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Experimental Study on Translation Motion Characteristics of Moored Symmetrical Semi-submersible in Regular Waves

Khairuddin, N.M.[1,2,3] **, Jaswar Koto* [2,3]*, Nur Ain, A.R.*[1]*, Mohd Azhari, J.*[1]*,*
Najmie, A.[1]
[1] *Faculty of Mechanical Engineering, Universiti Teknologi MARA, Malaysia*
[2] *Department of Aeronautic, Automotive and Ocean Engineering,*
Universiti Teknologi Malaysia Skudai, Malaysia
[3] *Ocean and Aerospace Research Institute, Pekan Baru, Riau, Indonesia*
** nmkhairuddin@uitm.edu.my*

ABSTRACT

This paper proposes to carry out experiment procedures to investigate the translation motion characteristics of symmetrical semi-submersibles in long crest regular waves. The hydrodynamic response of floating structures in waves is required to be modelled correctly to ensure stability and safety. The symmetrical semi-submersible model was constructed based on a scale ratio of 1:81 in this experiment and was installed with horizontal mooring lines in a wave dynamic basin. This paper also discusses the model preparation procedures, including the mooring lines setup, instrument setup and experiment setup, before conducting the experiment. According to the experiment data, the symmetrical moored semi-submersible experienced wave frequency motion and slow varying motion due to drift force and mooring lines for sway motion; while the heave and surge motion only experienced wave frequency motion.

Keywords: *Hydrodynamic Response; Semi-submersible; Wave Crest; Short Crest Wave; Long Crest Wave*

Introduction

Semi-submersible offshore production platforms are an alternative for deep sea crude oil drilling. Compared to jacket or fixed-type platforms, semi-submersibles can operate with a self-floating structure. In 2016, the operation

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of semi-submersibles covered 40% of total offshore structures worldwide, serving as drilling and production systems [14].

Sharma et al. [14] reviewed and reported that the process of design has evolutionary reliance on challenges of operating depth. However, an evolution of process design must be followed by a detailed of analysis and has various options. Besides, semi-submersibles only require low initial investment and operating costs, since the platform contains small waterline areas. Research by Rudman and Cleary [12] states that an analysis of influences of the mooring system is necessary during the design stage. Since the platform is positioned and anchored 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 by the platform. These excitations are sensitive to different types of mooring systems.

Previous research by Islam et al. [5] exposed a method to find the dynamic behaviour of offshore structures. Some researchers investigated the pitch instability of deep draft semi-submersible drafts in irregular waves, in realistic sea conditions [10]. In the past few years, researchers such as Hong et al. [4], Montasir et al. [11] and Chen et al. [2], have revealed the coupling effects between floating offshore structures and the mooring system. These coupling effects could be predicted in their motion and analyses, in terms of time and frequency [17]. The need for coupled analysis has long been recognized [8]. Research by Low and Langley [9] introduced couple analysis tools. The numerical analysis of nonlinear couple dynamic responses of Spar platforms under regular sea waves has been cover by Agarwal and Jain [1].

Coupled dynamic analysis technique for fully couple dynamics has been developed using the quasi static approach. Chen et al. [3] calculated the motions of a spar and its mooring system in three different water depths by using a quasi-static approach and a coupled dynamic approach. The present genetic algorithm to optimize the mooring design of floating platforms has been investigated by Shafieefar and Rezvani [13]. Siow et al. [15] predicted the semi-submersible’s motion response by using diffraction potential theory and heave viscous damping correction. They contribute some improvement to predict the heave responses of semi-submersibles with diffraction potential by linearized the Morison drag [16].

The horizontal mooring system attached above water level does not represent a practical method of mooring but is rather used to study the loading on and response of the semi-submersible, 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 the horizontal mooring system has been used by Khairuddin et al. [6] to present the mooring lines force behaviour of semi-submersibles in regular waves to reveal the behaviour of mooring lines in terms of time and frequency. They also conducted physical model testing for semi-submersibles using a horizontal mooring lines system to investigate the added mass and heave damping behaviour in regular waves [7].

The 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 investigated 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 systems, were considered due to the mooring lines.

Experimental Approach

There are five part of experimental approach will be described in this section. The first part describes the law of similarity. Second part describes the model preparation while the third part explain the instrument that were used in the experiment. The fourth and last part describes the mooring lines setup and the experimental setup.

Law Similarity Outline

In this study, the semi-submersible model and mooring line are scaling based on the Froude Number and Strouhal Number similarity. This means that the model and prototype have similarity in terms of Froude Number and Strouhal Number (gravitational force and inertia force is satisfied). Froude’s law of similarity is the most appropriate scaling law applicable for the moored and unmoored floating structure experiments.

Typically, the effect of viscous is ignored for the motions of ship or ocean engineering structures among 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, as Equation (1) and Equation (2) follows:

$$\frac{V_m}{\sqrt{gL_m}} = \frac{V_p}{\sqrt{gL_p}} \tag{1}$$

$$\frac{V_m T_m}{L_m} = \frac{V_p T_p}{L_p} \tag{2}$$

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 Equation (1) 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 ($\gamma = 1.025$).

Table 1: Scaling Law 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 Preparation

In this study, the symmetrical semi-submersible (Figure 1) was designed and constructed so that it can be tested in a water basin to simulate the characteristic of translation motion. This symmetrical semi-submersible model was constructed based on a full-scale model. In this experiment, the symmetrical semi-submersible model was scaled down with the ratio of 1:81.

After completing the model construction, several tests were conducted to ensure the model is coherent to the prototype design. Firstly, the inclining test, swing test (Figure 2) and decay test were carried out to identify the hydrostatic particular for the symmetrical semi-submersible model. This was performed to determine the natural period, vertical center of gravity of the model (KG), metacentric (GM) and the radius of gyration for pitch and roll.

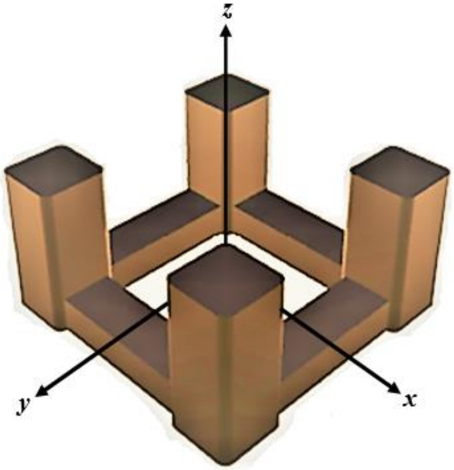

Figure 1: Symmetrical Semi-submersible

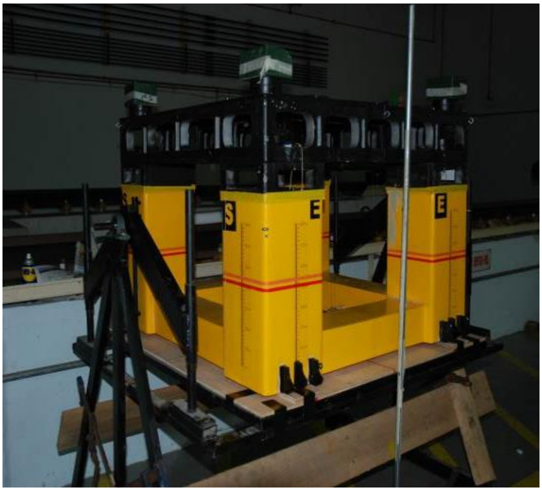

Figure 2: Swing test to calibrate its center of gravity

Throughout the model preparation from the experiment, the analysis of the results was done by measuring the parameter and values which are obtained from the test. Table 2 shows the summary of results of model preparation test conducted.

Table 2: 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	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

Instrument of Model Test

The symmetrical semi-submersible was assumed to have six degrees of freedom during the experiment. Wave probe (Figure 3) of resistance was employed and attached to the model to measure the generated wave elevation during the test.

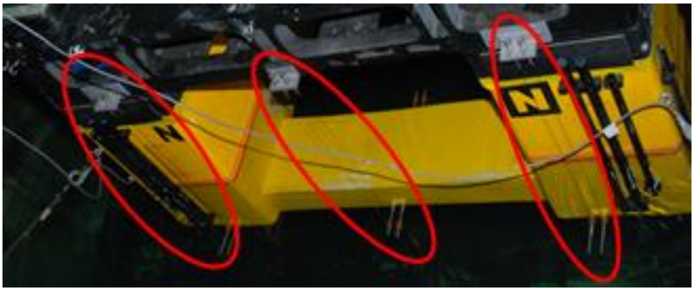

Figure 3: Wave probe to measure the wave elevation

The optic tracker (Figure 4) used was Qualysis, which is a high-speed camera used to capture the motion from the ball maker (Figure 5) that has been fixed onto the model. Once the ball maker that is attached to the model makes a movement, the optic tracker or high-speed camera captures the motion and records the amplitude motion of the symmetrical semi-submersible.

Figure 4: Optic tracker to capture the motion of ball maker

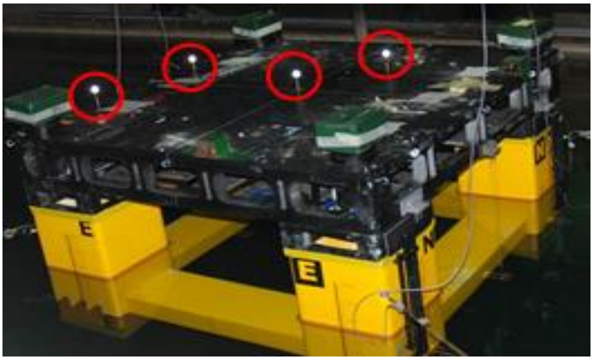

Figure 5: Ball maker

The translation motion in the X, Y and Z axis of the symmetrical semi-submersible has been recorded on a computer device using Qualysis Track Manager (Figure 6) in a time domain series**.**

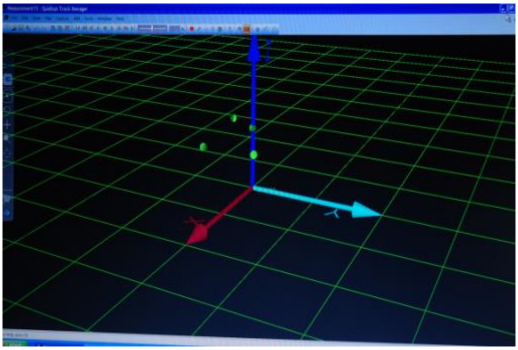

Figure 6: Qualysis Track Manager to record the motion of marker

Mooring Line Setup

Steel springs which connected with a force transducer were used to simulate the mooring line of the moored semi-submersible. The semi-submersible has a mooring system arranged in four lines, with springs attached in such a way that the horizontal spring stiffness is 0.08 N/m, corresponding to the prototype value of 69 kN/m. The soft springs used must be calibrated to suit the required spring stiffness of 0.08 N/m. The achieved spring stiffness is shown in Table 3. The schematic arrangement of the springs to the model is shown in Figure 7.

Table 3: Summary of spring stiffness

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

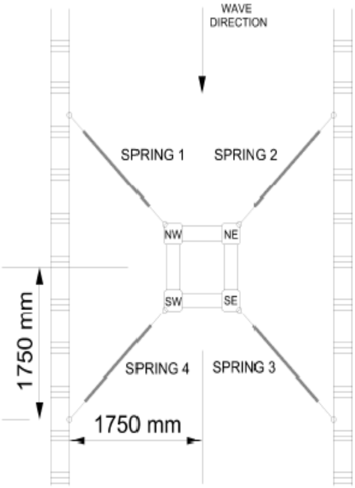

Figure 7: Schematic arrangement

Experimental Setup

The symmetrical semi-submersible model was attached to the towing carriage, which carries recording equipment that is fixed at 60 m from the wave generator. One wave probe (wave gauge) was fixed to the model to measure the generated wave elevation during tests. Symmetrical semi-submersibles are set so that the North West Column and North East Column face the wave direction.

Before the test, the mooring spring is attached to the axial riser and column. Mooring lines were calibrated so that the stiffness becomes 0.08 N/m by attaching the ring gauge at the end of the spring, at the column side. The ring gauge (Figure 8) measures the load acting on the mooring line.

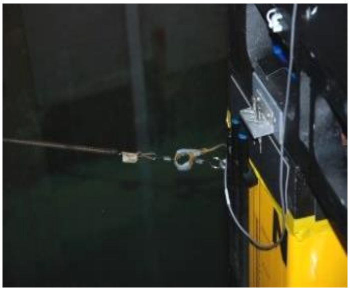

Figure 8: Ring gauge attached to the model

The experiments were conducted under regular waves for head sea conditions in the frequency range of 0.429 Hz to 1.7189 Hz, in steps of 0.1433 Hz, according to the capability of the wave generator. Table 4 shows the frequency of oscillation that has been chosen with the constant wave height of 0.0988 m.

Table 4: Model wave condition

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

The wave generator was initiated when the wave passes through the model, and the optic tracker starts the recording process. The measurement recorded up to about 120 seconds. All the data were obtained using the Qualysis Tracker Manager.

Result and Discussion

In this study, the translation motion in the X, Y and Z axes is consider as a Sway, Surge and Heave motion respectively. The collected time domain samples are presented in Figures 9 to 11, which present the surge, sway and heave motions of the symmetrical semi-submersible, respectively, in time series collected from the model experiment.

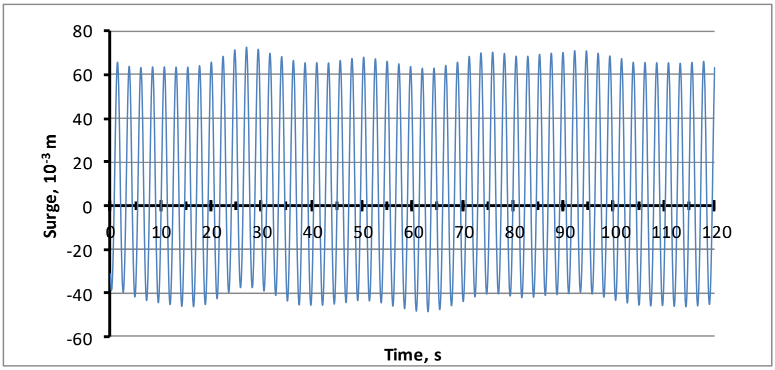

Figure 9: Surge motion in time series from model experimental at wave frequency 0.4297 Hz and wave height 0.0988 m

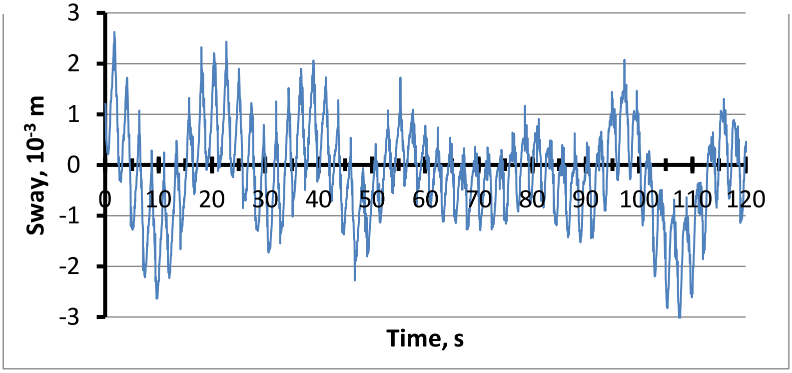

Figure 10: Sway motion in time series from model experimental at wave frequency 0.4297 Hz and wave height 0.0988 m

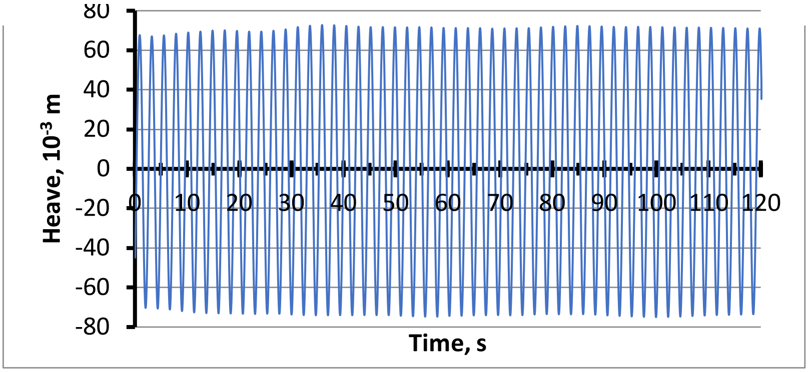

Figure 11: Heave motion in time series from model experimental at wave frequency 0.4297 Hz and wave height 0.0988 m

According to Figure 10, the sway motion experienced the wave frequency motion at this wave condition. The effect of drift force and mooring lines is significant to the pattern of sway motion in this head wave condition; it caused the semi-submersible to experience a continuous slow varying motion from the port to the starboard.

The slow varying motion can be observed from every peak point of sway motion in Figure 10. In terms of magnitude, sway motion demonstrated good characteristics, since the value is insignificant compared to the surge and heave motion. The maximum amplitude of sway motion in Figure 10 is around 0.003 m. With this magnitude, it has showed the effects of sway motion are very insignificant to the mooring lines tensions. To keep their positioning during the operation due to sway effect, this type of floating structure showed the good performance.

According to Figure 9, the effect of the mooring lines tensions caused a difference in the amplitude of the surge motion between forward and aft of semi-submersible, which looks significant for this wave heading condition. The amplitude for forward and aft are around 0.07 m and 0.05 m respectively. This behaviour has showed that, the mooring lines tension reach the peak point frequently in wave heading conditions. This surge motion only experienced the wave frequency motion.

Compared to the sway motion, the motion of surge and heave only experienced the wave frequency motion. According to Figure 11, the amplitude of heave motion is around 0.07 m. At this wave frequency, the heave motion experienced the resonance, where the computed heave RAO is around 1.42. These translation motions show that the symmetrical semi-submersible has good dynamic behaviour in a wave frequency of 0.4297 Hz.

Conclusions

This paper presented an experimental technique to investigate the hydrodynamic behaviour of moored semi-submersibles in regular waves. In the experiment, the symmetrical semi-submersible was setup in wave heading conditions scaled down from the full-scale size. The examples of time series motion data collected from the model experiment in a wave frequency of 0.4297 Hz and wave height 0.0988 m, were detailed in the paper. The sway motion of symmetrical semi-submersibles experienced two types of motions, namely, slow varying motion and wave frequency motion. In addition to collecting the samples of time series data, it also showed that the experiment was successful to capture the motion response of the symmetrical semi-submersible model due to the incoming or heading waves condition.

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