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Full paper

Experimental Analysis on the Mooring Lines Force Behaviour of Semi-submersible in Regular Waves

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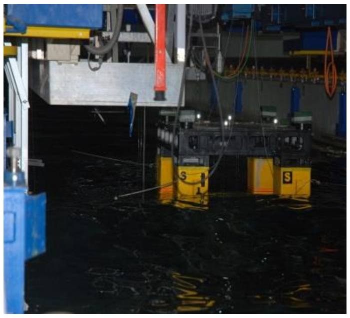
Graphical abstract



Abstract

The effect of the mooring line force of a typical semi-submersible with square column under regular sea waves for wave heading condition is reported in this paper. A 1:81 scale model of 58748 M.Tonne moored semi-submersible was tested in Marine Technology Towing Tank of Universiti Teknologi Malaysia with 120 m in length, 4 m in width and 2.5 m in depth for the wave frequency from 0.4297 Hz to 1.7189 Hz in steps of 0.1433 Hz. In the tests, model was moored horizontally that are attached to the structure above the water surface level in the head sea with four linear springs forward and aft. Such a system does not have practical usage but is used to study the loading and response of the semi-submersible in the absence of the catenary mooring lines The force or tensions on the mooring lines was measured by load cells. The force measured by the load cells were analyzed to obtain the behavior of the mooring lines force at every frequency step. From the analysis of the experimental results, it is found that among the forward and aft mooring lines, the tension in forward mooring lines is 2 to 4 times more than the tension in aft mooring lines. The mooring forces are not equally shared by forward and aft mooring lines. It also showed that the behavior of all mooring lines forces at each column have a similar trend along the frequency.

Keywords: Experimental investigation; mooring line force; semi-submersible

■1.0 INTRODUCTION

Offshore production platforms have been installed predominantly as fixed steel template jacket or concrete gravity structures for operations in water depth up to 300 m. Manufacturing, installation and maintenance costs of fixed platforms rise rapidly as water depth increase [1]. Relatively small increases in manufacturing and installation costs with increasing water depth make the semi-submersible platforms an attractive alternative for deep water oil operations. About 40 % of floating structures available worldwide are semi-submersibles serving primarily as drilling and production systems. Semi-submersibles are multi-legged floating structures with a large deck [2].

The semi-submersible platform usually has small waterline areas, low initial investment and operational cost. When the semi-submersible platform is positioned through mooring system, the structure may experience large low frequency (LF) motions, known 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, so analysis the influence of mooring system to semi-submersible platform during the design stage is necessary [3].

In past years, many researchers have revealed the coupling effects between floating platform and its mooring system should be considered in predicting their motions [4, 5]. Coupled dynamic analysis technique has been developed from quasistatic approach [6] to fully couple dynamic approach [7, 8, 9]. Chen *et al.* use a quasi-static approach and a coupled dynamic approach to calculate motion of a spar and its mooring system in three water depths [10]. Shafieefar and Rezvani present genetic algorithm to optimize the mooring design of floating platforms [11]. Tong *et al.* compare the dynamic effect on semi-submerged platform with catenary and taut mooring system, respectively [12]. Sun and Wang study on motion performance of deep water spar platform under equally distributed mooring method and grouped mooring method [13].

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 semi-submersible in the absence of the catenary mooring lines [14]. This leads to a better understanding of the effects of the catenary mooring lines on the damping and motion responses.

Horizontal mooring system is where the structure is moored using horizontal springs 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 semi-submersible model when moored via horizontal springs to those when moored using catenary mooring system is considered due to the mooring lines [14].

■2.0 PROTOTYPE AND MODEL

The choice of scaling factor is important as the existing experimental facilities are limited. The types of gravity and inertia force are kept same for model and prototype. The model becomes dynamically similar to that of prototypes.

2.1 Outline of the Law Similarity

Normally, the effect of viscous is ignored for the motion of ships or ocean engineering structure due to waves. In the present tests, the Froude Number and Strouhal Number of the model and prototype are kept the same, which means the similarity of the gravitational force and inertia force is satisfied, i.e.:

$$\frac{V_m}{\sqrt{gL_m}}=\frac{V_s}{\sqrt{gL_s}} \qquad \frac{V_mT_m}{L_m}=\frac{V_sT_s}{L_s} \qquad (1)$$

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

Based on the above mentioned law of similarity, the relationships of physical variables between the prototype and model are listed 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_s/L_m	λ
Linear Velocity	V_s/V_m	$\lambda^{1/2}$
Angle	ϕ_s/ϕ_m	1
Period	T_s/T_m	$\lambda^{1/2}$
Area	A_s/A_m	λ^2
Volume	∇_s/∇_m	λ^3
Moment Inertia	I_s/I_m	$\gamma\lambda^5$
Force	F_s/F_m	$\gamma\lambda^3$

■3.0 MODEL DESCRIPTION

The model has four rectangular columns 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. Details of technical specification of the semi-submersible and the model are given in Figure 1 and Figure 2.

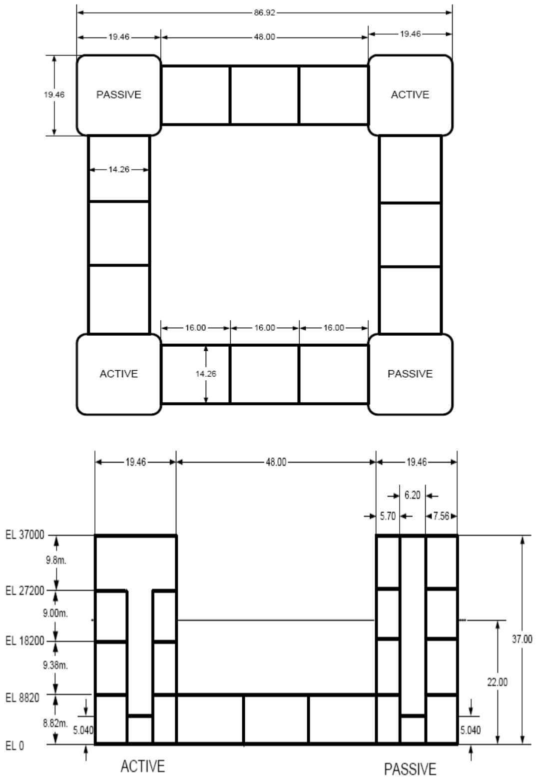


Figure 1 Main dimension of semi-submersible

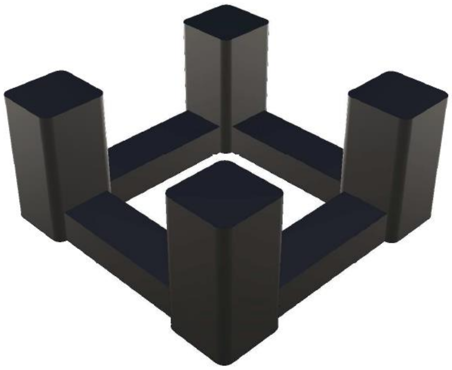


Figure 2 3-dimension (3D) view of model

There are three main parts of the experiment; the first part described the model preparation. Model preparation consists of inclining test, swing table, decay test and calibration of spring. 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 on the calm water condition. The second part described the mooring chain and setup arrangement in the towing tank in heading wave before mooring line forces experiment. The last part described the experiment to determine the force acting on the mooring line by using the force transducer (ring gauge). All experiments ware conduct in regular wave frequencies.

Before experiments were conducted, the model was properly ballasted to the appropriate loading conditions. The model was first ballasted to the required displacement and balanced in the water to the appropriate draught. However, the final adjustment 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 the inclining test. Table 2 showed the Semi-submersible particulars.

Table 2 Semi-submersible particulars

Designation	Unit	Full scale	Model
Column Centre line 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

3.1 Model Preparation

Throughout the model preparation from the experiment, the analysis of result done by measuring the parameter using the formula and particular value were obtained from the test. Table 3 shows the summary of the model preparation test results.

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

3.2 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.

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

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.

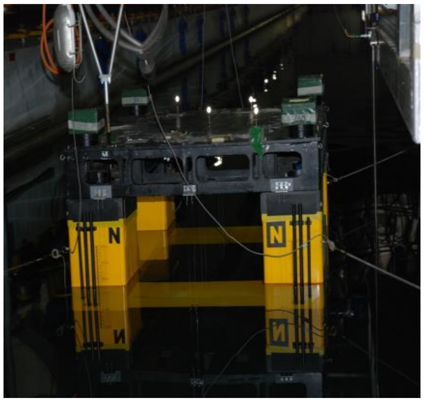


Figure 3 Attachment springs to the model

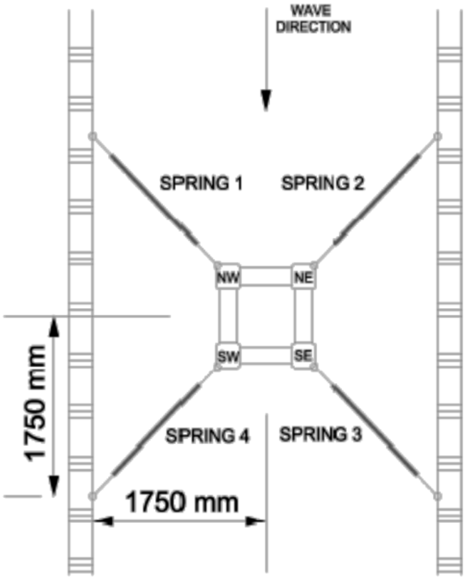


Figure 4 schematic arrangement of the springs

■4.0 EXPERIMENTAL INVESTIGATION

Model test was conducted 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.

4.1 Facilities and Instrumentations

The Marine Technology Towing Tank of Universiti Teknologi Malaysia is 120 m in length, 4 m in width and 2.5 m 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 as follows:

- 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 absorber 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 computer analysis system.

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

- A wave probe of resistance type for measuring the generated wave elevation during the test.
- Four (4) ring gauges for measuring the line loads.

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

Figure 5 Marine Technology Towing Tank of Universiti Teknologi Malaysia

4.2 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 1m distance in front of the model to measure the generated wave elevation during the test.

Before the test, the mooring spring will attach to axial riser and column. Mooring lines were calibrated so that the stiffness become 0.08 N/m by attached the ring gauge at the end of the spring at side column as shown in Figure 6. The ring gauge will measure the load acting on the mooring line.

Figure 6 Ring gauge attached to the semi-submersible

4.3 Test Procedure

The experiments were conducted under regular wave for head sea condition in range of frequency from 0.429 Hz to 1.7189 Hz in steps of 0.1433 Hz 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 the wave passing through the model, and then the capture started to record. The measurement has recorded up to about 120 seconds. All the data were obtained using the data acquisition system.

■5.0 RESULT AND DISCUSSION

5.1 Output data

Figure 6-10 showed the example of the output for the wave elevation and tension on the mooring line from the wave probe and ring gauge in time series. The data have 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 multiplying by the accelaration of garavity (9.81m/s^2).

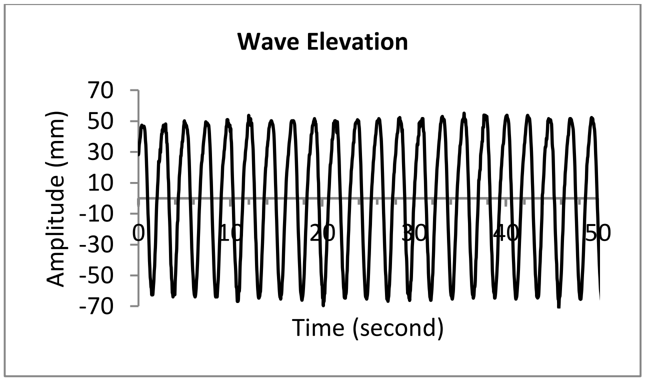


Figure 6 Wave response at L_w= 8.4552 m, T_w = 2.3271 m

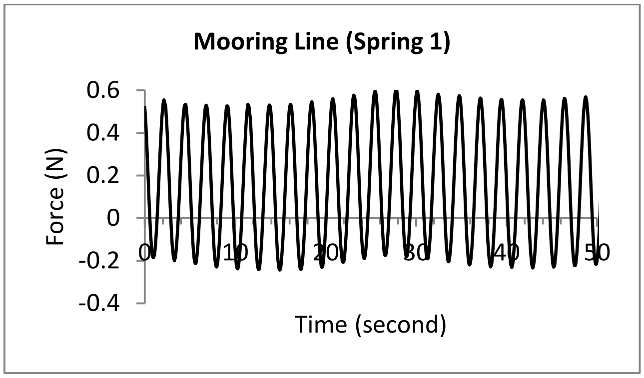


Figure 7 Mooring line force at North West column at *f* = 0.4297 Hz

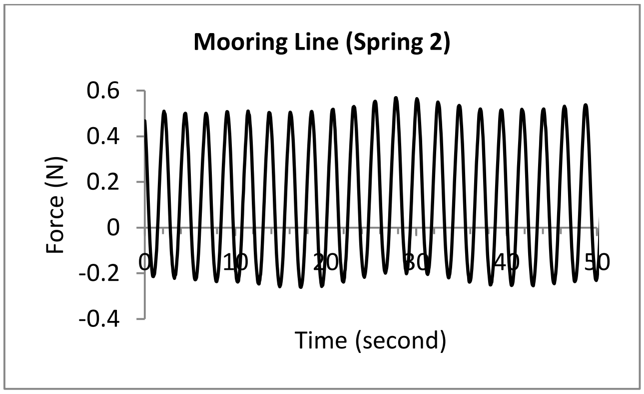


Figure 8 Mooring line force at North East column *f* = 0.4297 Hz

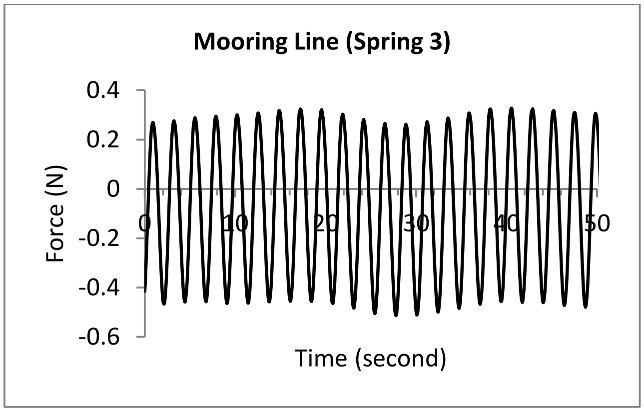


Figure 9 Mooring line force at South East column *f* = 0.4297 Hz

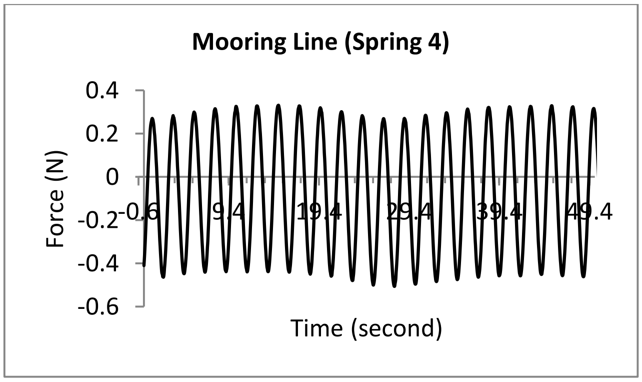


Figure 10 Mooring line force at South West column *f* = 0.4297 Hz

5.2 Analysis of the output data

The measured force or 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. The comparison of forward mooring lines forces and aft mooring lines forces as are presented as shown in Figure 11-13.

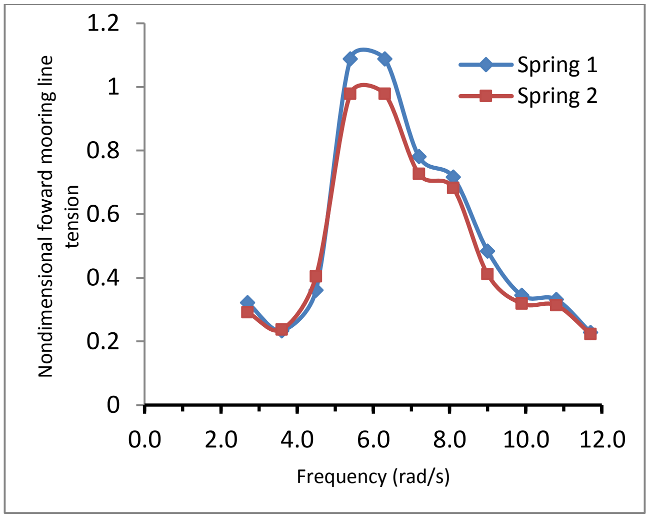


Figure 11 Nondimensional mooring line tensions in forward position

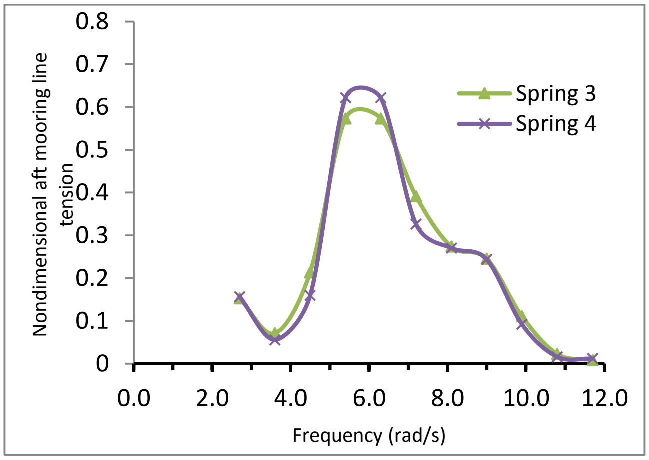


Figure 12 Nondimensional mooring line tensions in aft position

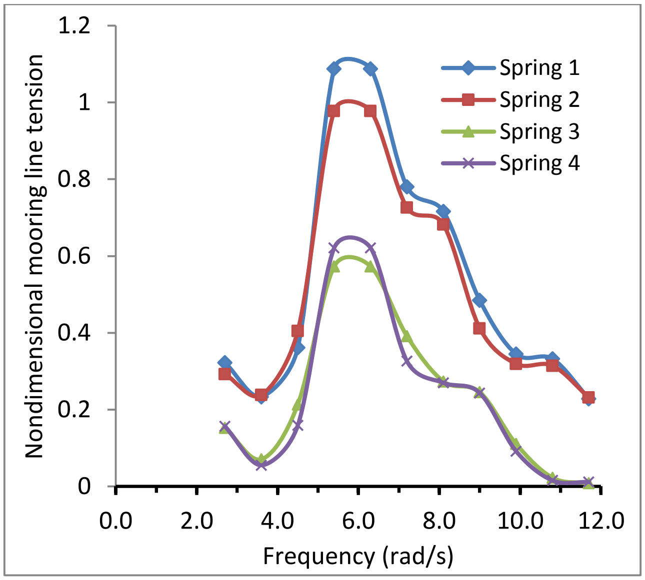


Figure 13 Nondimensional all mooring line tensions

Roughly, the forward mooring lines tensions are higher than the aft mooring lines tension. All mooring lines tension behaves with the similar trend along the frequency. The maximum 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 showed that all the mooring lines tension increased drastically and then decreased gradually after the frequency 6.3 rad/s.

5.2.1 Forward Mooring Line

The maximum line tension is observed 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 was 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. After frequency 6.3 rad/s to 11.7 rad/s the mooring line tension at both columns was decreased gradually from 1.0880 to 0.2287 at North West column and from 0.9871 to 0.2241 at North East column.

5.2.2 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.

6.0 CONCLUSION

From the analysis of the model test results of the moored semi-submersible with horizontal mooing lines, it is observed that:

i. The mooring forces are not equally shared by foward and aft mooring lines.
ii. The bahaviour of all mooring lines forces at each columns have a similar trend along the frequency.
iii. The tension in the foward mooring line is 2 to 4 times more than the tension in the aft line.

Based on the above conclusion, the present study successfully described the methods of investigate the mooring lines behavior of a semi-submersible in sea state. The behavior of the mooring lines force obtained from this research can be used to predict the force acting on the mooring lines of semi-submersible with same type dimension which operating in same range of frequency with this experiment.

For more quality of the result the experimental should consider the various type of wave response. To maintain similarity the full-scale condition the model should cover the several of wave heading because in real sea state semi-submersible is operating in numerous wave heading

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