Numerical and model test results for truss spar platform subjected to random waves

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Abstract

As the research for oil and other natural resources have progressed into deeper waters, the traditional fixed type of offshore structures have become unsuitable and new technologies had to be resorted to. In this study, a truss spar model was tested using regular and random waves in a wave basin and the responses in surge, heave and pitch were measured. A MATLAB program named 'TRSPAR' was developed to determine the responses by numerical method. Time domain integration using Newmark Beta method was employed. The platform was modelled as a rigid body with three 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. This program was run using the model parameters and it gave results which agreed well with the corresponding results obtained from the test measurements.

Keywords:

Truss spar platforms, Time domain analysis, Model tests, Modified Morison equations, Linear Airy wave theory.

Introduction

The spar platforms for offshore oil exploration and production in deep and ultra deep waters are increasingly becoming popular. A number of concepts have evolved, among them the 'classic' spar and 'truss' spar being the most prevalent. The classic spar has an upper buoyant cylindrical hard tank, a keel ballast tank (soft tank) and a flooded cylindrical midsection. The long middle section has large diameter and its design is mostly governed by construction loads. The truss spar platform is very cost-ineffective. In the late 1990s, development of truss spar concept advanced much with a large amount of research effort using model tests [7], and theoretical study [4]. Since then, ten truss spars have been designed, constructed and/or installed.

The truss spar consists of a top hard tank 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.

Several 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 truss spar model of scaling factor 1:73, restrained by four horizontal mooring lines, was tested using regular and random waves in a wave basin 120 m long and 4 m wide with a water depth of 2.5m. The responses in surge, heave and pitch were measured. A MATLAB program named 'TRSPAR' was developed to determine the responses. Time domain integration using Newmark Beta method was employed and the platform was modelled as a rigid body with three 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 program was verified by comparison with model test results.

Experiments on the model in the wave basin

The model

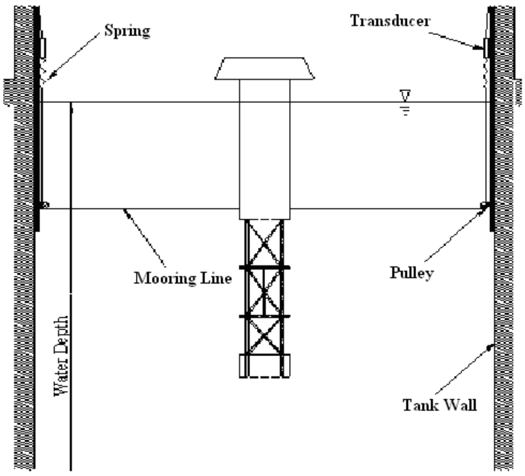
The model was designed based on the dimensions of a typical existing spar with a scale ratio of 1:73 and was fabricated using galvanized steel. It comprised of two main sections; a conventional spar-shaped upper hull, and a lower truss section, as shown in Figure 1. The hull was 442 mm in diameter and 917 mm deep. The lower part of the spar was ballasted with water to bring the spar to a draft 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)

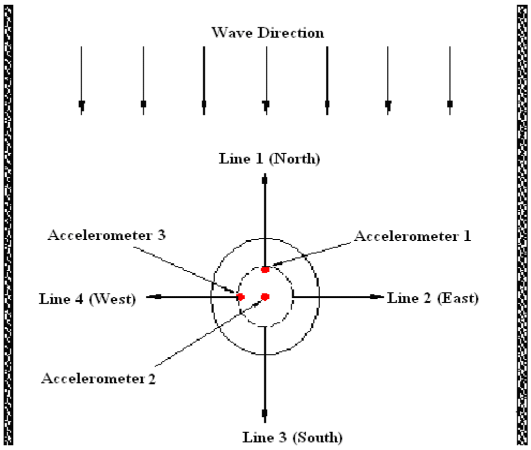
Experimental set-up

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 Figure 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 in all six degrees of freedom.

The wave environment was monitored with wave probes 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

Figure2 - Model test arrangement in the wave basin

Experimental program

Static Offset Test

This experiment was conducted to estimate the stiffness of the mooring lines. 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 modelled using multi-linear segments with different slopes (stiffness) as shown in Figure3.

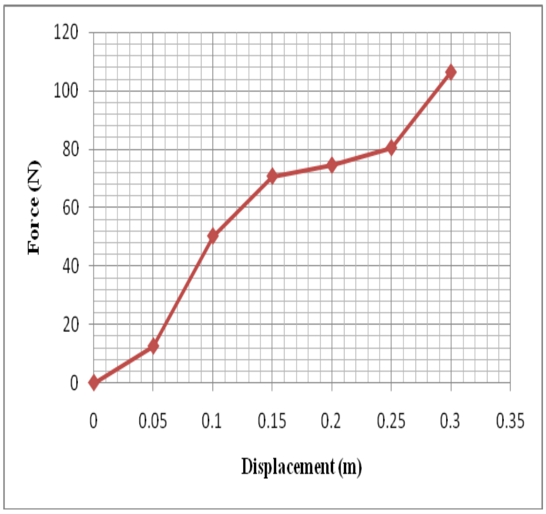


Figure 3 - Force-displacement relationship of the mooring lines

Decay Test

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 90 s.

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

Random Waves Tests

For the generation of random waves, the wave maker was oscillated with varying frequency and stroke. The range of stroke and frequencies of oscillation correspond to the energy distribution at the frequency range of the generated random sea state. In this way a sea state was generated at the actual location of the truss SPAR in the basin. At any instant, it contained the full range of frequencies with the wave energy distribution corresponding to the wave spectrum.

The random waves were adjusted such that the spectral density distribution compared with the required theoretical energy distribution as shown in Figure 4. The wave spectrum used was JONSWAP wave spectrum with Hs=0.15m and Tp=1.64sec.

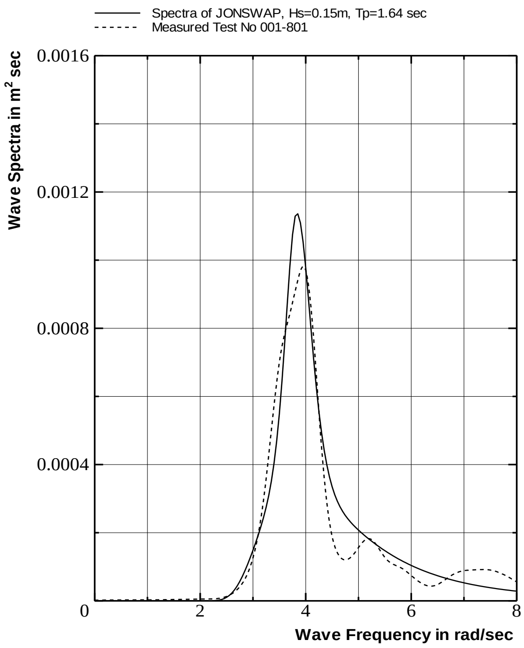


Figure 4 – Comparison between theoretical and measured wave spectrum

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 the 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 up the forces on the individual members. Incident wave kinematics was calculated by using Wheeler stretching formula. The mooring system was modelled as weightless springs, affecting the stiffness values. A numerical model for truss spar was developed that was able to predict the dynamic responses at any instant.

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 Figure 5, two coordinate systems were employed in the analysis (Cao et al, 1996), the space fixed coordinate system oxz and two dimensional local coordinate Gζη which was fixed on the body with the origin at its centre of gravity (CG). B was the centre of buoyancy and F denoted fairlead.

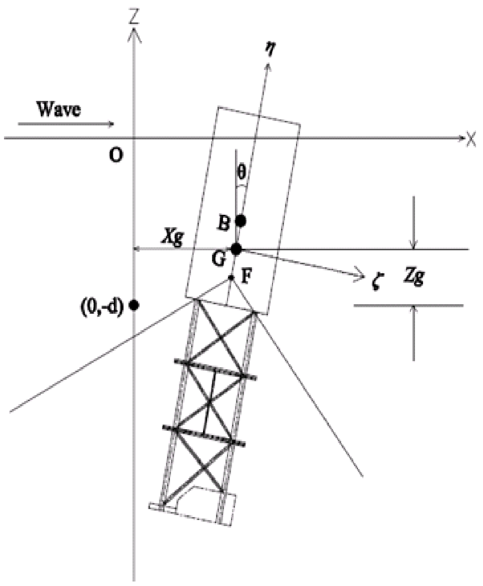


Figure -5 Three-DOF surge-heave-pitch model of the spar

$$\begin{Bmatrix} x \\ z \end{Bmatrix} = \begin{Bmatrix} 0 \\ -d \end{Bmatrix} + \begin{Bmatrix} x_g \\ z_g \end{Bmatrix} + \begin{Bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{Bmatrix} \begin{Bmatrix} \zeta \\ \eta \end{Bmatrix}$$

Equation 1- The relation between space-fixed coordinates and body-fixed coordinates

Where *Xg*, Zg denoted surge and heave motions at G, θ denoted the pitch angle about the y-axis and was positive clockwise. The coordinates of the G of the Spar at its mean position in calm water were given by (0,-*d*).

The wave forces on the hard tank were decomposed into the normal force F_{EXn}(normal to the centreline) and tangential force F_{Ext} (along the centreline). The normal wave force was determined using Morison equation at the instantaneous position of the structure and integrating along its centreline from the bottom of the hard tank (0,-d_1) to the free surface $\zeta(t)$ in body-fixed coordinate system $\xi G\eta$.

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

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

$$\int_{-d_1}^{\varsigma(t)} \rho C_m A(n) V_n \tau^T v \tau \begin{Bmatrix} 1 \\ n \end{Bmatrix} dn$$

Where

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

$$V_n = \left| V - r_s^{\cdot} - ((V - r_s^{\cdot}).\vec{\tau})\vec{\tau} \right|$$

$$\tau = \begin{bmatrix} \sin\theta \\ \cos\theta \end{bmatrix}$$

Equation 2- Modified Morison equation

C_m was the added mass coefficient, C_D the drag coefficient, V_n the relative normal velocity, and $\vec{\tau}$ the unit vector along the η axis. *a* and *V* were the wave particle acceleration and velocity respectively, and $r_s^{\cdot}$ was structure velocity. The last term in Equation 2, describes Rainey's normal axial divergence correction in which the velocity gradient matrix was given by:

$$v = \frac{\partial(u,w)}{\partial(x,z)}$$

Equation 3- Velocity gradient matrix

The tangential force could be determined by integrating the hydrodynamic pressure on the bottom surface S_B.

$$F_{EXt} = \iint_{S_B} \rho \frac{\partial \varphi^{(1)}}{\partial t} + \frac{1}{2}\rho \left|\nabla \varphi^{(1)}\right|^2 n_t \partial S$$

Equation 4- Tangential force

Where $\varphi^{(1)}$ was the first potential of incident waves which could be computed using linear Airy theory.

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

Equation 5- Transformation of FEXn and FExt spaced-fixed coordinate system OXZ

The equation of motion was solved by an iterative procedure using unconditionally stable Newmark's Beta method.

The program 'TRSPAR' included a provision for calculating the values of drag and inertia hydrodynamic coefficients at any point of the structure and at any instant, based on the KC (Keulegan-Carpenter) parameter. The charts provided by (Chakrabarti, 2001) based on wave tank tests done on a cylinder, were made use of. This provision was made use of for the numerical results of the model.

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. The model dimensions, properties and draft were used. The wave heights and wave periods corresponding to the generated waves in the basin were used for evaluating the wave force on the numerical model. All response results presented in this paper were with respect to the G.

The Response Amplitude Operators (RAOs) for surge, heave and pitch of the numerical model were compared with experimental results in Figures 6-8. The RAOs were determined as the ratio of response heights to wave heights.

As could be seen, the patterns of RAOs for surge, heave and pitch motions were fairly well predicted by the numerical model. The surge and heave RAOs agreed well with the measured values of regular waves but were much lower than the measured RAOs of random waves.

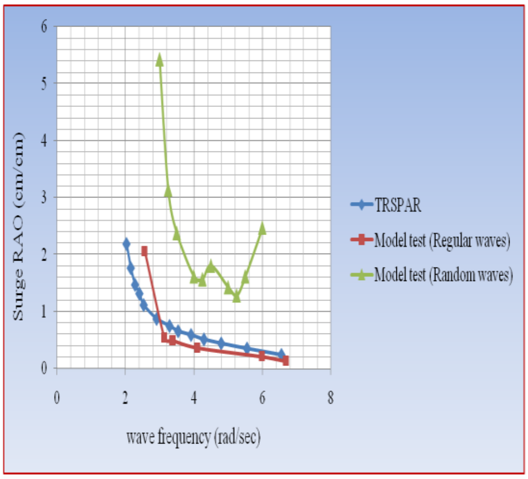


Figure 6 -Comparison of surge motion RAO

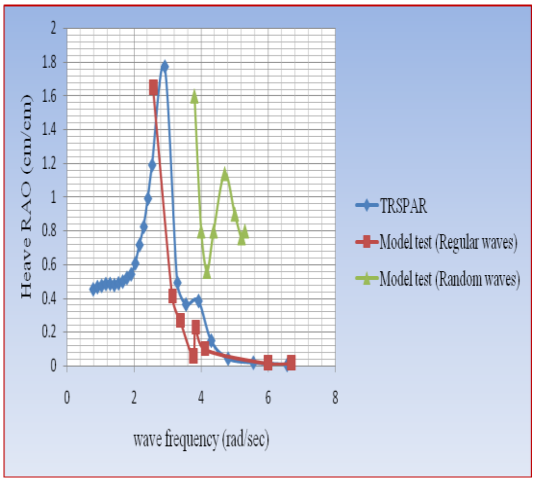


Figure 7 -Comparison of heave motion RAO

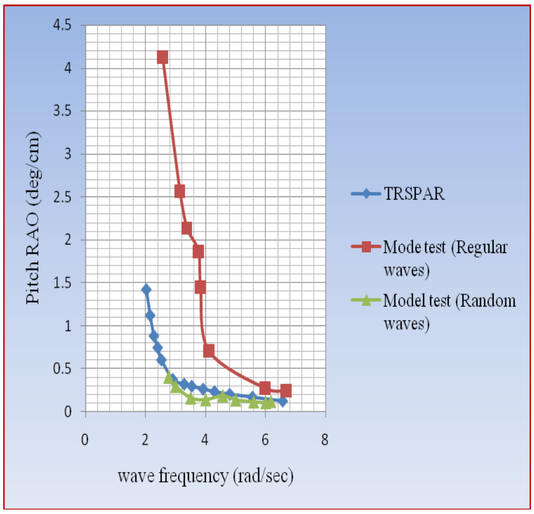


Figure 8 -Comparison of pitch motion RAO

The pitch RAOs agreed well with the measured values of random waves but was much lower compared with the measured RAOs of regular waves especially in the low wave frequency region. This discrepancy is attributed to the error in response measurements for model tests.

Conclusions

1) Available literature on the measured responses of truss spar models subjected to waves in wave basins, are only very few and this paper reports such a model study on a truss spar and compares with numerical results.

2) A MATLAB numerical program namely 'TRSPAR' was developed to determine the dynamic responses of a truss spar acted upon by regular and random waves.

3) 'TRSPAR' has provision for calculating the hydrodynamic coefficients at any point of the structure and at any instant, based on the KC parameter. This provision was made use of for obtaining the numerical motion responses of the model.

4) The responses obtained using 'TRSPAR' were compared with the results of model tests conducted in a wave flume. The trends of RAOs were well-predicted in all cases. But, the surge and heave RAOs measured for random waves and pitch RAO measured for regular waves gave higher values because of measurement errors.

Acknowledgements

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