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# Experimental Investigation of Motion and Wave Induced Forced on Semi-Submersible in Regular Wave

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## ABSTRACT

For the design of safe and economic offshore structure the knowledge of the wave environment and related wave-structure interactions is required. In general, frequency domain analysis has been regarded as an adequate tool for the assessment of motion and loads which are needed to derive the stress and hydrodynamics forces as well as operational limitations. For investigating the behavior of response to specific sea conditions, this research analyzes the behavior of the response due to motion and wave forces as well as hydrodynamics with focus on a type square column. The frequency domain investigation has used to provide the response behaviors on the wetted body of the semi-submersible in regular waves. For investigation,, the selected sea condition for regular wave is generated in a physical wave tank, and the behavior of the response on the semi-submersible is evaluated at model scale. Equation of motion was formulated to evaluate the added mass, damping and stiffness at every frequency step. In frequency domain analysis, the hydrodynamics responses were obtained.

**KEY WORDS:** *Experimental Investigation; Wave Induced 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 increased water depth make the semisubmersible 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].

Following a few catastrophic accidents involving mobile offshore drilling platforms, various studies were carried out to investigate the adequacy of stability criteria applied to offshore mobile platforms which followed an empirical basis considering service experience accumulated for ships over many years [3]. Sea keeping performance is of significant importance in vessel design due to the stationary nature of drilling and production platforms. For the purpose of the sea keeping design, its response assessment to environmental forces is evaluated using either physical experiments or computational simulations.

## 2.0 LITERATURE REVIEW

When designing an offshore structure, one of the first and most critical steps is to choose an appropriate method of computing the exciting force on the structure as well as the motion of structure [4]. There have some standard method to predict response on the floating structure for examples are model experimental method, full scale measurement method and the numerical method. For the computational, the wave diffraction theory as well as the empirical Morison theory is the popular method to determine the response on offshore structure. These methods has been discovered by the some researchers [4,5,6,7] and was showed the applicable results to analysis the response of floating structure.

Now a day, these methods have made much progress in contributing to the theoretical prediction of hydrodynamic forces and moment and also motion of floating structure [8]. At the same boat, even gave the contribution to predict the force and motion of floating structure but still produced the different value of results compare to the other method. According to the research conducted by Kudo and Kinashita (1981) and Mio, et al., (1985) mentioned the results from the numerical method and experimental method was different [9]. Even have more than hundred percent different at a certain frequency range of horizontal oscillation from the corresponding experimental values [9].

Although the force and moment and also the motion can be assessed either in full scale trial or model testing or in computational method but the combination of the various methods would be stronger performance prediction for the floating structure [10]. However, the accuracy of computational predictions needs to be confirmed by the others results such as experimental results [9]. The present research was carried out the experiment analysis to get the overview of the hydrodynamic behavior of semi-submersible in regular waves.

## 3.0 MATHEMATICAL MODELING

The analysis carried out was based on a simple mathematical model replacing the structure by mass spring system. The following basic assumptions were used: -

i. The structure behaves as a rigid body having six degrees of freedom only.
ii. The motions are uncoupled which one motion does not affect other motions.
iii. The complex sea state can be represented by a combination of an infinite number of sinusoidal waves.
iv. The response is linear represent the theory of superposition is valid, which means that the total response can be taken as a sum of responses due to individual sinusoidal excitation forces.

### 3.1 Component of Force

The forces involved in the equation of motion are divided into excitation forces and reaction forces. Usually, excitation forces of an any vessel are a component derived directly either from wave or wind force. In responses to the excitation forces, the vessel produces reaction forces (radiation forces). The following is the description of radiation forces (inertia forces, damping forces and restoring forces) and excitation forces

The radiation forces are defined as the force resulting from the radiation of the wave away from a vessel that forced the vessel to oscillate in calm water [11]. The solution of the radiation forces is usually related to the determination of the added mass and damping coefficient. The added mass term is part of the hydrodynamic force due to the motion in phase of acceleration. The damping term is part of the hydrodynamic force due to the motion in phase of velocity. Various techniques have been developed to compute the terms of added mass and damping.

Restoring force is part of the radiation force. In a physics context, is a variable force that gives rise to an equilibrium in a physical system. If the system is perturbed away from the equilibrium, the restoring force will tend to bring the system back toward equilibrium. Restoring force is calculated by multiplying the water plane area with the density of water and the acceleration of gravitational.

### 3.2 Equation of Motion

To find the force is very complex thing. Thus, two important assumptions are made to predict the force acting on floating body [12]. The assumption made is there is no wave and the body is made to oscillate in $z$ direction. Hence the force acting is hydrodynamic force, $F_h$. And for the other assumption made is the body has been fix and the wave coming to hit the body. Hence the force acting is wave force or exciting force, $F_w$.

$$F_h = -(\rho.g.A_w)\, z - (a)\, \ddot{z} - (b)\, \dot{z} \qquad (1)$$

Where: $\rho$ = density of water; $g$ = gravitational acceleration; $A_w$ = water plane area; $a$ = hydrodynamic reaction in phase with acceleration (added mass); $b$ = hydrodynamic reaction in phase with velocity (damping).

According to the Newton Second law, a body of mass, $m$ subject to a force, $F$ undergoes an acceleration a that has the same direction as the force and a magnitude that is directly proportional to the force and inversely proportional to the mass. Alternatively, the total force applied on a body is equal to the time derivative of linear momentum of the body.

$$m \times \ddot{z} = F \qquad (2)$$

$$m \times \ddot{z} = F_h + F_w \qquad (3)$$

$$m \times \ddot{z} = -(\rho.g.A_w)z - (a)\, \ddot{z} - (b)\, \dot{z} + F_w \qquad (4)$$

$$(m + a)\, \ddot{z} + b\, \dot{z} + cz = F_w \qquad (5)$$

The single degree of freedom system moving in the direction of the analogous spring mass system gives the equation (5). With:

$$z = z \cos(\omega t - \varepsilon) \qquad (6)$$

$$\dot{z} = -z\omega \sin(\omega t - \varepsilon) \qquad (7)$$

$$\ddot{z} = -z\omega^2 \cos(\omega t - \varepsilon) \qquad (8)$$

$$F_w = f \cos(\omega t) \qquad (9)$$

Where: z = displacement; $\dot{z}$ = velocity; $\ddot{z}$ = accelaration. After Substituting (6), (7), (8) and (9) in (5) obtained:

$$-(m + a)(z\omega^2 \cos(\omega t - \varepsilon)) - b(z\omega \sin(\omega t - \varepsilon)) + c(z \cos(\omega t - \varepsilon)) = f \cos(\omega t) \qquad (10)$$

Which provides:

$$a = \frac{1}{\omega^2}\left(c - \left(\frac{f \cos \varepsilon}{z}\right)\right) m \qquad (11)$$

$$b = \left(\frac{f}{z\omega}\right) \sin \varepsilon \quad (12)$$

$$c = \rho.g.A_w \quad (13)$$

## 4.0 EXPERIMENTAL APPROACH

There are four main part of experiment, which will be described in this chapter. The first part will be 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 centre 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 and third part will be described on the experiment to determine the wave excitation and force oscillation test on the structure by using the Six Component measurement system. The last part will be described on the experiment to determine the RAO of the structure using the optical tracking system. All experiments ware conduct in regular waves frequencies.

For the experiment, a scaled model of a semi-submersible has a square pontoon. 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 1and Figure 2.

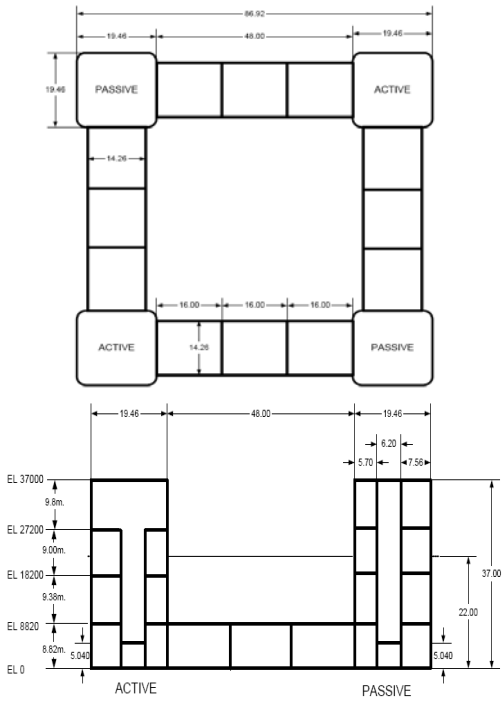


Figure 1: Main dimension of semi-submersible.

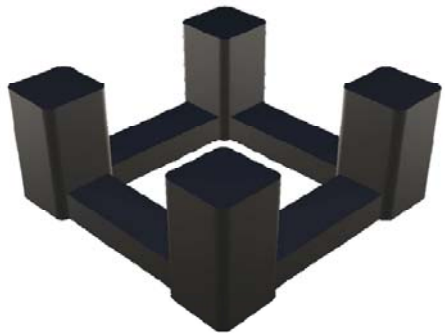

Figure 2: 3-dimension (3D) view of model.

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 water to the appropriate draught. However, the final adjustment of weight was done by considering the four draft marks at each column. The centre of gravity and the metacentric of the model was obtained using inclining test. The detail of the procedures is given in the following sections as well as the decay test, swing test and spring calibration.

### 4.1 Model Preparation Analysis

From the experiment, the analysis of result is done by measuring the parameter using the formula and particular value which are obtained from the test. Table 2 shows the summary of results of model preparation test conducted.

Table 1: 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 |

Table 2: Semi-submersible particulars.

| 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 | 0.448 | 36.32 | m |

| | | | |
|---|---|---|---|
| gyration, $K_{yy}$ | | | |
| 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 |

The experiments for all tests were conducted in range of frequency of oscillation. The experiment conditions for the semi-submersible assessment for force and wave excitation as well as its motion prediction are based on the requirement given as follow:

i. Range of frequency is between 0.4297 Hz to maximum 1.7189 Hz.
ii. Constant amplitude = 0.049 m.

In Table 3 showed the frequency of oscillation that has been chosen with the constant amplitude.

Table 3: 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 |

### 4.2 Wave Excitation Test

The tests were performed in towing tank with measurements 120X4X2.5 m in length, breadth, and depth respectively. Test using the Six Component Force Measuring System consists of two frames (upper frame and lower frame) interconnected by means of six transducers like in Figure 3. Forces and moments (in a Cartesian coordinate system) can be determined from the measurement of the six transducers. A towing carriage carrying recording equipments was fixed at 60 m from the wave generator. Six Components will attach to the model and the Planar Motion Mechanism (PMM) on towing carriage as showed in Figure 4.

The wave generator was started after sometime when the wave was passing through the model then the reading start to record. The measurement has record up to about 120 seconds.

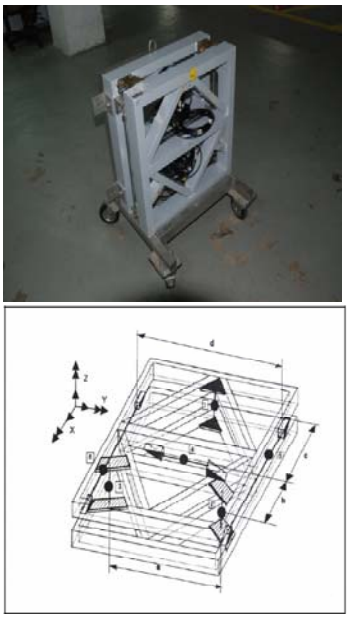

Figure 3: Six Component Force Measurement System.

Figure 4: Wave Excitation Test.

### 4.3 Force Oscillation Test

Forced oscillation test involved oscillating the model at a particular frequency and amplitude of oscillation. The test was completed to allow calculation of added mass/inertia and damping coefficients. Testing has used the Six Component Force Measuring System. This equipment is designed to be used with the Planar Motion Mechanism (PMM). When the PMM is stationary, hydrodynamic forces from water flow along the model or from waves can be measured. When the PMM is moving, the hydrodynamic reaction forces acting on the moving model can be determined.

The model with the system is positioned under the carriage and the extenders are connected to the cardan joints of the PMM. In force oscillation test, the force has applied to the model at particular frequency to measure heave force oscillation. All the measurement has recorded by data acquisition and analysis

system (DAAS).

### 4.4 Motion Test

The motion measurement may be accomplished by a light mechanical system having linear and angular potential transducers for direct measurement of responses [13]. A non-contacting method, such as an optical tracking system with the associated software is a better alternative for small structures or components. Unlike the mechanical systems, it requires no adjustment in the ballast in the model.

There are two types of force motions tests. Test in the regular wave and experiment in the irregular wave. But in this research, test has conducted only in regular wave. The motion test was conducted in the similar wave condition that has been used in force oscillation test .The test set-up of the model is showed in Figure 5 and Figure 6. Soft spring used in this test as mooring lines and the optic tracker was used to capture the motion of model in regular waves. Optic tracker has used is Qualysis which is the high speed camera to capture the motion from the ball maker that has been fix on the model. Model of semi –submersible has a mooring system arranged in four lines with springs in such a way that the overall horizontal spring stiffness which is 0.26 N/cm corresponds to the prototype value of 171kN/m.

Before the test, the mooring line will attach to axial riser force and column. Mooring lines was calibrate so that the stiffness become 0.26 N/m by attached the ring gauge at the end of the spring at column side. The ring gauge will measured the force acting on the mooring line. 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. Qualysis Track Manager has been used to analysis the motion of the model. The motion captured by the optic tracker was directly analysis by this software to the value of six degree of freedom (heave, surge, sway, roll, pitch and yaw).

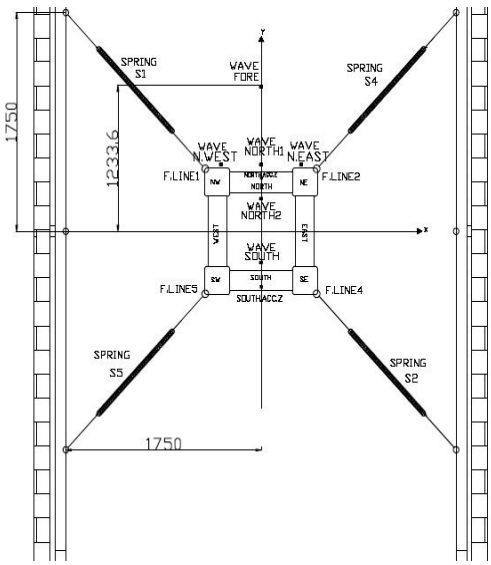


Figure 5: Test setup of model in head sea

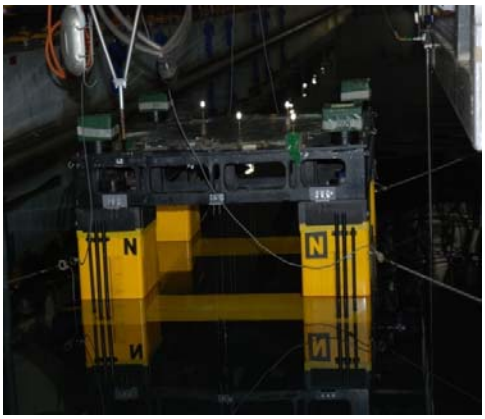

Figure 6: Motion test.

## 5.0 ANALYSIS OF THE OUTPUT

This section put emphasis on the analysis of the exciting force and wave as well as the hydrodynamic force of the semi-submersible that obtained from the experimental. Then it concentrates on the motion response in term of RAO from experimental approach.

### 5.1 Wave Excitation Test

The exciting wave has been obtained from the experiment by using the six component measurement system provides all the force and moment acting on structure. But in this research only the heave, roll and pitch moment has been considered to investigate. The result from the experimental illustrated the response of wave excitation at particular frequency. All the forces and moment is plotted on a base of frequency in radian/second as showed in Figures 7 - 9.

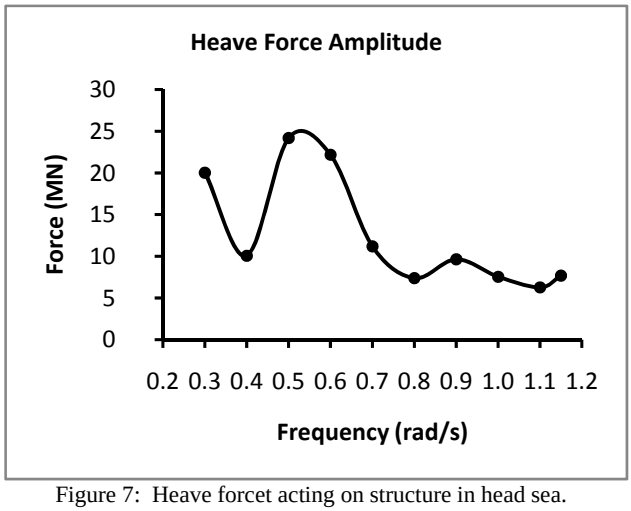


Figure 7: Heave forcet acting on structure in head sea.

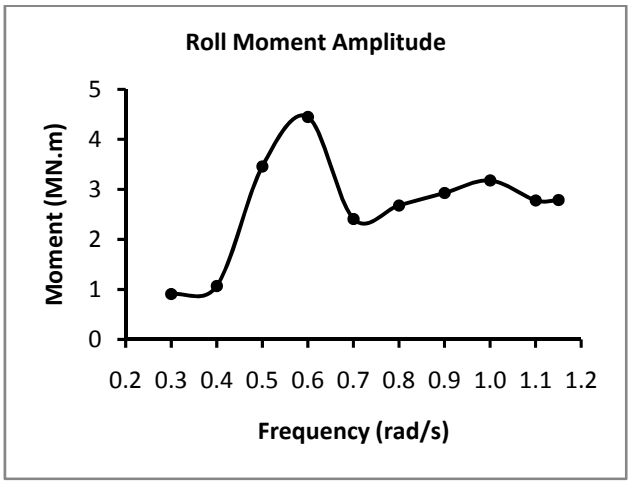


Figure 8: Roll moment acting on structure in head sea.

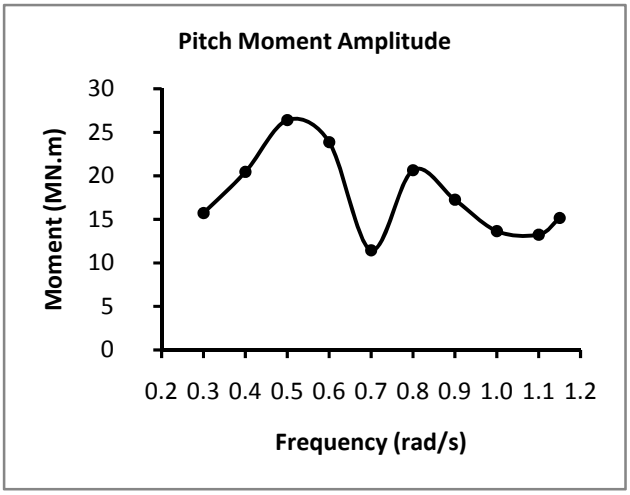


Figure 9: Pitch moment acting on structure in head sea.

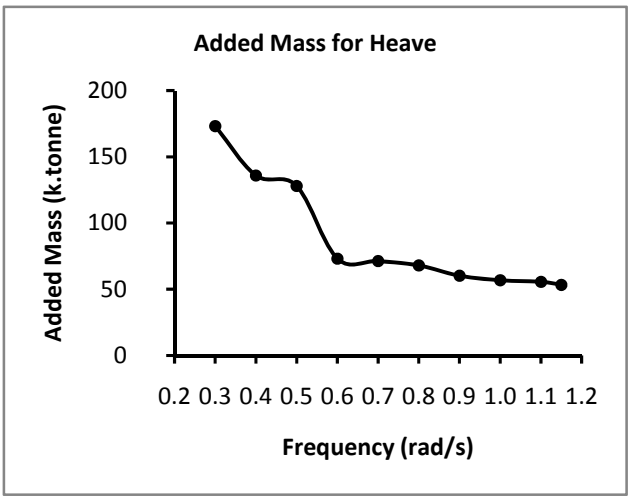


Figure 10: Dimensional added for heave.

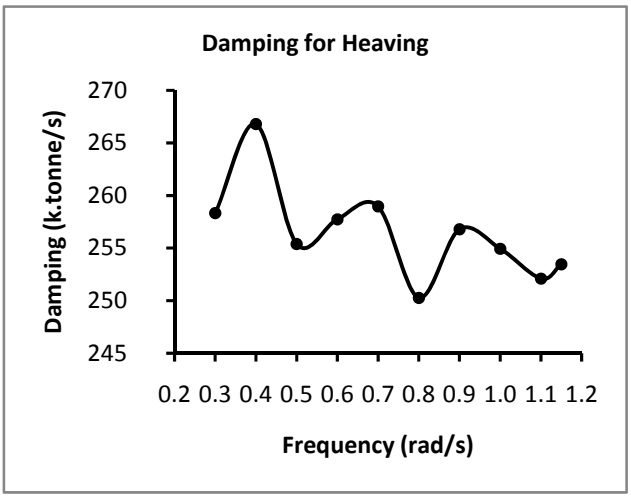


Figure 11: Dimensional damping for heave.

**5.2 Force Oscillation Test**

The investigation of the hydrodynamics response in regular wave was obtained from the information that has been obtained from the force oscillation test. The hydrodynamic responses which are the added mass and damping was analyzed by using the mathematical modeling in equation (11) and (12). This section will illustrate the hydrodynamic response of the experimental as showed in Figure 10 and Figure 11.

**4.3 Response Amplitude Operator (RAO)**

Usually the linear RAO is expressed in m/m and angular motion RAO is expressed in degree/meter. All the RAO also are plotted on a base of frequency in radian/second. Only the heave, roll and pitch moment have been considered to investigate.

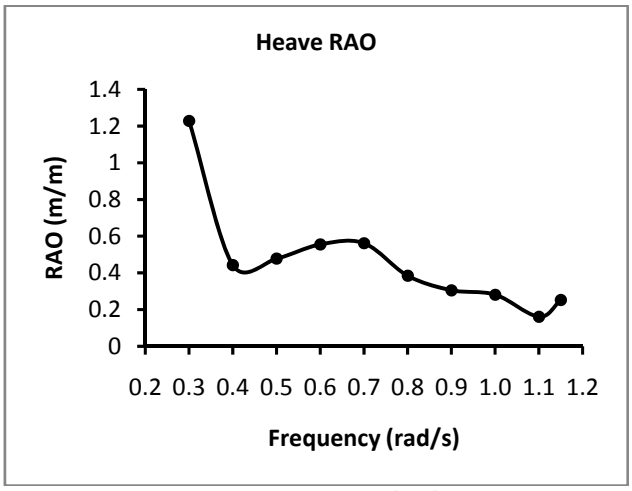


Figure 12: Heave RAO in head sea.

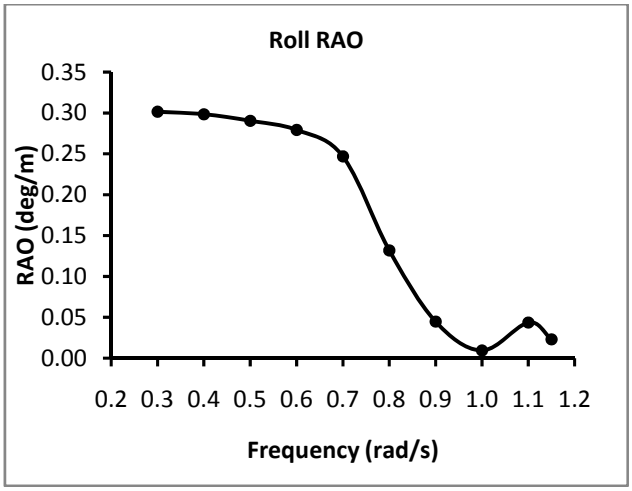


Figure 13: Roll RAO in head sea.

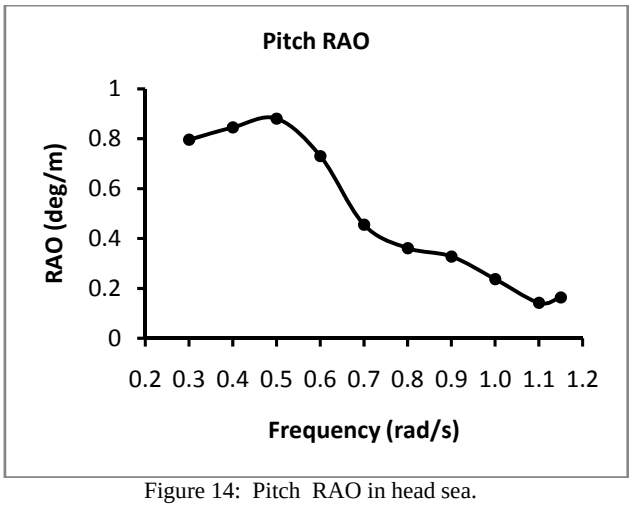


Figure 14: Pitch RAO in head sea.

## 6.0 DISCUSSION

The maximum heave forces, roll and pitch moments were found to be prominent at range frequency 0.5-0.6 rad/s, which are 24.20 MN, 3.46 MN.m and 27.2 MN.m respectively. Wave excitation test showed that in wave heading the roll moment is much lower compared to pitch moment. Almost along the frequencies she behaves with similar trend.

Roughly, trend of heave added mass decrease gradually with increasing frequency. The added mass showed at the lower frequency the value of added mass for heave is higher. It is because, for lower frequency the value of heave added mass is balanced by the increasing exciting force. Peak value of heave added mass at frequency 0.3 rad/s were 173.23 k.tonne. Heave damping showed the trend of the curve is not uniform. Peak value of experimental heave damping occurred at wave frequency 0.4 rad/s of 266.81 k.tonne/s. While at frequency 0.8 rad/s the damping showed the dip value, heave damping at this wave frequency is 250.26 k.tonne/s.

Heave and roll RAO have peak value at initial frequenncy with 1.23 m/m and 0.30 deg/m respectively. While the peak value RAO of pitch accour at frequency 0.5 rad/s which is 0.88 deg/m. Due to trend curve there is quite similar between roll and pitch. The roll RAO decreased from the maximum RAO of 0.30 deg/m to almost nil at frequency 1.0 rad/s. Maximum pitch RAO was 0.88 deg/m at the frequency 0.5 rad/s. The response then gradually decreased to minimum RAO at frequency 1.1 rad/s.

The most important things to consider about the experiment are their setup. An improperly ballasted model can cause wrong results. In the force oscillation test and motion test of semi-submersible the regular wave was generated to find the hydrodynamic and the RAO respectively at particular frequency. Although the aims of the experiment are to find the hydrodynamic and motion response in regular wave but practically was not happened in higher frequency. The wave form regular only at the beginning of experiment, when wave start to hit the column the reflection of the wave make the wave become irregular along the experiment. Model experiment cannot cover the real situation fully, however it gives us valuable information about the real situation, that was causes difference in comparing results.

## 7.0 CONCLUSION

The prediction of exciting force and moment as well as the motion response of semi-submersible is considered to be a complex matter as compared to the others vessel. Calculation of exciting force and moment are important to see the overview of the added mass and damping for semi-submersible. In addition to that, the motion responses are important in assessing the performance of the semi-submersible.

Even though the investigation of the response of floating structure had been carried out widely but more validation studies remain necessary to improve the computational methods and to establish the range of their applicability [15].

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.

The present study successfully described the methods of investigate the hydrodynamic response and assessing motion response performance of a semi-submersible in sea state.The exciting force and moment obtained from this research can be used to predict the exciting force and moment of semi-submersible same type dimension which operating in same range of frequency with this experiment.

**ACKNOWLEDGEMENT**

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