Effect of Current on the Dynamic Motion of Truss Spar Platforms

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Abstract—**Truss spar platform is the second spar 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 and current 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 very little effect of the current on the response amplitude. However, it caused significant increase in the surge mean offset.**

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

I. INTRODUCTION

As the offshore industry extract and deplete the hydrocarbon reservoirs below the sea bed in deep water depths at a very high rate, it is increasingly required to develop the technology for extracting such deposits in ultra deep water. The increased water depth makes the use of fixed platforms uneconomical leaving a variety of floating platform types as the only viable options for oil and gas production operations.

One such option is the classic spar platform which has been regarded as a competitive floating structure for deep and ultra deepwater oil production. This structure is basically a very large floating vertical cylinder structure having draft around 200 m and diameter around 40 m. The deep-draft cylindrical spar has been shown to be an efficient platform for deep water production, drilling, and storage [2]. Its deep draft gives excellent motion characteristics even in most severe sea states, which has been proven through numerical simulations, model tests and field observations. The relevant theory and comparison with experiments for this kind of spar have been reported in literature [8-13].

Truss spar, which is the second generation of 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, the truss section is relatively transparent to the ambient current, resulting in significantly less surge offset and mooring requirements. The third generation cell spar excels 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 are subjected to vortices only to a lesser extent 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 forces 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.

II. NUMERICAL PROCEDURE

Considering the incident waves as long crested and advancing in the x-direction, a spar is approximated by a rigid body of three degree 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 Gζη 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:

$$[M]\{X^{\cdot\cdot}\}+[C]\{X^{\cdot}\}+[K]\{X\}=[F(t)] \qquad (1)$$

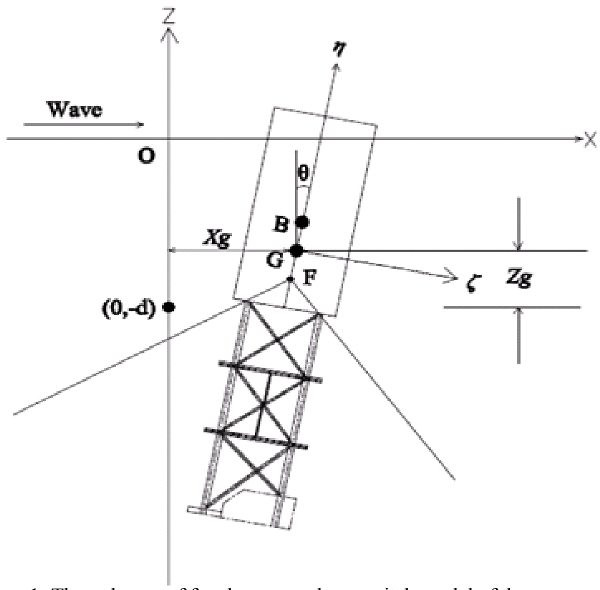


Figure 1: Three degree of freedom surge-heave-pitch model of the spar

where:

- ❖ $\{X\}$ is the structural displacement vector with respect to the center of gravity,
- ❖ $\{X^{\cdot}\}$ is the structural velocity vector with respect to the center of gravity,

$\{X^{\cdot\cdot}\}$ is the structural acceleration vector with respect to the center of gravity,

- ❖ $[M]$ is a mass matrix $= M^{SPAR} + M^{Added\ \ Mass}$
- ❖ $[K]$ is stiffness matrix $= K^{Hydrostatic(hy)} + K^{Horizental\ Spring(hz)}$,
- ❖ $[C]$ is structural damping matrix.
- ❖ [F(t)] is the hydrodynamic force vector and is calculated using modified Morison equation.

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

$$\begin{bmatrix} F_{EXn} \\ M_{EX} \end{bmatrix} = \int_{-d_1}^{\varsigma} \rho(1+C_m)A(n)a_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn$$

$$+\int_{-d_1}^{\varsigma} \frac{1}{2}\rho C_D D\left|V_n\right|V_n \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn \qquad (2)$$

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:

$$F_{EXt}=\iint \rho\frac{\partial \vartheta_1}{\partial t}+\frac{1}{2}\rho\left|\nabla\vartheta_1\right|^2 n_t \partial s \qquad (3)$$

where ϑ_1 is the first order potential of incident waves.

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

$$\begin{Bmatrix} F_{EXx} \\ F_{EXz} \end{Bmatrix} = \begin{Bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{Bmatrix} \begin{Bmatrix} F_{EXn} \\ F_{EXt} \end{Bmatrix} \qquad (4)$$

In addition to the wave forces, current 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.

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.

III. 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.

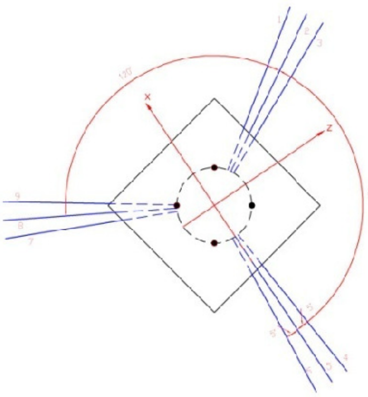
Each mooring line consisted of a chain-wire-chain taut leg having the same geometric and material properties of the prototype mooring system. The mooring lines were assumed to be hinged at both ends. Each mooring line was given an initial tension equal to 2312 KN.

TABLE I
PHYSICAL CHARACTERISTICS OF MARLIN TRUSS SPAR

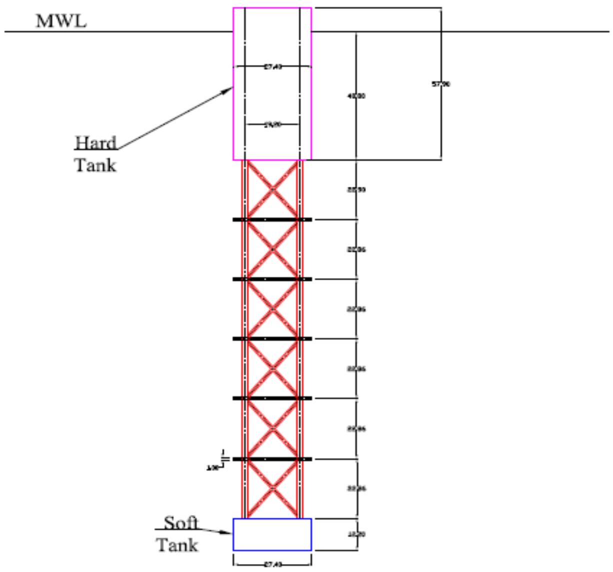
Weight	389,80 ton
Vertical centre of gravity (KG)	126.34 m
Buoyancy, basic	389,80 ton
Vertical centre of buoyancy (KB), basic	152.4 m
radius of gyration for pitch	86.2 m

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) Mooring line arrangement



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 two cases:
Case 1: Regular wave
Case 2: Regular wave and current

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

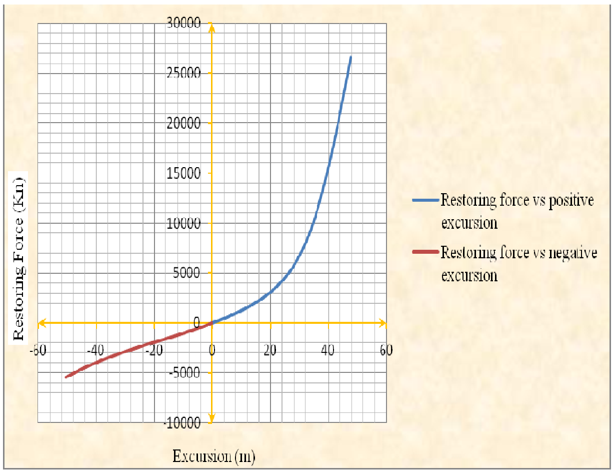


Figure 3: Surge static offset test: offset vs. restoring force.

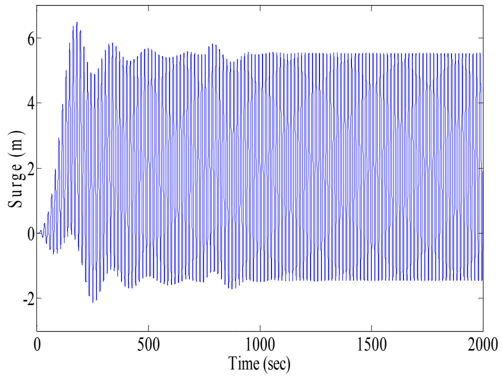


Figure 4: Surge time series

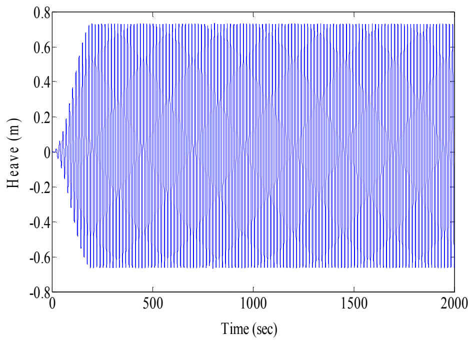


Figure 5: Heave time series

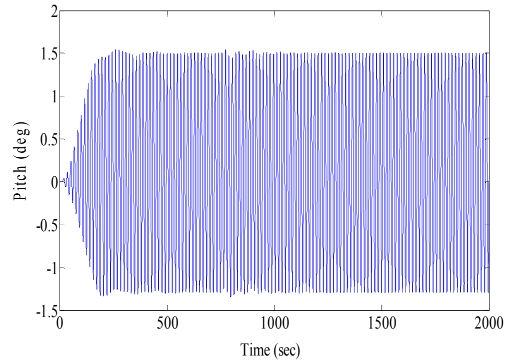


Figure 6: Pitch time series

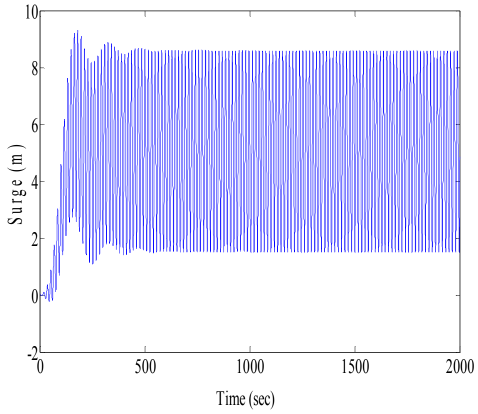


Figure 7: Surge time series

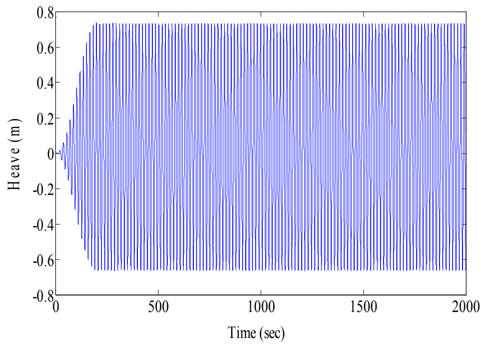


Figure 8: Heave time series

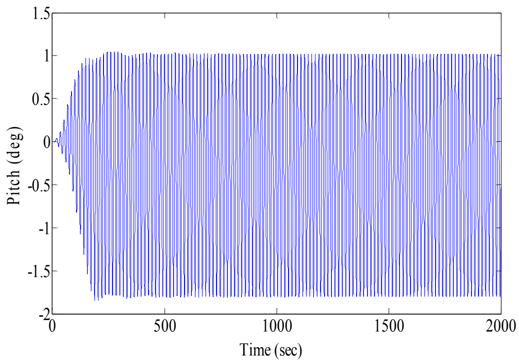


Figure 9: Pitch time series

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

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

IV. CONCLUSIONS

1. A numerical time domain model was developed to predict the dynamic responses of truss spar platforms in different environmental conditions.
2. The presence of current did not affect the amplitude of motions. This is because current is capable of producing only drag force that is very little for large diameter structures like spar. However, it increased the surge mean offset significantly.

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