partial U}{\partial t}$ represent the velocity and acceleration respectively of the plate perpendicular to its plane.

$\{K\}[x_G]$ is the system stiffness matrix multiplied by displacement vector. The stiffness matrix is composed of two main components, hydrostatic and mooring line stiffness matrices. The mooring lines, which are represented here by linear massless springs attached at the spar fairleads, are the only source of stiffness in the direction of surge motion. The hydrostatic buoyancy force provides the heave restoring force. Both types of stiffness contribute to the pitch stiffness. The resultant restoring force can be defined as

$$\{K\}[x_G] = \left[\underbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix}}_{Hydrostati} + \underbrace{\begin{bmatrix} k_x & 0 & k_x h_2 \\ 0 & 0 & 0 \\ k_x h_2 & 0 & k_x h_2^2 \end{bmatrix}}_{Mooringlines} \right] \begin{bmatrix} x_G \\ z_G \\ \vartheta \end{bmatrix} \tag{7}$$

where

$k_2 = \pi \rho g (D/2)^2$

k_3 = buoyancy force × distance from G to B

k_x = horizontal spring stiffness

h_2 = distance from G to fairlead

ρ, g and D are the water density, gravity acceleration and structure diameter respectively.

The wave forces are decomposed into the normal force F_{EXn} and tangential force F_{Ext}

$$\begin{bmatrix} F_{EXn} \\ M_{EX} \end{bmatrix} = \int_{-d_1}^{\varsigma} \rho(1 + C_m) A(n) a_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn + \int_{-d_1}^{\varsigma} \frac{1}{2}\rho C_D D \left|V_n\right| V_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn \tag{8}$$

where

$$a_n = \left| a - \left(a.\vec{\tau}\right)\vec{\tau} \right|$$

$$V_n = \left| V - r_s - ((V - r_s).\tau)\tau \right|$$

C_m is the added mass coefficient, C_d is the drag coefficient, V_n the relative normal velocity and $\vec{\tau}$ is a unit vector along the *n*-axis. *a* and *V* are respectively wave particle acceleration and velocity and r_s is structure velocity.

The tangential force can be determined by integrating the hydrodynamic pressure on the bottom surface as:

$$F_{EXt} = \iint \rho \frac{\partial \vartheta_1}{\partial t} + \frac{1}{2}\rho \left|\nabla \vartheta_1\right|^2 n_t \partial s \tag{9}$$

ϑ_1 is the first order potential of incident waves.

Forces F_{EXn} and F_{Ext} are transferred into spaced-fixed coordinate system *oxz* as:

$$\begin{Bmatrix} F_{EXx} \\ F_{EXz} \end{Bmatrix} = \begin{Bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{Bmatrix} \begin{Bmatrix} F_{EXn} \\ F_{EXt} \end{Bmatrix} \tag{10}$$

In addition to the wave forces, current and wind forces are also considered. The current velocity is incorporated in time domain by adding the average current velocity to the horizontal wave velocity in the drag term and carrying out the simulation process. The static wind force was added to the exciting forces acting along x axis.

In the time domain, Newmark Beta integration technique was used to solve the equation of motion incorporating all the time dependent nonlinearities, mass and added mass, structure and viscous damping, mooring line and hydrostatic stiffness. At each step, the force vector was updated to take account of the change in the mooring line tension.

RESULTS AND DISCUSSION

A numerical simulation for Marlin truss spar with nine mooring lines as shown in Fig. 2 (three in each group), was conducted. The physical characteristics of the structure and the characteristics of the mooring lines are summarized in tables I and II respectively.

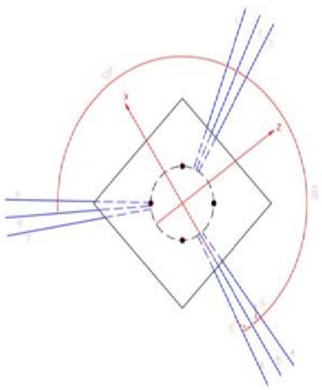
Each mooring line consisted of a chain-wire-chain taut leg having the same geometric and material properties of the prototype mooring system. The mooring lines were assumed to be hinged at both ends. Each mooring line was given an initial tension equal to 2312 KN.

TABLE I
PHYSICAL CHARACTERISTICS OF MARLIN TRUSS SPAR

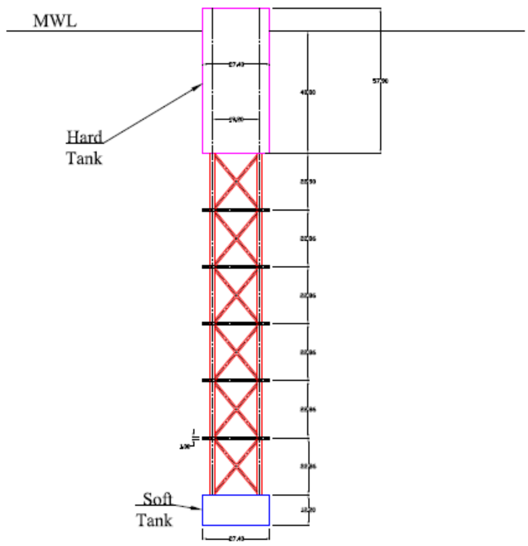
Weight	389,80 ton
Vertical centre of gravity (KG)	126.34 m
Buoyancy, basic	389,80 ton
Vertical centre of buoyancy (KB), basic	152.4 m
radius of gyration for pitch	86.2 m

TABLE II
CHARACTERISTICS OF MOORING LINES

	Upper section	**Middle section**	**Lower section**
Type	***K4 chain***	***K4 chain***	***K4 chain***
Size (m)	0.124	0.124	0.124
Length (m)	76.2	1828.8	45.72
Wet weight (kg/m)	280.5	65.4	280.5
Eff. modulus EA (Kn)	665,885	133,8915	858,925
Breaking strength (Kn)	131,89	124,55	131,89



a) Arrangement of Mooring Lines



b) Overall spar configuration

Figure 2. Marlin truss spar

The static offset tests were numerically conducted by applying variable static forces at the fairlead position. As a result, mooring line stiffness curve was obtained as shown in Fig 3.

Time domain analysis for the particular truss spar was conducted to obtain the dynamic responses. This was done for three cases:
Case 1: Regular wave
Case 2: Regular wave and current
Case 3: Regular wave, current and wind

The responses of the truss spar platform due to regular waves with H=13m and T=16sec were determined first and shown in Fig. 4 - Fig. 6 for surge, heave and pitch respectively. All the motions presented in this study were at the CG.

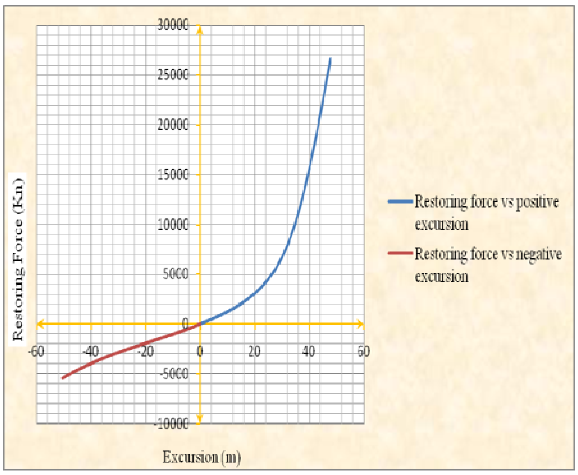


Figure 3. Surge static offset test: offset vs. restoring force.

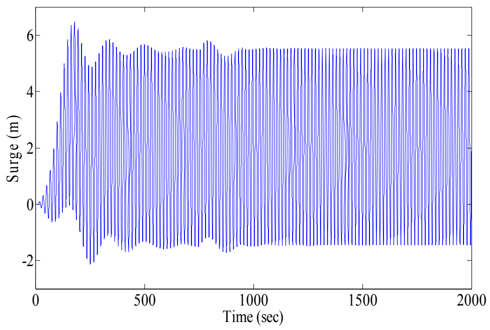


Figure 4. Surge time series

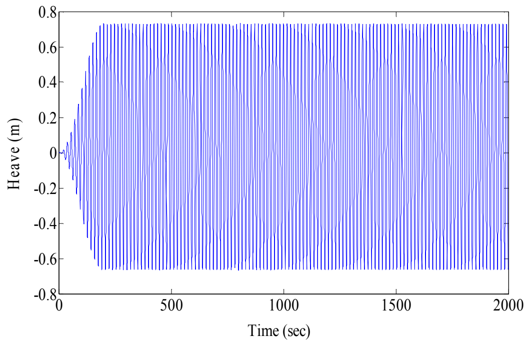


Figure 5. Heave time series

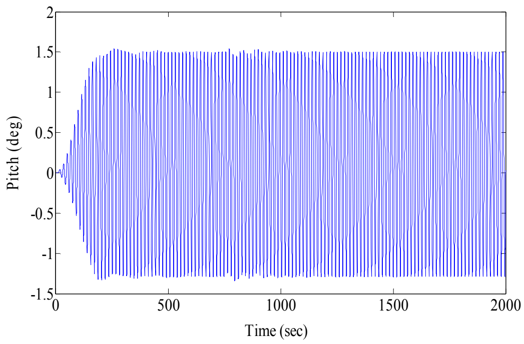


Figure 6. Pitch time series

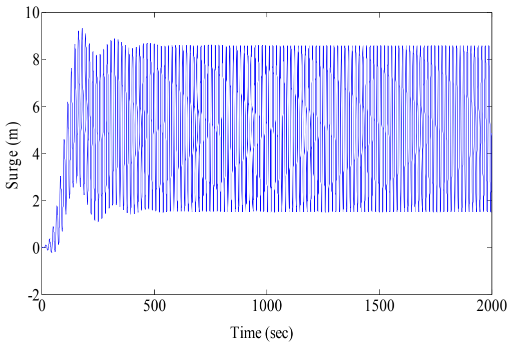


Figure 7. Surge time series

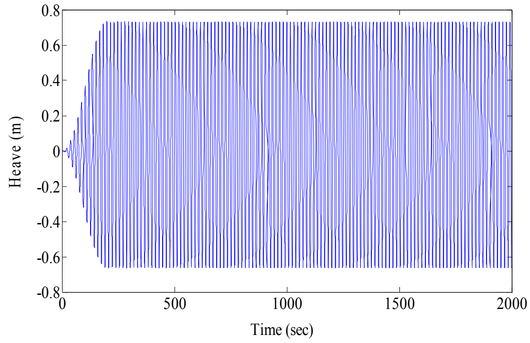


Figure 8. Heave time series

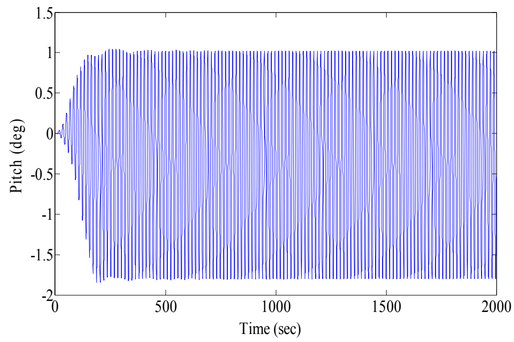


Figure 9. Pitch time series

In case 2, a uniform current with 0.5 m/sec velocity was added to the above mentioned regular wave. Figs. 7 - 9 show the simulation results in this case. It is clear that, adding current to regular wave has insignificant effect on the amplitude of the motions. However, the current significantly affected the surge mean offset, which increased from 1.95 m (Fig. 4) to 4.83 m (Fig. 7).

In case 3, a steady wind with a constant string force of 454 KN was added to the previous case. The simulation results due to this environmental condition are shown in Figs. 10 - 12 for surge, heave and pitch respectively. It was shown that wind force has insignificant effect on the responses amplitude. However, it increased the surge mean offset significantly, which reached 8.23 m.

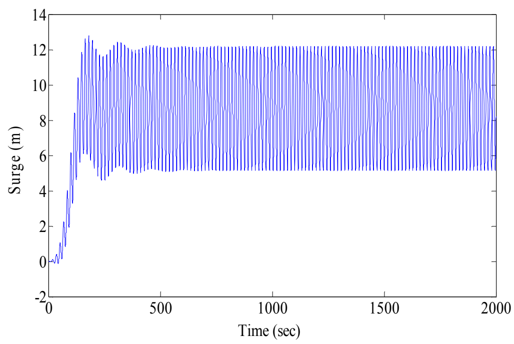


Figure 10. Surge time series

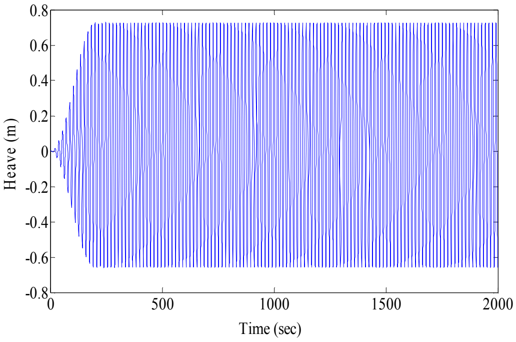


Figure 11. Heave time series

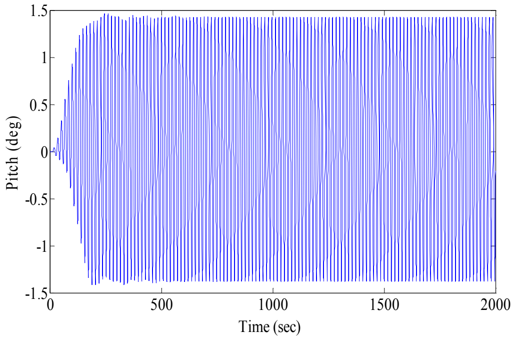


Figure 12. Pitch time series

The increase in the structure mean offset should be considered in the design of the mooring lines and risers since it significantly increases the tension.

CONCLUSION

A numerical code named "TRSPAR" has been developed to predict the dynamic motions of truss spar platforms subjected to various environmental loads. TRSPAR has been used in this study to evaluate the effect of current and wind forces on the motions of a typical truss spar platform. Based upon the results, the following conclusions have been drawn:

1. Presence of current did not affect the amplitude of the motions. However, it increased the surge mean offset significantly.

2. Incorporation of the wind force in the analysis had insignificant affect on the response amplitude. It resulted in increasing the structure's mean offset.

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