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Interactions between Heave Response of Semi-Submersible and Its Mooring Line in Regular Waves-Experimental Analysis

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ABSTRACT

The reaction to the translation motion specifically heave response to the mooring line tension of a typical semi-submersible with square column under regular waves in wave heading condition is presented in this paper. A semi-submersible model with 112.1 kg weighted and geometrically scale 1:81 has been tested in physical wave tank under wave frequency from 0.4297 Hz to 1.7189 Hz with interval 0.1433 Hz. Model was moored horizontally which attached to the structure above the water surface level in head wave with four linear springs at corresponding column respectively. Such a system does not have practical usage but is used to study the loading and response of the semisubmersible in the absence of the catenary mooring lines. The tensions on the mooring lines is measured by load cells coincide with the non-contacting optic tracker. Optic tracker is used to accomplish the measurement of heave response. The force measured by the load cells were analyzed to obtained the behavior of the mooring lines tension at every particular frequency. From the experimental analysis, it is found that under wave heading condition the forward tension is 2 to 4 times greater compared to the aft tension. The heave obviously showed that their response directly influenced by the mooring line tension. The mooring forces are not equally separated by forward and aft mooring lines. It also showed that the behavior of all mooring lines forces at each columns have a similar trend along the frequency.
KEYWORDS: Experimental Investigation, Mooring Line Force, Semi-submersible, Heave Response.

INTRODUCTION

Semi-submersible offshore production platforms is an alternative for deep sea crude oil drilling. Compared to jacket or fixed type platform, semi-submersible is able to operate with self floting structure. In 2016, the operation of semi-submersible are dominant by 40 % of total offshore structures worldwide are serving as drilling and production systems.

In [11] has reviewed and reported that the process of design has evolutionary depend on challages of operating depth. However, an evolutionary of process design must be followed by detailed of analysis and has various option. Besides, semi-submersible only required low initial investment and operating cost since the platform has small waterline areas. In [9] stated that an analysis of influences mooring system is necessary during design stage. Since the platform is positioned and achored through the mooring system, the structure may experience large low frequency (LF) motions, defined as slow-drift motions, under nonlinear low frequency wave forces excitation. Meanwhile, the wave frequency forces excitation may cause significant dynamic responses of platform. These excitations are sensitive to different types of mooring system.

In [4] has exposed the method have been done by researchers to find the dynamic behavior of offshore structure. In [8] investigated the pitch instability of deep draft semi-submersible draft in irregular waves whereas the realistic sea conditions. In past years, many researchers have revealed the coupling effects between floating offshore structure and its mooring system. These coupling effects could be predicted in their motion and analyses in time and frequency domain [7, 14]. The need for coupled analysis has long been recognized by [15]. In [3] stated the couple analysis tools subsequently have been introduced. In [1] covered the numerical analysis of nonlinear couple dynamic response of Spar platforms under regular sea waves.

Coupled dynamic analysis technique for fully couple dynamic has been developed persistent from quasi static approach. In [2] calculated the motions of a spar and its mooring system in three water depths by using a quasi-static approach and a coupled dynamic approach. In [10] present genetic algorithm to optimize the mooring design of floating platforms. In [12] predict the semi-submersible's motion response by using diffraction potential theory and heave viscous damping correction. They contribute some improvement in order to predict the heave response of semi-submersible with diffraction potential by linearized the Morison drag [13].

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Horizontal mooring system attached above water level does not represent a practical method of mooring but is used to study the loading on and response of the semisubmersible in the absence of the catenary mooring lines. This leads to a better understanding of the effects of the catenary mooring lines on the damping and motion responses. The idea of horizontal mooring system has been used by [5] to present the mooring lines force behavior of semi-submersible in regular waves for physical model testing to reveal the behavior of mooring lines in time domain and frequency domain. They also conducted the physical model testing for semi-submersible using a horizontal mooring lines system to investigate the added mass and heave damping behavior in regular waves [6].

Horizontal mooring system in physical model testing is where the structure is moored using horizontal springs that are attached to the structure above the water surface level. Such a system does not have practical usage. However, the investigation of the responses of the structure moored with horizontal springs can be studied as being influenced by the damping of only the hull. Hence, differences between the responses of the semisubmersible model when moored via horizontal springs to those when moored using catenary mooring system are considered due to the mooring lines.

PROTOTYPE AND MODEL

The choice of scaling factor is important as the existing experimental facilities are limited. The types of actual gravity and inertia force are constant for the model and prototype. Means, the model has control to become dynamically similar to that of prototype.

Outline of the Law Similarity

Normally, the effect of viscous is ignored for the motions of ship or ocean engineering structure among waves. Froude Number and Strouhal Number are constant for the model and prototype which means the similarity of the gravitational and inertia force are satisfied, i.e.:

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}}, \frac{V_m T_m}{L_m} = \frac{V_p T_p}{L_p} \tag{1}$$

where V, L and T represent velocity, linear dimension and the motion period of the body respectively. The subscripts m and p denote the variables for the model and prototype respectively.

Based on the above mentioned law of similarity, the physical relationships between the model and prototype are shown in Table 1. Where λ means linear scale ratio and γ means specific gravity of seawater (γ = 1.025).

Table 1: Variables between the prototype and model

Item	Symbol	Scale Ratio
Linear Dimension	L_p/L_m	λ
Linear Velocity	V_p/V_m	$\lambda^{1/2}$
Angle	$\emptyset_p/\emptyset_m$	1
Period	T_p/T_m	$\lambda^{1/2}$
Area	A_p/A_m	λ^2
Volume	∇_p/∇_m	λ^3
Moment Inertia	I_p/I_m	$\gamma\lambda^5$
Force	F_p/F_m	$\gamma\lambda^3$

MODEL DESCRIPTION

The model has four rectangular column and pontoon. For the experiment, linear scale ratio λ between the prototype and model is λ = 81.0 The length of 1:81 scale model is 1.073 m and weight 107.84 kg. The technical specification of the semi-submersible and the model are shown in Figure 1and Figure 2.

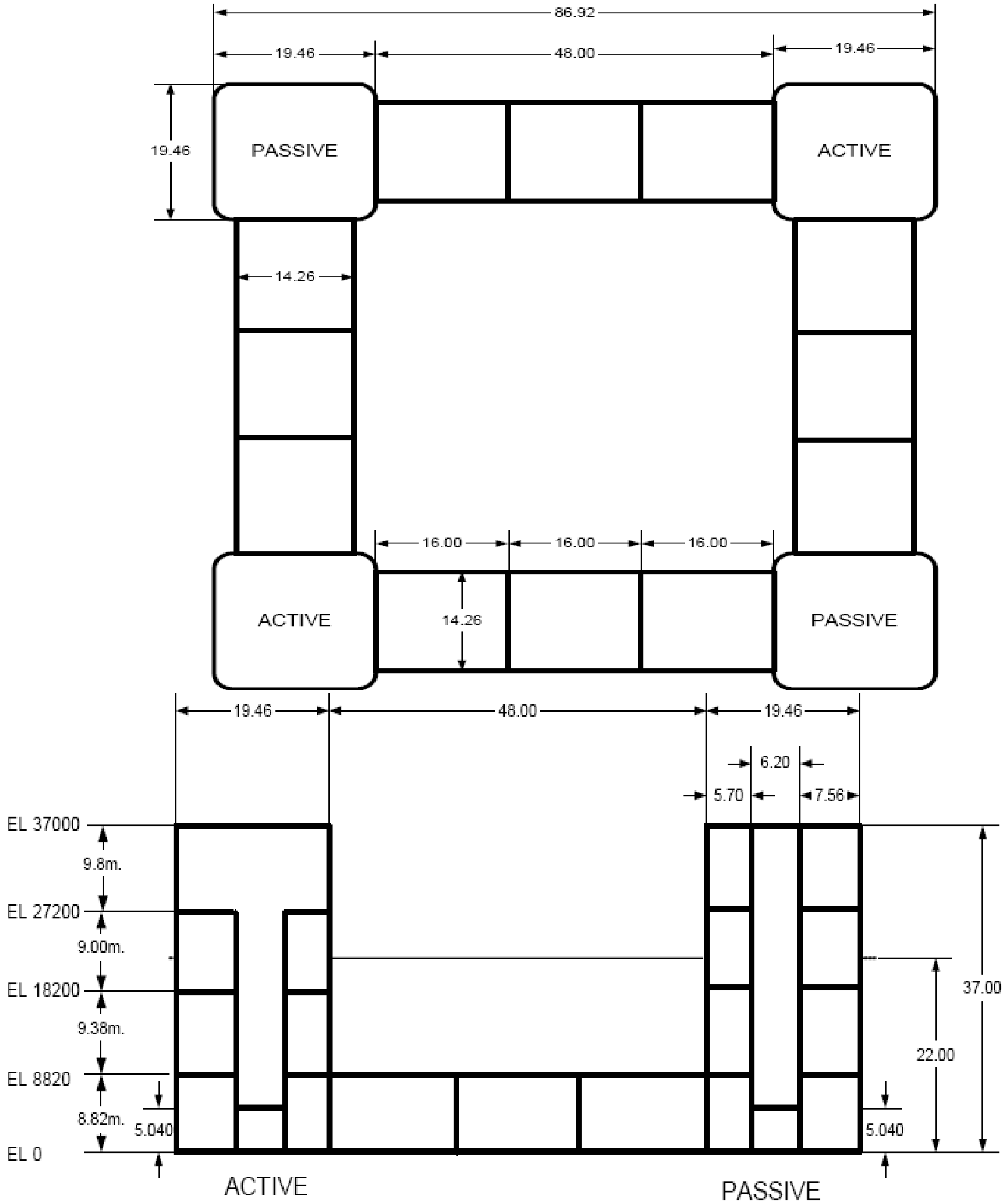

Figure 1: Main dimension of semi-submersible

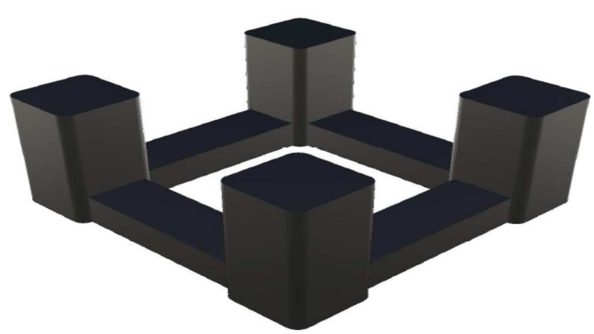

Figure 2: 3-dimension (3D) view of model

There are three main part of experiment, the first part described on model preparation. Model preparation consists of inclining test, swing table, decay test and spring calibration. It is performed to determine the natural period, vertical center of gravity of the model (KG), metacentric (GM), radius of gyration for pitch and roll as well stiffness of the soft spring. The inclining test and decay test was conducted in the calm water condition. The second part described the setup of optic tracker and the mooring chain arrangement in towing tank in head wave before heave response -mooring lines forces experiment. The last part described on the experiment to determine the heave response and force acting on the mooring line by using the high speed motion tracker and force transducer (ring gauge) respectively. All experiments ware conduct in regular wave frequencies.

Before the model was attached to carriage and run the experiment, the model was well ballasted to the appropriate loading conditions. The ballasting procedure was made to find the required displacement and balanced in water to the appropriate draught. The final arrangement of weight was done by considering the four draft marks at each column. The center of gravity and the metacentric of the model were obtained using inclining test. Table 2 showed the Semi-submersible particulars.

Table 2: Semi-submersible particulars

Designation	Unit	Full scale	Model
Column Centreline Spacing	m	67.460	0.832
Column Width	m	19.460	0.240
Column Corner Radius	m	2.200	0.027
Pontoon Width	m	14.260	0.176
Pontoon Height/Level 1 Flat	m	8.820	0.108
Level 2 Flat Elevation	m	27.200	0.335
Level 3 Flat Elevation	m	37.000	0.456
Overall Length, L	m	86.920	1.073
Overall Breadth, B	m	86.920	1.073
Overall Draft,d	m	22.000	0.271

Model Preparation

Throughout the model preparation from the experiment, the analysis of result was made by measuring the parameter using the formula and particular value which are obtained from the test. Table 3 shows the summary of results of model preparation conducted.

Table 3: Summary from the model preparation

Description	Model	Prototype	Unit
Mass displacement, Δ	0.112	58748	M.tonne
Overall draft, d	0.271	22	m
Center of gravity above base, KG	0.387	31.347	m
Center of buoyancy above base, KB	0.1	8.1	m
Metacentric height above base, KM	0.489	39.609	m
Metacentric, GM	0.0896	7.268	m
Metacentric above center of buoyancy, BM	0.389	31.509	m
Pitch radius of gyration, K_{yy}	0.448	36.32	m
Roll radius of gyration, K_{xx}	0.434	35.22	m
Heave Period, T_h	2.03	18.27	s
Pitch Period, T_p	3.39	30.51	s
Roll Period, T_r	3.34	30.06	s
Moment of Inertia, I_T	0.389	31.509	m^4
Mass moment of inertia for pitch, I_{yy}	0.021	72.87	$M.tonne.m^2$
Mass moment of inertia for roll, I_{xx}	0.023	77.50	$M.tonne.m^2$
Mooring stiffness, k	0.008	69.0	kN/m

Mooring Spring and Arrangement

Steel spring connected with force transducer was used to simulate the mooring line of the moored semi-submersible. The semi-submersible has a mooring system arranged in four lines with springs in such a way that the horizontal spring stiffness which is 0.08 N/cm corresponds to the prototype value of 69k N/m. The soft springs used has to be modified to suit the required spring stiffness of 0.08 N/cm. The achieved spring stiffness is shown in Table 4.

The typical attachment of the springs to the model is shown in Figure 3. The schematic arrangement of the springs is shown in Figure 4.

Table 4: Summary of spring stiffness

Spring	Column	Stiffness (N/cm)
S1	North West(NW)	0.0794
S2	North East (NE)	0.0794
S3	South East (SE)	0.0791
S4	South West (SW)	0.0798

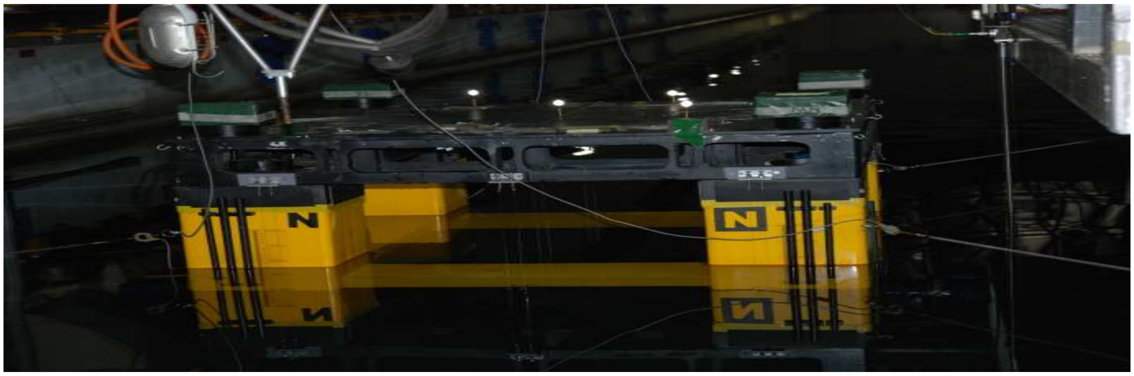

Figure 3: Attachment springs to the model

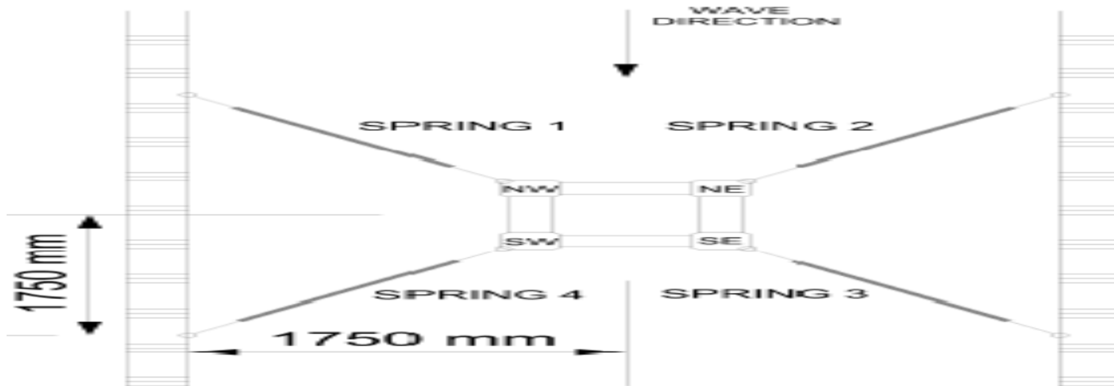

Figure 4: Attachment springs to the model

EXPERIMENTAL INVESTIGATION

Model test was conduct in the towing tank under regular waves in head sea condition. The present experimental investigation on semi-submersible model has been carried out with the objective to investigate the mooring lines force behavior.

Facilities and Instrumentations

The Marine Technology Towing Tank of Universiti Teknologi Malaysia is 120m in length, 4m in width and 2.5m in depth as Figure 5. Various ocean environments can be simulated and the water depth can be adjusted as required. The main facilities of the towing tank are:

- Hydraulic wave maker of single-flap type. Both regular and irregular waves can be generated and the maximum wave height is up to 0.4m.
- Wave absorb beach located opposite to the wave maker. The performance of wave absorber is 95% absorption.
- Uniform current can be generated by towing the model in calm water and waves. At the design conditions, the maximum current speed in the whole basin up to 4.0 m/s.
- Towing carriage with maximum speed of 4.0 m/sec. By adjusting the direction of the motion, the model test can be conducted in oblique seas.
- Various instruments for measuring waves, forces and motions of the model or ocean engineering structure model.
- Data acquisition and analysis computer system.

The instruments employed for the present test program are as follows:

- A wave probe of resistance type for measuring the generated wave elevation in test.
- 4 ring gauges for measuring the line loads.

All the instruments are carefully calibrated prior to the commencement of experiment so as to get reliable measuring data in the test.

Figure 5: Marine Technology Towing Tank of Universiti Teknologi Malaysia

Experimental Setup

For the present study, the model of semi-submersible attached to the towing carriage which carrying recording equipment was fixed at 60 m from the wave generator. One wave probe (wave gauge) was fixed at distance 1m in front of the model to measure the generated wave elevation during test.

Before the test, the mooring spring will attach to axial riser and column. Mooring lines was calibrate so that the stiffness become 0.08 N/m by attached the ring gauge at the end of the spring at column side. The ring gauge will measured the load acting on the mooring line**.**

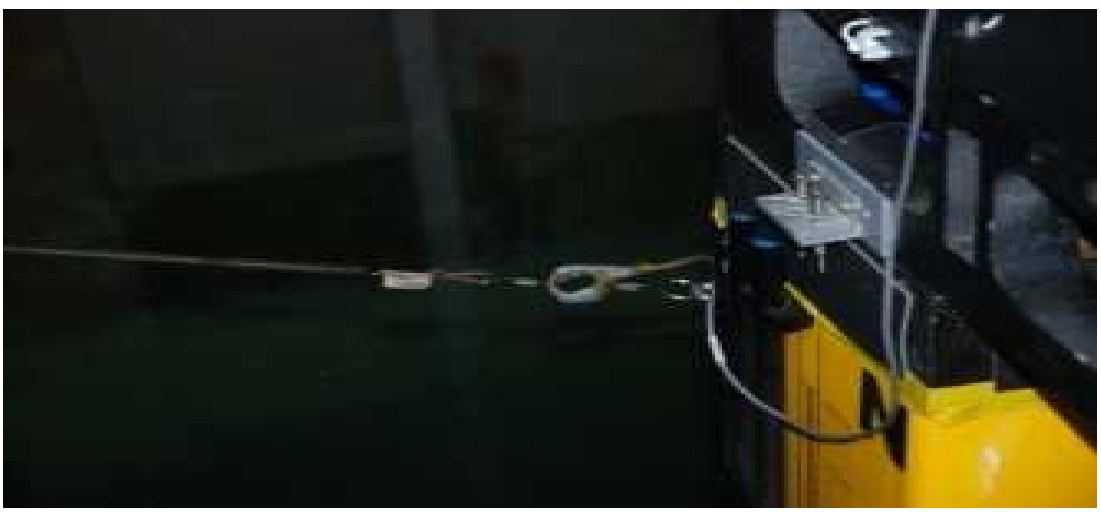

Figure 6 : Ring gauge attached to the semi-submersible

Test Procedure

The experiments conducted under regular waves for head sea condition in range of frequency from 0.429Hz to 1.7189Hz in steps of 0.1433Hz according to capability of wave generator. In Table 5 showed the frequency of oscillation that has been chosen with the constant amplitude.

Table 5: Model wave condition

f (Hz)	H_w (m)	T_w (s)	L_w (m)
0.4297	0.0988	2.3271	8.4552
0.573	0.0988	1.7453	4.756
0.7162	0.0988	1.3963	3.0439
0.8594	0.0988	1.1636	2.1138
1.0027	0.0988	0.9973	1.553
1.1459	0.0988	0.8727	1.189
1.2892	0.0988	0.7757	0.9395
1.4324	0.0988	0.6981	0.761
1.5756	0.0988	0.6347	0.6289
1.7189	0.0988	0.5818	0.5284

The wave generator was started after sometime when the wave was passing through the model then the capture start to record. The measurement has record up to about 120 seconds. All the data were obtained using the data acquisition system.

RESULTS AND DISCUSSION

Output Data

Figure 6-7 showed the example of the output from wave probe and optic tracker for the wave elevation and heave response at model scale unit in time series at wave frequency f = 0.4297Hz.

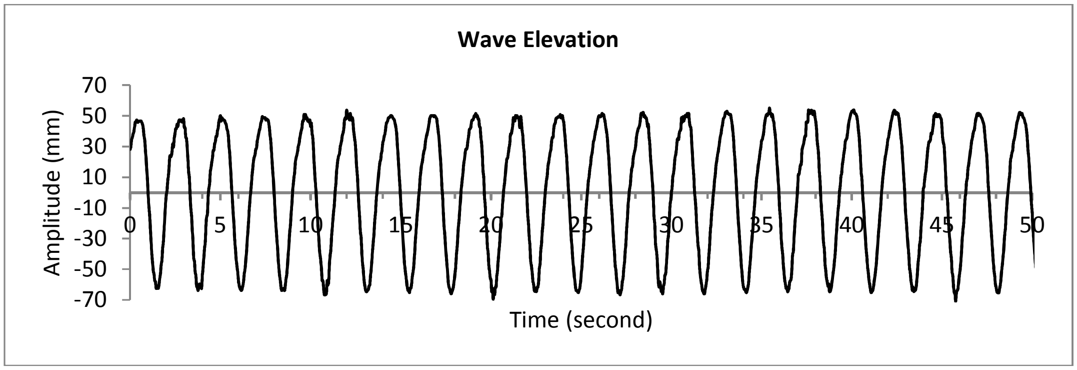

Figure 6: Wave response at L_w = 8.4552 m, T_w = 2.3271 m

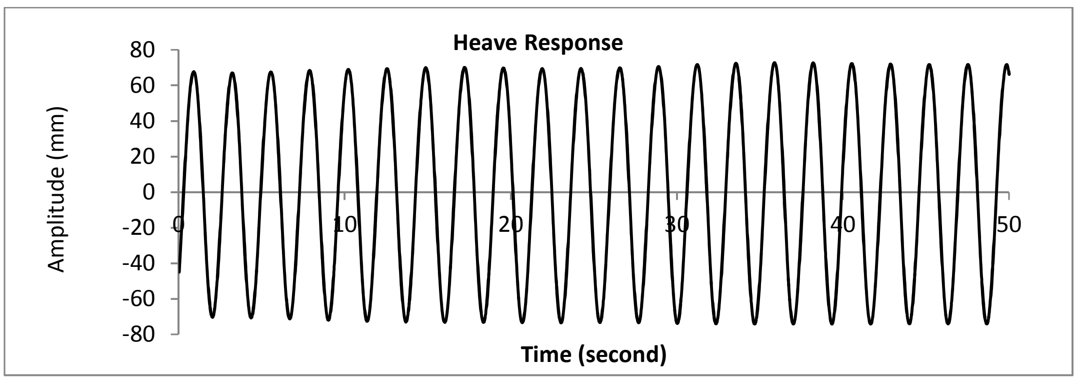

Figure 7: Heave response at f = 0.4297Hz

Tension force on the mooring line from ring gauge in times series has been showed in Figure 8-11. The data has been expressed in model scale units. Ring gauge provided the data in kilogram (kg) unit and then it was converted to the Newton (N) unit by multiply with the garavity accelaration (9.81m/s^2).

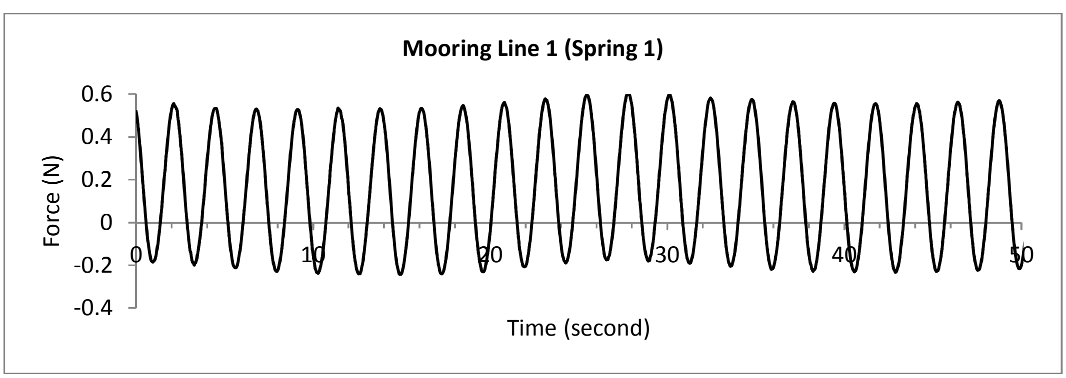

Figure 8: Moring line force at North West column at f = 0.4297Hz

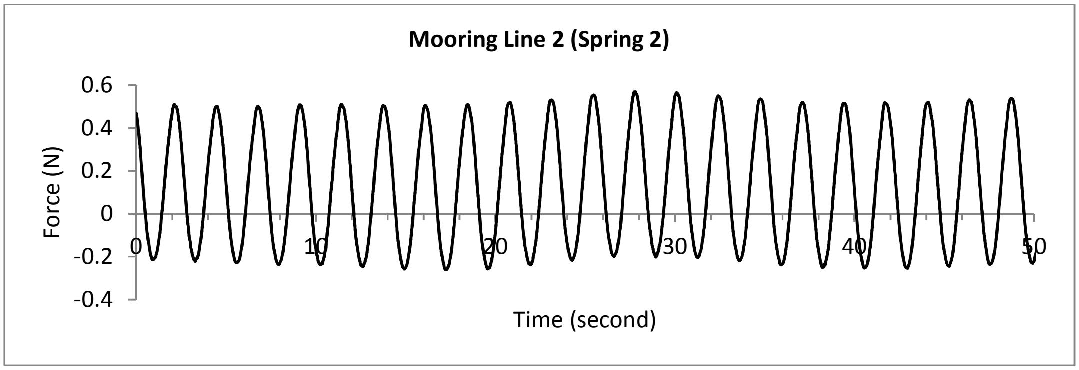

Figure 9: Moring line force at North East column at f = 0.4297Hz

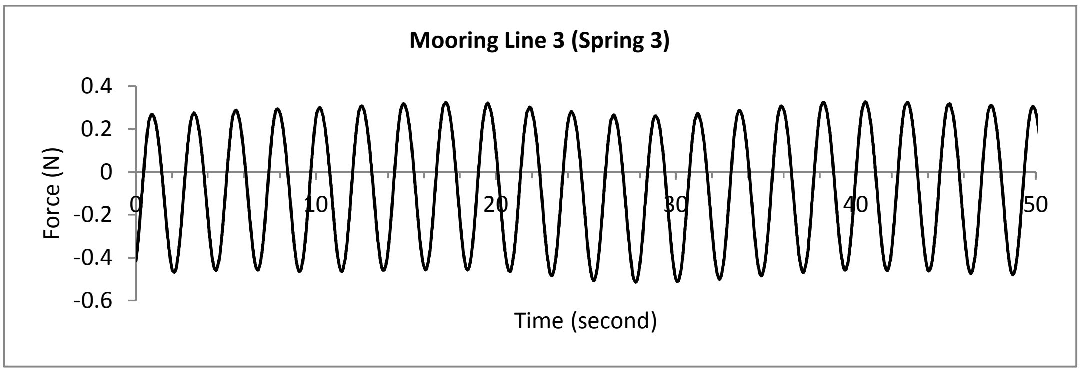

Figure 10: Moring line force at South East column at f = 0.4297Hz

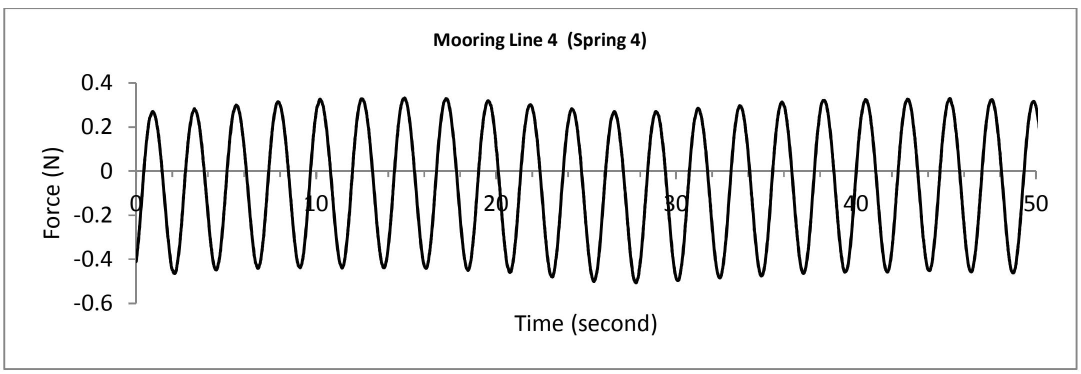

Figure 11: Moring line force at South West column at f = 0.4297Hz

Analysis of the Output Data

The measured tensions in the four mooring lines under the regular waves are nondimensionalised with the weight of mooring spring. The nondimensional mooring line tension is plotted against the wave frequency in rad/sec. Part of the data obtained from the experimental is presented here. The analysis focused on the translation motion which is heave motion. The comparison of forward mooring lines forces and aft mooring lines forces due to heave motion has been presented as shown in Figure 11-14.

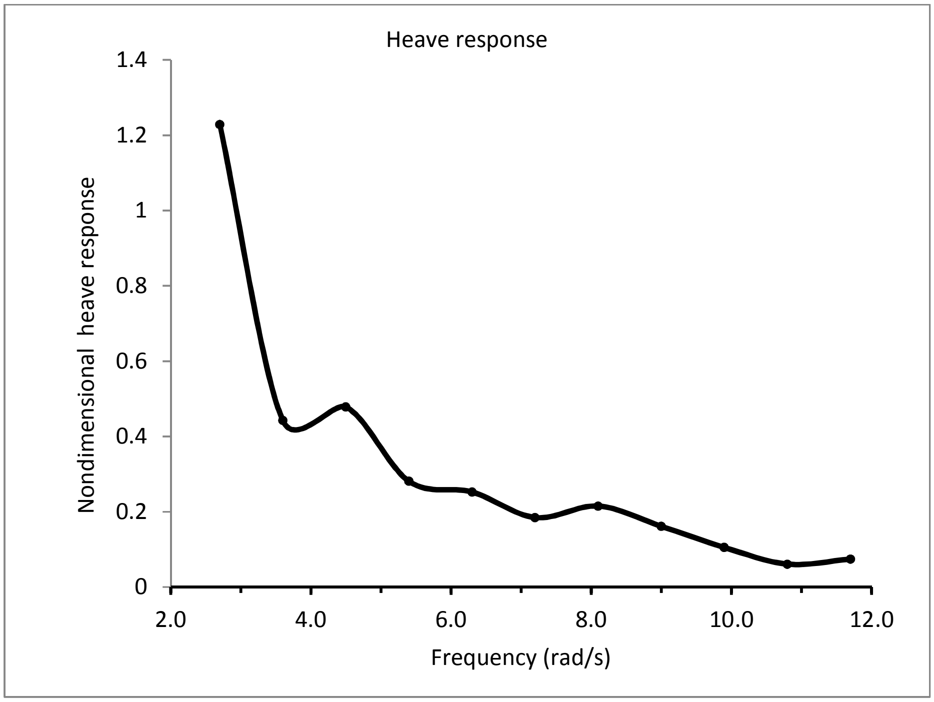

Figure 11: Nondimensional heave response

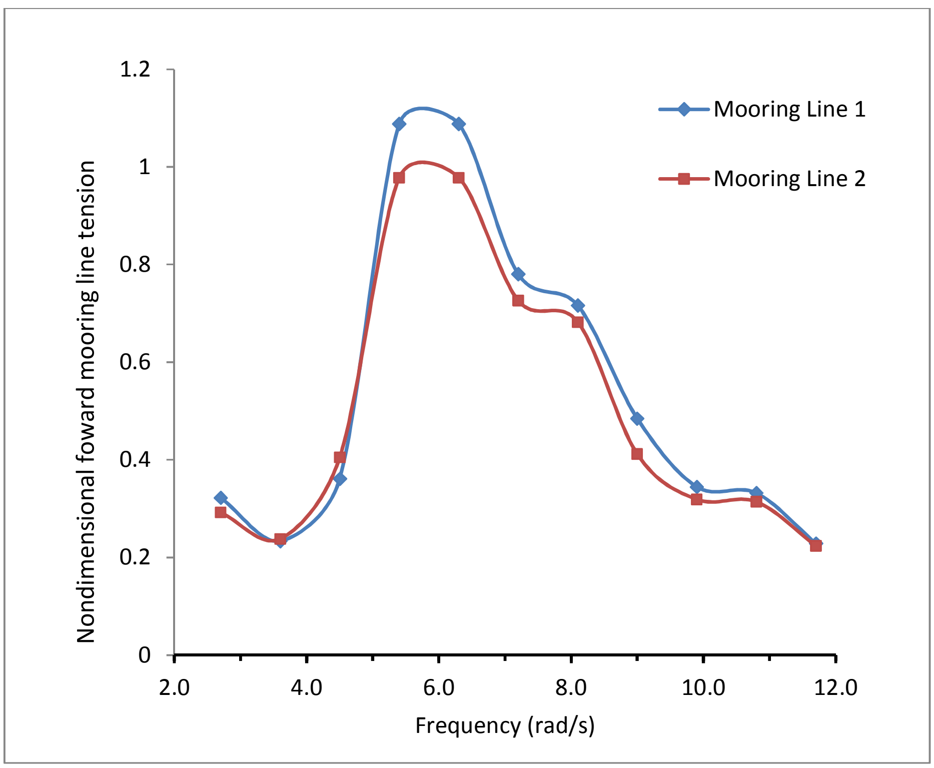

Figure 12: Nondimensional mooring line tensions in forward position

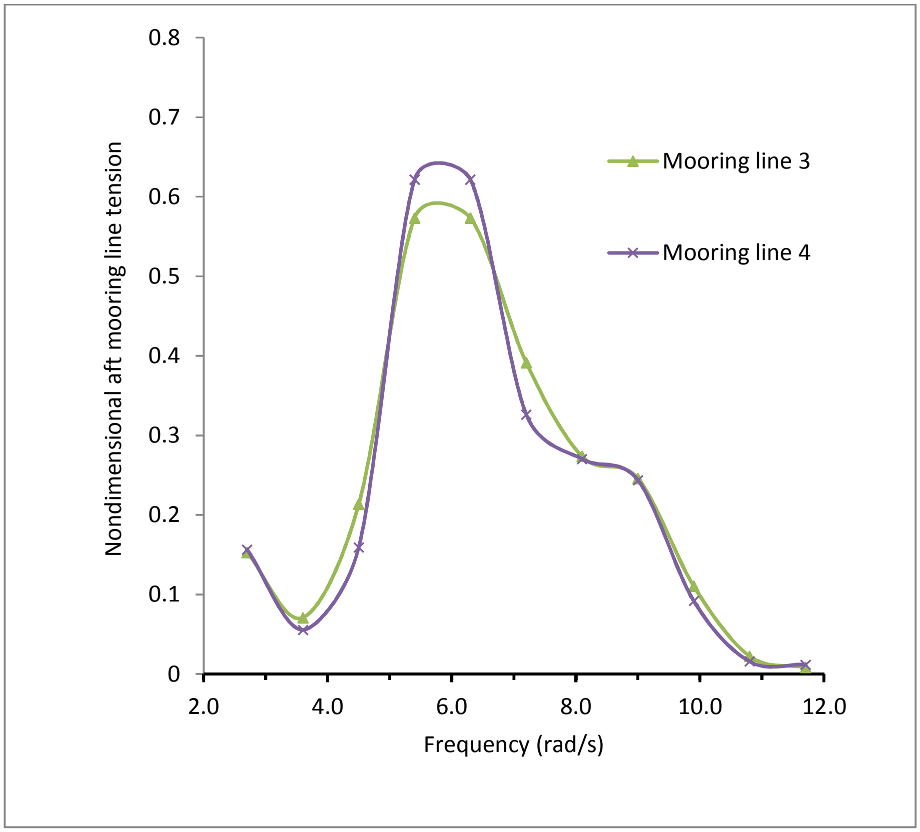

Figure 13: Nondimensional mooring line tensions in aft position

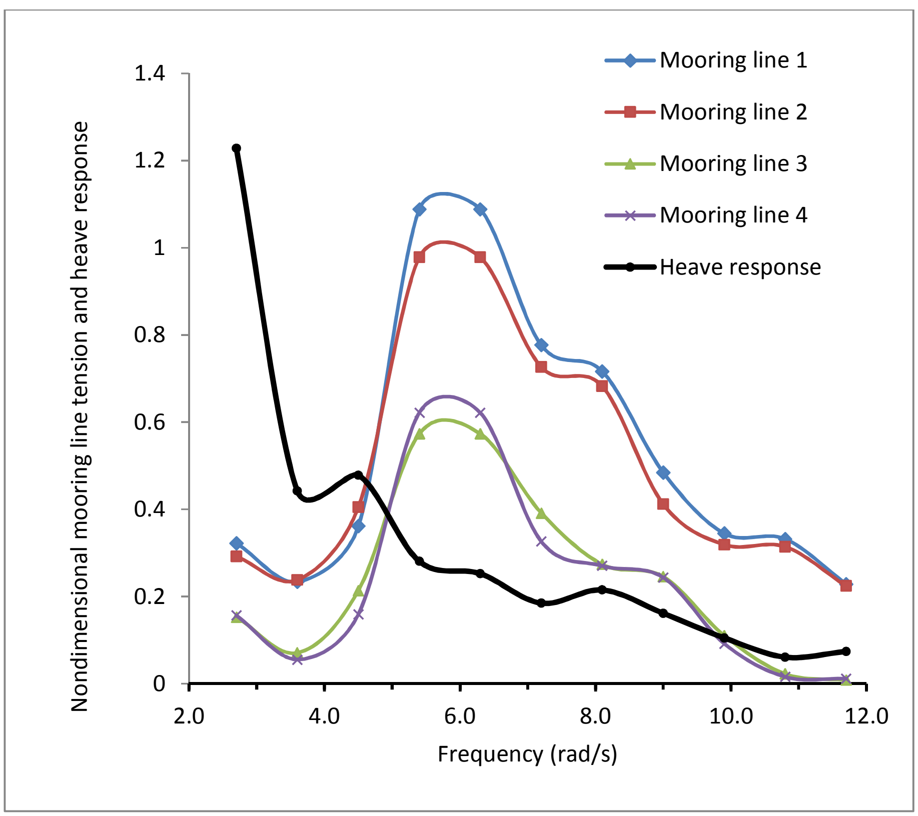

Figure 14 : Nondimensional mooring line tension and heave response

Heave Motion

It clearly showed evident that the heave response directly influences mooring tensions and other operations. The heave time history in Figure 7 shows the cluster of reversals occurring at varying time intervals. The phenomenon shows the regularity of the behavior. It can be observe in Figure 11 the heave motion drastically reduce in between frequency 2.7 rad/s to 3.6 rad/s dissimilar with the reduction of mooring lines tensions which is steadily reduce at that particular frequency. Meanwhile, mooring lines tensions demonstrated significant augment at frequency 4.5 rad/s to 5.4 rad/s. Afterward the dynamism of heave response and mooring lines tensions seem analogous comparable. At that corresponding frequency also the heave response and mooring lines tension behaves contrary which is the moorings tension ascending and at the same time the heave response vice versa.

Physically, the forward mooring lines tensions are greater than the aft mooring lines tension. All mooring lines tension behaves with the similar response along the frequency. The peak all lines tension is observed prominent at frequency 6.0 rad/s and the minimum mooring lines tension is occurs at frequency 11.7 rad/s. From the frequency 4.5 rad/s to 5.4 rad/s it displayed that all the mooring lines tension rise drastically and then decreased continuously after the frequency 6.3 rad/s.

Forward Mooring Line

The maximum lines tension is detected as 1.0880 and 0.9781 for North West column (spring 1) and North East column (spring 2) respectively at frequency 6.0 rad/s. For minimum line tension value is 0.2287 and 0.2240 occur at column of North West and North East respectively at frequency 11.7 rad/s. At frequency 4.5 rad/s the mooring line tension at South West column increased drastically from 0.1592 to 0.6216 at frequency 5.4 rad/s. Similarly, the mooring line tension at South East column from frequency 4.5 rad/s to 5.4 rad/s the line tension drastically increased from 0.4050 to 0.9781. Thereafter frequency 6.3 rad/s to 11.7 rad/s the mooring lines tension at both columns decreased gradually from 1.0880 to 0.2287 at North West column and from 0.9871 to 0.2241 at North East column.

Aft Mooring Line

The maximum line tension is observed as 0.6216 and 0.5733 for South West column (spring 4) and South East column (spring 3) respectively at frequency 6.0 rad/s. For minimum line tension value is 0.0118 and 0.0083 occur at column of South West and South East respectively at frequency 11.7 rad/s. At frequency 4.5 rad/s the mooring line tension at North West column was increased drastically from 0.3613 to 1.0880 at frequency 5.4 rad/s. Similarly, the mooring line tension at North East column from frequency 4.5 rad/s to 5.4 rad/s the line tension drastically increased from 0.2135 to 0.5732. After frequency 6.3 rad/s to 11.7 rad/s the mooring line tension at both columns was decreased gradually from 0.6216 to 0.0118 at South West column and from 0.5733 to 0.0083 at South East column.

CONCLUSION

The investigation of the model test of moored semi-submersible with horizontal mooing lines in regular waves, it revealed that:

i. The heave response directly influenced by the mooring line tension.
ii. The mooring lines tensions at foward and aft are not equally shared
iii. The bahaviour of all mooring lines forces at each columns have a similar tendency in wave heading.
iv. The tension at the foward mooring lines are 2 to 4 times greater than the tension at the aft moring lines in waves heading conditon.

Based on the above conclusion, the present study successfully described the methods to investigate the loading on and response of the semisubmersible in the absence of the catenary mooring lines. The behavior of the mooring lines force obtained from this research can be used to predict the force acting on the mooring lines and the heave response of semi-submersible with similar type dimension which operating in same range of frequency with this experiment.

The set-up, instrumentation and data analysis techniques are important parts of model testing. Perfection of set up that matches the actual floating system, suitable and accurate instrumentation as well as good data processing would assure accurate results that meet the model test objectives.

For more quality of the result, the experiment of physical model testing should consider the various type of wave response. To sustain the similarity of full-scale condition the model should involve the several wave heading because in real sea state semi-submersible is operating in plentiful wave heading. Semisubmersible model tests, which is the concentrate of motion and relative response of mooring lines tension has produced satisfactory results and is continuing to compare to simulation results.

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