Model Tests on Truss Spar Platform

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***Abstract*- The exploration of hydrocarbon reservoirs in ultra deep water requires the use of innovative floating platform configurations. The hydrodynamic interaction of such platforms with ocean waves and the understanding and quantification of the nonlinear components of theses interactions have been a subject of continuing research. A truss spar model was tested using regular waves in a wave basin and the responses in surge, heave and pitch were measured. A MATLAB programme was developed to determine the responses by numerical method. This programme was run using the model parameters and it gave results which agreed well with the corresponding results obtained from the test measurements.**

I. INTRODUCTION

As the offshore industry depletes hydrodynamic reservoirs below the sea bed in deep water depths (up to 1500m), it is increasingly required to develop such deposits in considerably high deeper water. The increased water depth makes the use of sea bed mounted platforms uneconomic 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 is basically a very large floating vertical cylinder structure of around 200m draft and 40m in diameter. Such hull configurations have several advantages over other options such as TLP and ship shape hulls. Some of these advantages include structural simplicity, low motions in moderate and extreme ocean waves because of their relatively long natural periods, good protection of riser connections to the sea bed, low cost and so on (Vardeman et al.[1]).

In the late 1990s, development of truss spar concept was advanced to maturity with a large amount of research effort in model test (Prislin et al 1998, Troesch et al 2000), and theoretical study (Kim et al 1999, Luo et al 2001, Wang et al 2002). Since then nine truss spars have been designed, constructed or installed in the Gulf of Mexico fields.

The truss spar consists of a top hard and a bottom soft tank separated by a truss midsection. The soft tank mainly contains solid ballast to provide stability, whereas the hard tank provides buoyancy and contains trim ballast. The truss section contains a number of horizontal heave plates designed to reduce heave motion by increasing both added mass and hydrodynamic damping.

In recent years the realization that large spar platforms offer low cost production options in very deep water has prompted several experimental studies and numerical simulations to obtain a better understanding of their response to ocean waves. Research using numerical simulations has utilized the two traditional frequency domain and time domain approaches. One such study presented by Weggel et al. [2] uses the frequency domain technique and directly gives the statistical parameters of the spar response at relatively low computation cost. However it may be subject to large errors due to the linearization of some non-linear terms, such as the viscous term, in the equations of motion. There is evidence that this linearization probably overestimates viscous effects [3]. Most researchers prefer, therefore, to simulate spar motion in the time domain and this is the approach adopted in this paper.

Simulation of the motion of a spar buoy requires the definition of the equations of motion and the evaluation of all forces acting on it due to wind, current ocean waves and mooring lines. The conventional approach in offshore engineering is to use the linear form of the equations to describe the motions of rigid bodies. For large motions the non-linear equations of motion [4] should be used but it is only practical if the exciting forces can be calculated without evolving wave diffraction analysis.

A key element of the analysis of a spar buoy is to evaluate the forces and moments on it due to ocean waves and currents. One possibility to obtain these is to perform a numerical analysis of the fully non-linear interaction between the spar and its surrounding fluid. Although it is not impossible, this task require very powerful computer resources and is, therefore, not feasible in practice. An alternative approach is to carry out a diffraction analysis based on second order potential theory (see for example, Ran et al. [3]). The computation cost of this approach is still quite high. Also this method usually generates results in the frequency domain and thereafter a transformation is needed to obtain forces in the time domain.

Another approach, often used in offshore engineering for wave force evaluation, is based on slender body theory that requires much less computational effort and can be directly implemented in time domain analysis. In this approach, the body is assumed 'thin' and the force (and/or moment) is obtained by the sum of the forces on each short segment of the slender body. The force in each segment is decomposed into two parts - an inviscid force and viscous drag force. One typical slender body wave force formulation is the well-known Morison equation, in which the first part is proportional to the relative acceleration and the second part to the product of the relative velocity.

A truss spar model connecting to four horizontal mooring lines with scaling factor 1:73 was tested using regular waves in a wave basin 90 m long and 4 m wide with a water depth of 2.5m. The responses in surge, heave and pitch were measured. A MATLAB programme was developed to determine the responses. Time domain integration using Newmark Beta method was employed and the platform was modeled as a rigid body with six degrees of freedom restrained by mooring lines affecting the stiffness values. Wheeler Stretching Formula 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. The accuracy of this programme was verified by comparison with a set of laboratory model test results

II. EXPERIMENTS ON THE MODEL IN THE WAVE BASIN

A. The Model

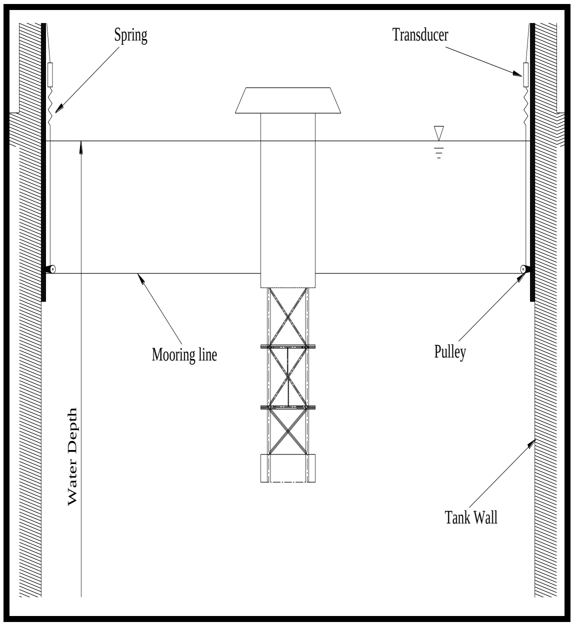
The model was designed based on the dimensions of a typical existing spar with a scale ratio of 1 in 73 and was fabricated using aluminum. It comprised of two main sections; a conventional spar-shaped upper hull, and a lower truss section, as shown in Fig. 1. The hull was 442 mm in diameter and 917 mm deep. The lower part of the spar was ballasted with water to bring the spar to a draught of 1.79 m. The truss was made up of three standard 312 × 312 × 312 mm bays, two 13 × 442 × 442 mm heave plates and a soft tank of 146 × 442 × 442 mm. The legs were 25 mm diameter and the horizontal and diagonal structural elements were 10 mm in diameter. The total length of the truss part was 1.021 m.

Figure. 1 Truss spar model (Scale: 1:73)

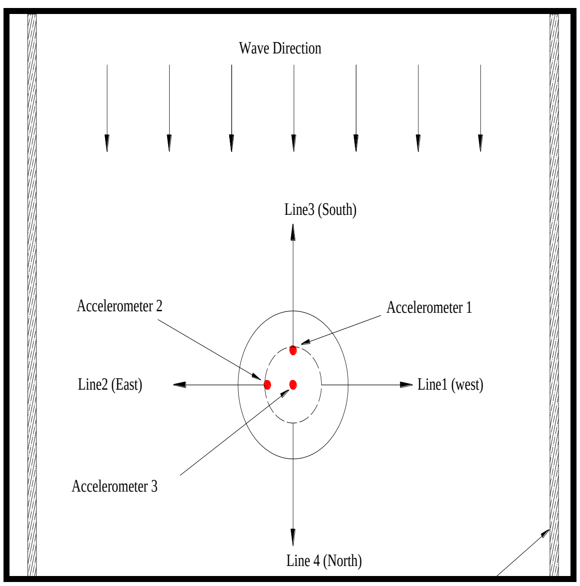
B. Experimental Set-up

The experiments were carried out in the Marine Technology Laboratory of University Technology Malaysia (UTM) at Skudai, Johor Baru. The basin was 120 m long and 4 m wide. The depth of the basin was 2.5 m. The waves were generated by a hydraulically driven flap type wave maker capable of generating waves up to a maximum height of 440 mm and a wave period less than 2.5 s. A beach at the far end of the basin absorbed the waves. The model test arrangement is shown in Fig. 2, showing the horizontal soft mooring system comprising of four wires attached to linear springs. Within the constraints of the mooring system, the model was free to respond to the wave loading with six degrees of freedom.

The wave environment was monitored with a wave probe on the upstream side of the model. The responses were measured with two accelerometers fitted on the deck and at the CG of the model. Tensions in the wires were measured with four linear strain-gauge type force transducers.



(a) Section view



(b) Top view

Fig. 2 Model test arrangement in the wave basin

C. Experimental Program

Static offset test. This experiment was conducted to estimate the mooring lines stiffness. The model was pulled horizontally from the downstream side and then released to allow for the free vibration to die down. Readings from the transducers were recorded. The nonlinearity of the force-displacement relationship of the mooring lines was modeled using multi-linear segments with different slopes (stiffnesses) as shown in Fig.3.

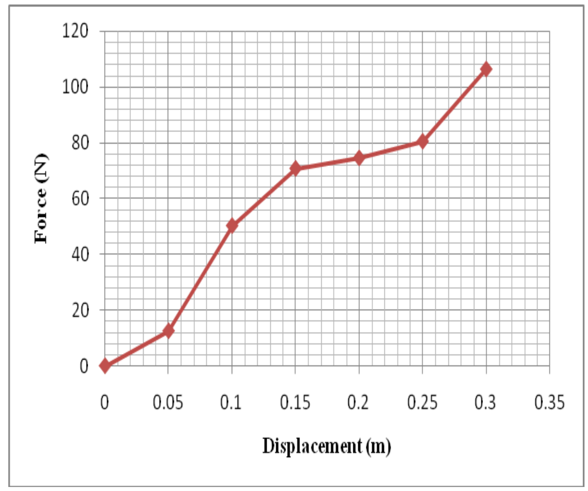


Figure. 3 Multi-segment force-displacement relationship of the mooring lines

Decay tests. Decay tests were conducted to calculate the damping ratio and the natural periods of the system in surge heave and pitch. The model was given an initial displacement and the subsequent motions were recorded. The results are shown in Table 1.

Table 1
. Natural periods of vibration of the model

Motion Type	Natural Period (sec)
Heave	2.468
Surge	2.414
Pitch	2.531

Regular waves tests. Table 2 summarizes part of regular waves that were created for this experiment. Each regular wave test was run for a period of 1.5 min.

Table 2.
Wave height and period of regular waves used for testing

Wave Height (cm)	Wave Period (sec)
5.48	0.94
6.98	1.05
8.16	1.53
5.52	1.64
2.68	1.67
7.02	1.86
5.84	2

III. NUMERICAL MODEL

The nonlinear time domain numerical model performed step-by-step numerical integration of the exact large amplitude equation of motion, producing time histories of motions. The fluid forces on individual members were computed by thr modified Morison Equation in which the integration of the forces was performed over the instantaneous wetted length. The total force at each time step was obtained by summing the forces on the individual members. Incident wave kinematics was calculated by using Wheeler Stretching Formulae. The mooring system was modeled as weightless springs, affecting the stiffness values. A numerical model for a truss spar was developed that accurately reflected the model test setup, including the water depth and mooring system.

Considering that the incident waves were long crested and were advancing in the x-direction, the truss spar was approximated by a rigid body of three degrees of freedom (surge, heave and pitch), deriving static resistance from support systems (mooring lines) and hydrostatic stiffness.

As shown in Fig. 4, two coordinate systems were employed in the analysis (Cao et al, 1996), the space fixed coordinate system *oxz* and two dimensional local coordinate $G\zeta\eta$ which was fixed on the body with the origin at its center of gravity (CG). B is the center of buoyancy and F denoted fairlead.

The space-fixed coordinates were related to the body-fixed coordinates by:

$$\begin{Bmatrix} x \\ z \end{Bmatrix} = \begin{Bmatrix} 0 \\ -d \end{Bmatrix} + \begin{Bmatrix} x_G \\ z_G \end{Bmatrix} + \begin{Bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{Bmatrix} \begin{Bmatrix} \zeta \\ \eta \end{Bmatrix} \quad (1)$$

where x_G, z_G denoted surge and heave motions at CG, θ denoted the pitch angle about the y-axis and was positive clockwise. (0,-d) were the coordinates of the CG of the Spar at its mean position in calm water.

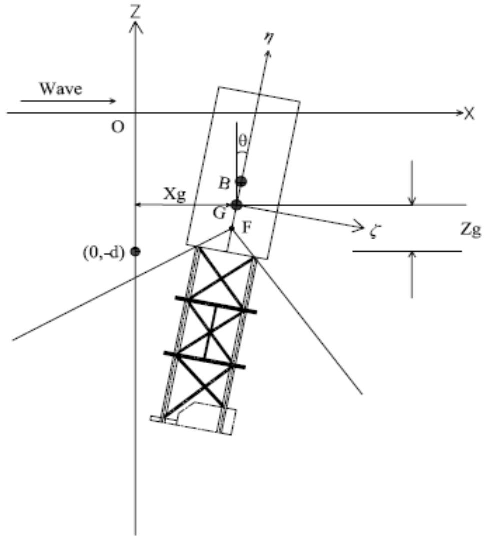


Figure. 4 Three-DOF Surge-heave-pitch model of the spar

The dynamic equations of the surge-heave-pitch motions of the spar were given by:

$$[M]\{x^{\cdot\cdot}\} + [C]\{x^{\cdot}\} + [K]\{x\} = \{F(t)\} \quad (2)$$

The elements of this equation were defined as follows:

$\{x\}$ was the structural displacement vector with respect to the center of gravity, $\{x^{\cdot}\}$ was the structural velocity vector with respect to the center of gravity, $\{x^{\cdot\cdot}\}$ was the structural acceleration vector with respect to the center of gravity.

$[M]$ was a mass matrix = $M^{SPAR} + M^{Added\ Mass}$. The added mass was determined by integrating sectional added mass from the bottom of the structure to the instantaneous surface elevation.

$[K]$ was stiffness matrix = $K^{Hydrostatic(hy)} + K^{Horizontal\ Spring(hz)}$.

$[C]$ was structural damping matrix.

$\{F(t)\}$ was the hydrodynamic force vector calculated using modified Morison equation The wave forces are decomposed into the normal force F_{EXn} and tangential force F_{EXt}

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

$$+ \int_{-d_1}^{\varsigma} \frac{1}{2}\rho C_D D|V_n|V_n \begin{Bmatrix}1\\n\end{Bmatrix} dn \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where

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

$$V_n = |V - r_s - ((V - r_s).\vec{\tau})\vec{\tau}|$$

$$F_{EXt} = \iint \rho \frac{\partial \vartheta_1}{\partial t} + \frac{1}{2}\rho |\nabla \varphi_1|^2 n_t \partial s \ldots\ldots\ldots\ldots\ldots(4)$$

Cm 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 strucure velocity.The tangential force can be determined by integrating the hydrodynamic pressure on the bottom surface. ϑ_1 is the firdt potential of incident waves.

In time domain using numerical integration technique the equation of motion can be solved, incorporating all the time dependent nonlinearities, stiffness coefficient changes due to mooring line tension with time, added mass from Morison equation, and with evaluation of wave forces at the instantaneous displaced position of the structure. At each step, the force vector is updated to take into account the change in the mooring line tension. The equation of motion is solved by an iterative procedure using unconditionally stable Newmark Beta method and this is programmed using MATLAB.

IV. COMPARISON OF RESULTS

The responses of the truss spar model were determined numerically using the model parameters and the results were compared with the corresponding experimental values. All response results presented in this paper are with respect to the CG.

The Response Amplitude Operators (RAOs) for surge, heave and pitch of the numerical model were compared with experimental results in Figs. 5-7.

As can be seen, the RAOs for surge, heave and pitch motions were fairly well predicted by the numerical model. The trend of the surge RAO agreed well with the measured values with 20% higher values for the frequency range 3-7 rad/s. The heave RAOs agreed very well. For the pitch RAO, the simulation results followed the same trend as experimental results but it gave much lower values in wave frequencies between 3-6 rad/sec. This could be due to the horizontal mooring system used in the experimental model which restricted the horizontal motion (surge) thereby causing large pitch responses.

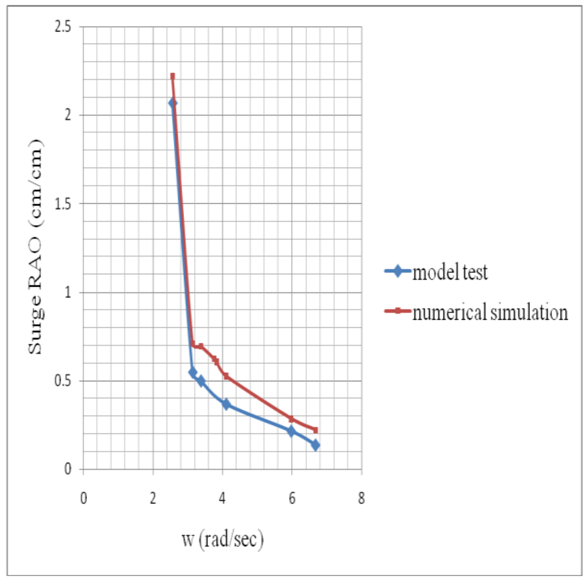


Figure. 5 Comparison of Surge motion RAO

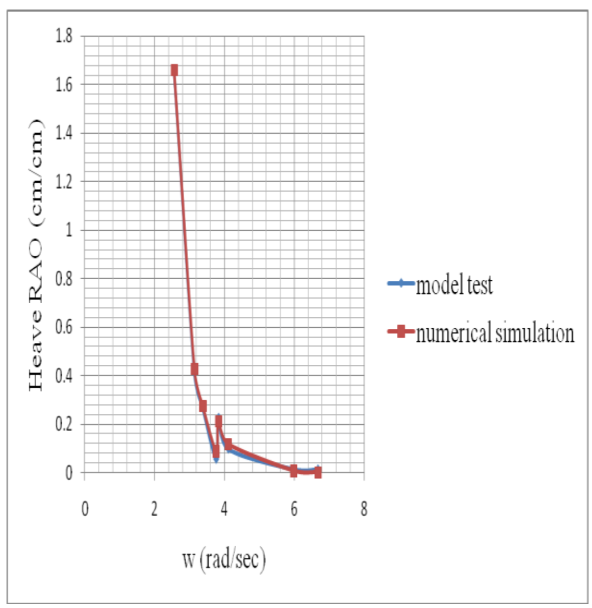


Figure. 6 Comparison of Heave motion RAO

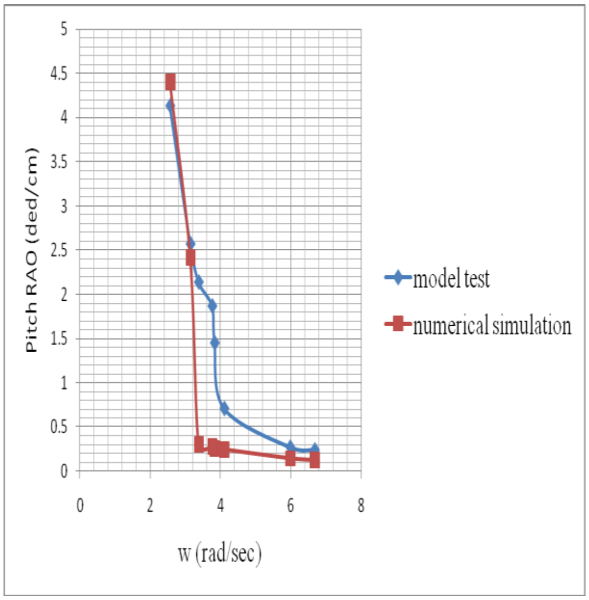


Figure. 7 Comparison of Pitch motion RAO

V. CONCLUSIONS

1) A MATLAB numerical programme was developed to determine the dynamic responses of a truss spar acted upon by regular waves.

2) The responses obtained using the above MATLAB programme were compared with the results of model tests conducted in a wave flume. Except for some differences in the surge and heave amplitudes for the frequency range 3-7 rad/s, the trends and the magnitudes of the response RAOs agreed well.

ACKNOWLEDGEMENTS

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