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Experimental Study on Effect of Mooring on Motion Response of Rounded-Shape FPSO Model

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ABSTRACT

This paper discusses the motions response of moored rounded-shape FPSO model due to the wave effect. The research analyzed the possibility of wave motion response of rounded-shape FPSO model affected by different mooring systems. Experiment of a scale FPSO model of 1:112 was conducted in basin tank at the National Research Institute of Fisheries Engineering, Japan. In the experiment, the FPSO model was firstly tested by attaching model scale of Catenary mooring lines to rounded-shape FPSO model. Then the experiment was repeated by attaching model scale of Taut mooring lines to the rounded-shape FPSO model. Comparing results obtained using Taut and Catenary mooring lines in regular wave were presented. This research concluded that the mooring systems would not give significant effect to wave frequency motion response of the rounded-shape FPSO.

KEY WORDS: *Round Shape FPSO; Wave Motion Response; Taut; Catenary; Mooring Systems.*

1.0 INTRODUCTION

Deep water oil and gas exploration is a costly industry activity due to the required of high technology level during exploration. In deep water region, floating structures is more comparative compare to fix structure. To control the movement of floating structure mooring system can be applied if the water depth is within reasonable depth. Generally, two types of mooring system available there are catenary mooring and taut mooring. Both the mooring system is applying in offshore industry to control the movement of most of the floating structures currently.

Besides, the new Round Shape FPSO model is selected as the model to test in this study where the motion response of this designed FPSO attached with mooring was tested in the motion experiment. In term of system requirement, the FPSO is required better performance in stability either static or dynamic condition compare to resistance performance. The different of operation requirement causesrelated industry to develop new generation FPSO with more practical hull form to the offshore desire.

In year 2008, Lamport and Josefsson, (2008) carried a research to study the advantage of round shape FPSO over the traditional ship-shape FPSO [1]. The comparisons were made to compare motion response, mooring system design, constructability and fabrication, operability, safety and costing between both the structures. One of the finding on their study is themotions of their designed structures are similar at any direction of incident wave with little yaw excitation due to mooring and riser asymmetry. Next, Arslan, Pettersen, and Andersson (2011) are also performed a study on fluid flow around the round shape FPSO in side-by-side offloading condition. FLUENT software was used to simulate three dimensional (3D) unsteady cross flow pass a pair of ship sections in close proximity and the behavior of the vortex-shedding around the two bluff bodies [2].Besides, simulation of fluid flow Characteristic around Rounded-Shape FPSO by self-develop programming code based on RANs method also conducted by A. Efi et al.[3].

In this paper, the effect of mooring to the FPSO motion response is studied by experiment method. The wave motion experiment was conducted by attached the model scale catenary mooring to the Round FPSO and then the same test was repeated by replace the model scale catenary mooring with taut mooring. These wave tank experiments were conducted in National Research Institute of Fisheries Engineering (NRIFE), Japan in regular wave condition using 1:110 of Rounded-shape FPSO model scale. The model also fixed in the wave tank with model scale mooring line so the experiment can capture the wave frequency motion and slow drifts motion [6]. The mooring design is conducted before the experiment so the suitable mooring line is applied to achieve the experiment target [7]. In this paper, the main discussions are focused in the effect of difference mooring system to the motion of Round Shape FPSO. The motion experiments results collected by fixed the FPSO with catenary mooring and taut mooring are compared. The comparison showed that both the mooring system do not give significant effect on Round Shape FPSO wave frequency motion.

2.0 MODELLING RULE

In this study, the FPSO model and mooring lines in model scale are scaling follow the Froude similarity. Froude's law of similarity is the most appropriate scaling law applicable for the free and moored floating structure experiments. The Froude number has a dimension corresponding to the ratio of u^2/gD where u is the fluid velocity, g is the gravity acceleration and D is a length of the model or prototype. The Froude number Fr is defined as $Fr = u^2/gD$.

Let the subscripts p and m stand for prototype and model respectively and λ is the scale factor, then the scaling for length, speed, mass and force is shown in Table 1.

Table 1: Scaling law between model and prototype [4].

Dimension	Scaling equation
length, l (m)	$l_p = \lambda l_m$
speed, u (m/s)	$u_p = \sqrt{\lambda} u_m$
mass, m (kg)	$m_p = \lambda^3 m_m$
Force, F (N)	$F_p = 1.025\lambda^3 F_m$
Mooring line stiffness in water, K (N/m)	$K_p = 1.025\lambda^2 K_m$

3.0 WAVE TANK EXPERIMENT

3.1 Mooring Selection

In this experiment, four model scale mooring lines attached to the Round Shape FPSO to provide horizontal restoring force to the model. The catenary mooring lines in full scale is designed by using the catenary theory and then scaled down to model scale follow by the scaling rule. The mooring line profile used in this experiment is showed in Figure 1 and the segment particular is showed in Table 2.The size of these mooring lines is pre-determined before the model experiment and the suitability of the mooring lines is analyzed using numerical simulation method to simulation the mooring performance in both static and dynamic condition.

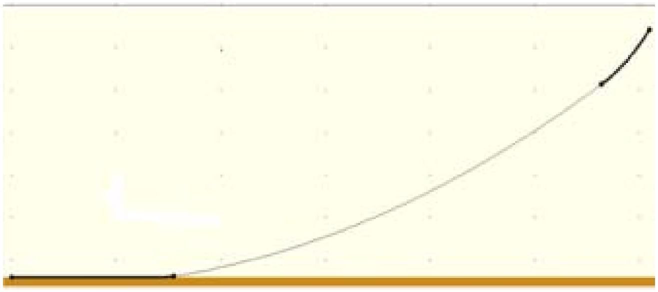

Figure 1: Mooring line profile

Table 2: Model catenarymooring line segment information

Particular	Segment A	Segment B	Segment C
	Model	Model	Model
Nominal Diameter (mm)	3.0	3.0	3.0
Type	Chain	Wire Rope	Chain
Segment Length (m)	4.0	9.4	1.4
Air Weight (kg/m)	0.16	0.0369	0.16
Water weight in water (kg/m) Model scale water density: 1000kg/m^3	0.1425	0.03119	0.1425
Breaking Load (KN)	10.79	5.40	10.79
Modulus Elasticity (GPa)	114.59	61.00	114.59

The second mooring lines applied to control the motion of FPSO were prepared based on taut mooring concept. By consider the depth of water tank and the size of model; the model scale mooring lines have the length of 14.5 meters each line. The whole mooring lines attached in this test was made from same material. The segment information of the taut mooring lines applied in the model experiment as in Table 3:

Table 3: Model taut mooring line segment information

Particular	In Model Size
Nominal Diameter (mm)	3.0
Type	Wire Rope
Segment Length (m)	14.5
Air Weight (kg/m)	0.0369
Water weight in water (kg/m) Model scale water density: 1000kg/m^3	0.03119
Breaking Load (KN)	5.40

Modulus Elasticity (GPa)	61.00

3.2Experimental Setup
This experiment is conducted in wave dynamic tank with the length, wide and depth of 60m, 25m and 3.2m respectively. Before the experiment start, the Round FPSO model was fixed in the middle of tank by four mooring lines which connected between the fairleads located in bottom of FPSO with the anchors which sink into the bottom of tank. Each anchor used in the experiment has the weight of 20kg in air. The position of the anchors and the arrangement of the mooring lines inside the tank were same for both catenary mooring test and taut mooring test. The mooring arrangements are showedin Figure 2 and the view of FPSO model inside wave dynamic tank after installed with mooring lines is showed in Figure 3.

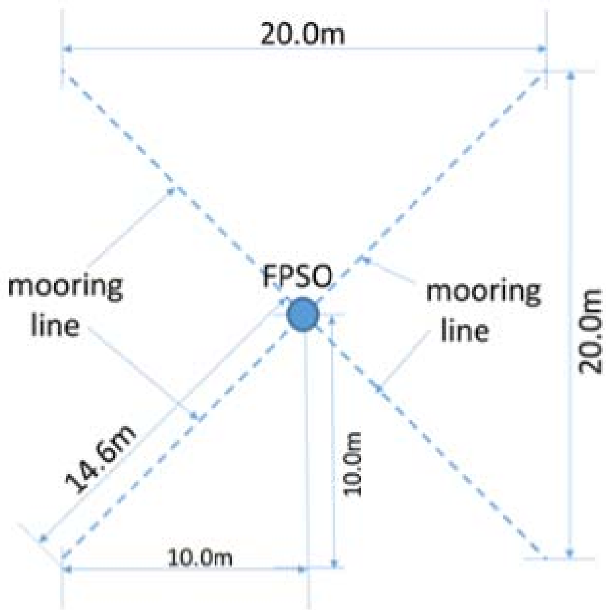

Figure2: Arrangement of mooring lines and anchor in wave basin.

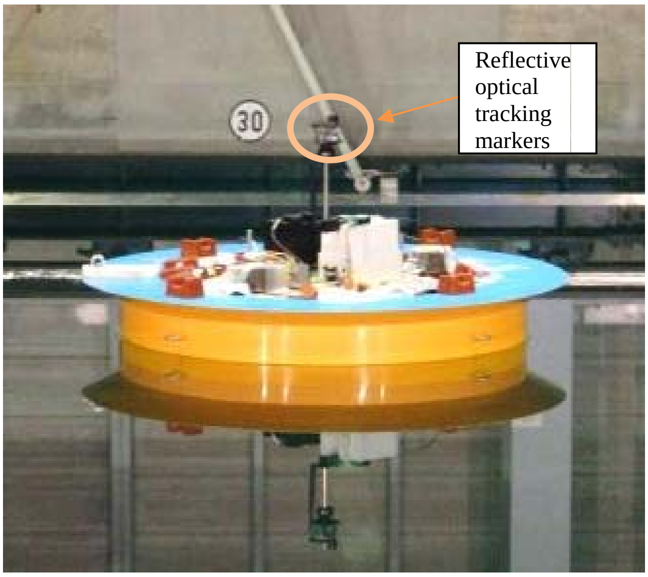

Figure3: FPSO model fixed with mooring lines in wave basin in static condition.

The round shape FPSO model is experienced six degrees of freedom during the experiment. The linear DOF motions of the FPSO models on model size mooring are measured by theodolite camera system. The theodolite camera is able to capture the positions of the reflective optical tracking markers placed on the FPSO model automatically. In this setup, the height of the reflective optical tracking markers is 0.547m above the vertical center of gravity of the Round Shape FPSO model[6]. The Rotational DOF motions of the FPSO models are measured by gyroscope installed in the center of gravity of the FPSO.

A servo-type wave height measurement device (Servo 式波高計) is attached to the carriage which located at the position between FPSO model and wave generator to record the wave height generate by the wave generator. To ensure the wave height measure by wave measuring device is not influence by the exist of Round FPSO, the carriage installed by the servo-type wave height measurement device is moved to the location where the distance between the FPSO to wave measuring device and the distance between wave generator to wave measuring device are 15mboth.

All the measurement devices are linked to separate computer to maximize the consistency of the measuring speed. To synchronize the devices and ensure all devices start and stop measure the data without delay, a Wireless remove is used to given the order to start and stop all measurement devices [6].

3.3 Linear Motion Data Transformation
As mentioned, the height of the reflective optical tracking markers is 0.547m above the vertical center of gravity of the Round Shape FPSO model. This also means that the position of the FPSO in wave tank measured by the theodolite camera is not located at the center of gravity of the model. To obtain the exact position of the model referred to model's the center of gravity, the linear motion data must be transferred to the center of gravity of the model. To transfer the data, respective roll, pitch and yaw

motion of the model occurred at the same time must be considered in the calculation. The relationships between the positions of the reflective optical tracking markers with the position of center of gravity of model by consider the roll, pitch and yaw motionsare showed in Figure 4.

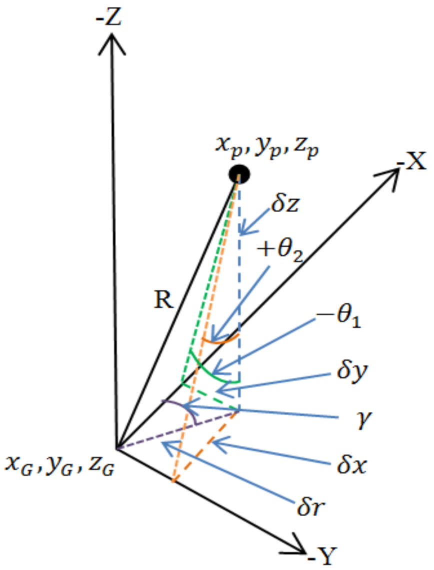

Figure 4: The relations between the positions of reflective optical tracking markers with position of center of gravity of model

From the Figure4,x_p, y_p, z_p represent the x, y and z position of the reflective optical tracking markers while x_G, y_G, z_G are the x, y and z position of the center of gravity of model. The relationship between both the position is in the function of length of rod, R, roll angle (θ_1), pitch angle(θ_2), yaw angle (θ_3) and model initial heading angle (γ). Therefore, the position information at model center of gravity can be calculated as follow:

$$x_g = x_p - \delta x \quad (1)$$

$$y_g = y_p - \delta y \quad (2)$$

$$z_g = z_p - R + \delta z \quad (3)$$

Where, $\delta x, \delta y$ and δz can be calculated by following equation

$$\delta z = \left[\frac{R^2}{Tan^2(\theta_1)+Tan^2(\theta_2)+1}\right]^{1/2} \quad (4)$$

$$\delta r = [R^2 - \delta z^2]^{1/2} \quad (5)$$

$$\alpha = Tan^{-1}\left(\frac{Tan\,\theta_1}{Tan\,\theta_2}\right) \quad (6)$$

$$\delta x = \delta r\ Cos(\theta_3 + \alpha + \gamma) \quad (7)$$

$$\delta y = \delta r\ Sin(\theta_3 + \alpha + \gamma) \quad (8)$$

After the position of model referred to its center of gravity is obtained for entire time series, the information can be used to calculate all 6 degree of motions of model. In this experiment setup, the Rotational motions of the FPSO models are measured by gyroscope installed in the models' center of gravity, hence, the measured roll, pitch and yaw motion by the gyroscope can be directly used for the model rotational motions data. However, extra treatment is needed for the linear motions which measured by theodolite camera because the time domain position data obtained from the theodolite camera is the model position in the wave tank without consider it direction. By consider the model initial position and initial heading direction, the position data returned from theodolite camera can be used to obtain the model surge, sway and heave motion. In Figure 5, the plan drawing showed the different of global coordinate where these data are measured by theodolite camera and the local coordinate system which required in calculating the linear motion of the FPSO due to the wave.

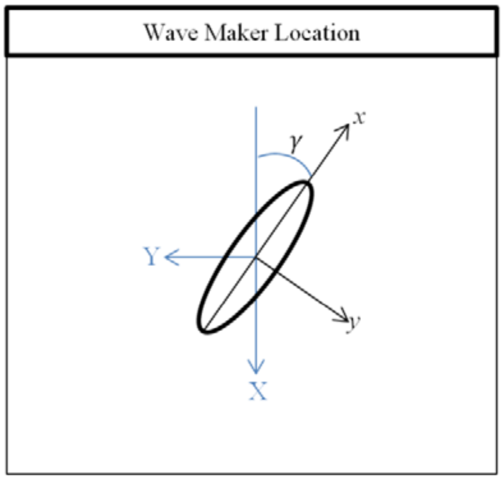

Figure 5: Plan view of coordinate system.

In Figure 5, X and Y represent the global direction use in the experiment setup while x and y are the local direction where the zero position of local coordinate system is located in the model center of gravity before the wave arrived. The model initial heading angle (γ) is measured from wave progress direction and positive follow clock direction. By reset the zero global coordinates to the model center of gravity at calm sea condition, the 6 DOF motions of the model can be calculated as follow,

$$L = (X^2 + Y^2)^{1/2} \quad (9)$$

$$\beta = Tan^{-1}\frac{Y}{X} \quad (10)$$

And the six degree freedom of motion for the Round Shape FPSO can be calculated from the equation (11) to equation (16).

$$Surge, E_1 = L\ Cos(\beta - \gamma + 180) \quad (11)$$

$$Sway, E_2 = L\ Sin(\beta - \gamma + 180) \quad (12)$$

$$Heave, E_3 = Z_g \quad (13)$$

$$Roll, E_4 = \theta_1 \quad (14)$$

$$Pitch, E_5 = \theta_2 \quad (15)$$

$$Yaw, E_6 = \theta_3 \quad (16)$$

3.4 Fourier Series Transformation

The experiment data collected in time series provide the information of wave frequency motion for all 6 degree of motion and slow drift motion for horizontal plan motion. To split the different motion data, the analysis can be conducted in frequency domain where the amplitude of the different types of motion can be extracted from the motion amplitude occur at respective frequency.

According to sampling theorem, discretely frequency (Fs) of signal data must be at least twice to the highest continuous signal frequency (F). The continuous signal frequency should discrete by the rate follow the sampling frequency, 1/Fs. Let the discrete sample of the continuous signal have the magnitude of x(k), k=1,2,3,…,n and period between the sample is 1/Fs than a function of a continuous signal, f(t) can be reconstructed back from the discrete sample by the equation below:

$$f(t) = \sum_{k=1}^{k=n} x(k)\, sinc(t \times fs - k) \quad (17)$$

Where,

$$sinc(x) = \frac{\sin(\pi x)}{\pi x} \quad (18)$$

To convert the data in time domain to the frequency domain, Fast Fourier Transform method can be applied. The relationship between function in the time domain, f(t) and frequency domain F(f) can be related by the equation below:

$$F(f) = \int_{-\infty}^{\infty} f(t) e^{-j2\pi f(t)} dt \quad (19)$$

Also, for the variable *j*, it represents the square root of (-1) in the natural exponential function.

$$e^{j\theta} = \cos(\theta) + j \sin(\theta) \quad (20)$$

Therefore, the discrete data can be written in complex number form as follows:

$$x_i = x(i)_{real} + j\, x(i)_{imaginary} \quad (21)$$

And,

$$x(i)_{real} = \sum_{k=0}^{k=n} X(k) \times \cos\left(\frac{2\pi ki}{n}\right) \quad (22)$$

$$x(i)_{imaginert} = \sum_{k=0}^{k=n} X(k) \times \sin\left(\frac{2\pi ki}{n}\right) \quad (23)$$

And, $i = 2^b$ is the number of data require by Fast Fourier Transform method where b can be any integer number larger than or equal to 1.

Finally, the magnitude, phase and frequency of the signal can be calculated by following equations:

$$X(i)_{magnitude} = \|X(i)\| = \frac{2\times\sqrt{x(i)_{real}{}^2 + x(i)_{imaginert}{}^2}}{n} \quad (24)$$

$$X(i)_{phase} = tan^{-1}\left[\frac{x(i)_{imaginert}}{x(i)_{real}}\right] \quad (25)$$

$$X(i)_{frequency} = i \times \frac{Fs}{n} \quad (26)$$

4.0 MODEL PARTICULARS

The objective of this research is predicting the wave motion response of new designed Round Shape FPSO and analyse the effect of mooring system to the wave frequency motion response. The designed Round Shape FPSO has the diameter at the draft equal to 111.98meters and draught of 31.91meters. The model was constructed from wood following the scale of 1:110 (Table 1).

Upon the model complete constructed, inclining test, and roll decay test were conducted to identify the hydrostatic particular of the Round Shape FPSO model. The dimension and measured data of the model was summarized as in Table 4.

Table 4:Particular of Round Shape FPSO

Symbol	Model	Fullscale
Diameter (m)	1.018	111.98
Depth (m)	0.4401	48.41
Draught(m)	0.2901	31.91
Free board(m)	0.150	16.5
Displacement (m^3)	0.2361	314249
Water Plan Area (m^2)	0.8139	9848.5
KG (m	0.2992	32.9
GM (m)	0.069	7.6

5.0 MOORING EFFECT ON ROUND SHAPE FPSO WAVE RESPONSE

The result of Round Shape FPSO surge, pitch and heave motion response characteristic predicted by experiment method is showed in Figure 6 to Figure 8. The motion experiment was conducted to the same model but fixed with different mooring system. In the beginning, the motion experiment was conducted with the Round Shape FPSO model fixed with catenary mooring system. After that the experiment was conducted to the Round FPSO model fixed with the taut mooring system. The experiment results were collected in time series with the sampling rate of 20 data per seconds. To identify the wave frequency motion of the model, the time domain data were converted to the frequency domain using Fourier series transformation method. And then, the motion magnitudes at the wave frequency were identified.

As shows in Figure 6 to Figure 8, the motion experiment results for model fixed with catenary mooring (red dot) and motion experiment results with model fixed with taut mooring (green mark) were plotted verses the wave length. The experiment conducted in the head sea condition, hence only the surge, pitch and heave motion is considered here. By compared the experiment results conducted with the model fixed with different mooring system, it is observed that the magnitude of wave frequency motions detected from the experiment is same for both experiments. Besides, the both set of experiments also show the same tendency with the numerical simulation results. From this observation, the results were shown that the type of mooring setup would not give significant effect to the model motion response if the wave frequency motion is considered more important than the slow drift motion.

The purposed of the mooring applied in the stationary keeping system is control the large offset movement of the floating structure. The movement control by mooring system is the slow drift motion where it is caused by the drift force from wave particle motion. Based on the theoretical review on predict the Round Shape FPSO Motion Response using diffraction potential and Morison, it is observed that the wave exciting forces act on the model surface are much higher than the drift forces [5]. In this situation, the mooring system which designed to absorb the lower drift forces could not influence much on the wave frequency motion of the model where it is induced by higher wave exciting forces. To highlight this discussion, the surge motion response of the Round Shape FPSO (Figure 6) can be referred as an example here. The surge motion is the horizontal plane motion where the movement on this plane is controlled by the mooring system. However, by comparing the surge RAO of Round Shape FPSO model when it fixed by the catenary mooring and the surge RAO of Round Shape FPSO model when it fixed by the taut mooring, it is showed that both set of the motion responses result collected from the experiments shown the similar tendency and almost similar magnitude of the motion response at any respective wave length. Obviously, the neglect of the mooring forces when study the wave frequency motion is acceptable since the effect is very limited in this type of motion.

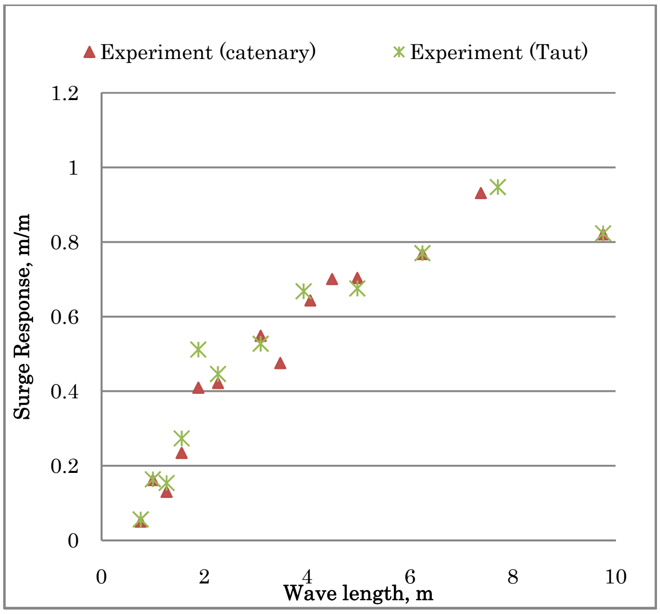

Figure 6: Surge motion responses of Round Shape FPSO

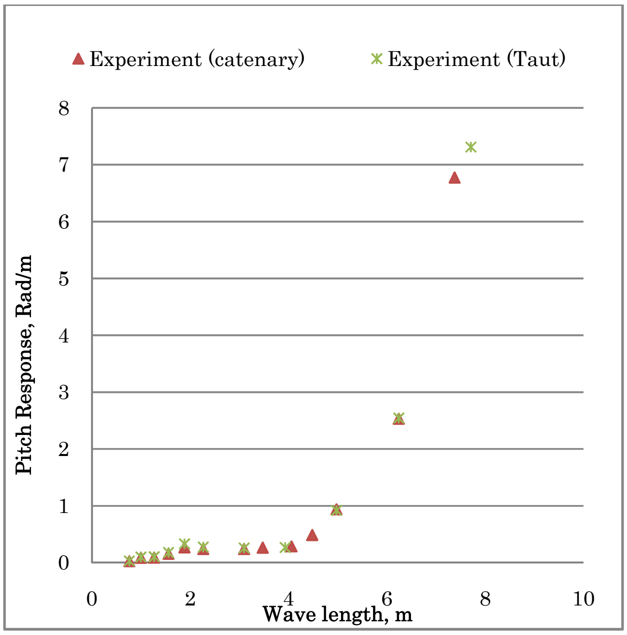

Figure 7: Pitch motion responses of Round Shape FPSO

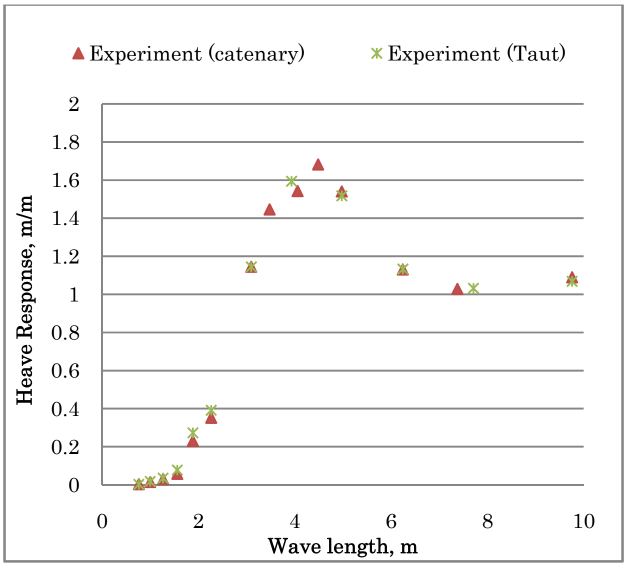

Figure 8: Heave motion responses of Round Shape FPSO

6.0 CONCLUSION

The study of the wave frequency motion of Round Shape FPSO is conducted by using experimental method in this research. To identify the effect of mooring system to the wave frequency motion, the motion experiments were conducted to the same Round FPSO model with two different types of mooring systems. Comparing both set of the experiment results, it is observed that the wave frequency motions responses are almost similar on both set of experiments results. The main reason of this observation also explained by comparing the magnitude of wave exciting force and slow varying drift force. The large difference between both types of forces act on the model caused the effect of mooring system which designed to absorb the slow varying drift forces only able to cause very limited effect to the wave frequency motion. The provided experiment results also showed that the neglect of mooring effect in study the wave frequency motion is possible where it do not show difference between both set of experiment results.

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