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EXPERIMENTAL STUDY OF MOTIONS OF TWO FLOATING OFFSHORE STRUCTURES IN WAVES

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Summary

Drilling is carried out in deeper to deeper waters around the globe to meet growing demands for oil and natural gas, and a number of multi body structures are deployed in various oil fields in the world. Investigation of hydrodynamic interaction of offshore structures is therefore worthwhile. Hydrodynamic interaction between floating offshore structures affects motion and relative motion especially during loading and offloading operations. Hydrodynamic interactions may lead to large motions of floating bodies that would cause damage to moorings and offloading systems and may collide with each other. This research work discusses experimental results of hydrodynamic interaction in surge, heave and pitch motion, relative motion and relative distance between a Tension Leg Platform (TLP) and semi-submersible (Tender Assisted Drilling) in regular waves. The experiment is conducted without tendon because of the depth limitation of the Towing Tank. However, in order to consider the contribution of mooring in linear direction, appropriate stiffness of horizontal springs have been used. The experiment was conducted for a full scale wave height of 3.77 m to 12.49 m for a separation distance of 21.7 m.

From the analyses of the experimental and numerical results, it can be concluded that nonlinearity of the wave has an important effect on increasing the motion especially in the natural frequency region. Finally, a number of recommendations have been made for further study.

Key words: *Tension leg platform; Tender assisted drilling; Floating semi-submersible; Hydrodynamic interaction*

1. Introduction

Oscillation of floating structures caused by wind, wave and current affects the operation of loading and offloading systems. One of the noticeable features of deep water moored structures is a need to pay attention to multi body operation; because it requires more accurate analysis of hydrodynamic interactions between closely moored vessels [1]. They may experience resonant motions, which should be avoided as much as possible under installation, operation and survival conditions. The vertical plane motions induced by heaving, rolling and pitching should be kept adequately low to guarantee the safety of the floating structure, risers and umbilical pipes and other important facilities of oil production [2]. The operability and safety of a floating body's operation is greatly influenced by the relative motions between them, so, the accurate motion prediction of two bodies including all the hydrodynamic interactions is of great importance [3] .

Normally motions of floating structures are analyzed by using strip theory and potential theory. A number of notable studies have been carried out to solve the problem of hydrodynamic interactions between multi bodies [4-6]. They used strip theory for the analysis of hydrodynamic interaction problems between two structures positioned side by side.

Hess and Smith, Loken, and Van Oortmerssen [7-9] studied non-lifting potential flow calculations about arbitrary 3D objects. They utilized a source density distribution on the surface of the structure and solved for distribution necessary to make the normal component of fluid velocity zero on the boundary. Plane quadrilateral source elements were used to approximate the structure surface, and the integral equation for the source density was replaced by a set of linear algebraic equations for the values of the source density on the quadrilateral elements. By solving this set of equations, the flow velocity both on and off the surface was calculated. Wu et al. [10] studied the motion of a moored semi-submersible in regular waves and wave induced internal forces numerically and experimentally. In their mathematical formulation, the moored semi-submersible was modelled as an externally constrained floating body in waves, and derived the linearized equation of motion.

Yilmaz and Incecik [11] analyzed the excessive motion of a moored semi-submersible. They developed and employed two different time domain techniques due to mooring stiffness, viscous drag forces and damping; there are strong nonlinearities in the system. In the first technique, first-order wave forces acting on the structure were considered as solitary excitation forces and evaluated according to the Morison equation. In their second technique, they used mean drift forces to calculate slowly varying wave forces and simulation of slow varying and steady motions. Söylemez[12]developed a technique to predict damaged semi-submersible motion under wind, current and wave. The author used Newton's second law for approaching equation of motion and developed numerical technique of nonlinear equations for intact and damaged condition in time domain. Choi and Hong [13] applied HOBEM to the analysis of hydrodynamic interactions of a multi-body system. Clauss et al. [14] analysed numerically and experimentally the sea-keeping behaviour of a semi-submersible in rough waves in the North Sea. They used a panel method TiMIT (Time-domain investigations, developed at the Massachusetts Institute of Technology) for wave/structure interactions in time domain. The theory behind TiMIT is strictly linear and thus applicable for moderate sea condition only.

An important requirement for a unit with drilling capabilities is the low level of motions in the vertical plane - motions induced by heave, roll and pitch. Matos et al. (2011) [2] numerically and experimentally investigated the second-order resonant of a deep-draft semi-submersible's heave, roll and pitch motions. One of the means to improve the hydrodynamic behaviour of a semi-submersible is to increase the draft. The low frequency forces computation has been performed in the frequency domain by WAMIT a commercial Boundary Element Method (BEM) code which generated a different number of meshes on the structure and calculated pitch forces.

Since demand for oil and gas is growing, the water depth is becoming deeper and deeper, and the chance of multi body operation is increasing, so investigating the reliability of a numerical analysis method for hydrodynamic interaction is worthwhile .This research focuses on hydrodynamic interaction between a TLP and semi-submersible in regular waves numerically and experimentally. The motions obtained from regular waves can be used as transfer functions to carry out time domain simulation where the wave spectrums can be used to simulate the motion behaviour of floating structures in irregular waves. However, in this paper is limited to discuss the experimental results obtained between the TLP and semi-submersible and compares the same with the results obtained from numerical computations for wave heights full scale ranges from 5.8 m – 11 m and the separation distance of 21.7 m.

2. Experimental set up and Procedure

The University Technology Malaysia (UTM) model basin or towing tank has dimensions 120m long 4m wide 2.5m deep and is equipped with a movable towing carriage that runs on rails along the top of the tank side walls, with maximum speed of 5m/s and maximum acceleration of 1m/s2 as shown in Fig. 1. The carriage can achieve the maximum speed at minimum measuring time of 10 seconds. The rails are set up to account for the curvature of the earth so that it maintains a constant distance from the water surface. The tank is equipped with a wave-maker at one end and a perforated steel beach at the other end to absorb the wave energy. The wave-maker consists of a wave flap that is actuated by a hydraulic system controlled from the towing carriage terminal. The maximum wave height that can be achieved is 0.44m for wave period of 1.7s. The wave generator of the basin is capable in generating regular and irregular waves over a wave period range of 0.5s to 2.5s. Useful towing length is approximately 90m.

Fig. 1 Marine Technology Centre, UTM model basin.

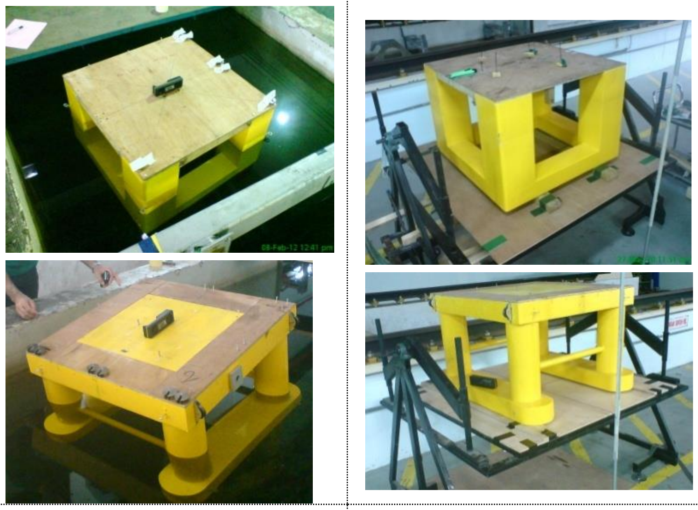
The semi-submersible model was constructed based on GVA 4000. The model has four circular columns connected to two pontoons and two braces. The TLP model also has four columns and four pontoons. Two pieces of plywood are fastened to the top of the TLP and semi-submersible to act as two decks to mount the test instruments. Both models were constructed from wood at 1:70 scale (Table 1).

Several preparations were completed in order to obtain the hydrostatic particulars. These included inclining test, swing frame test, oscillating test and bifilar test as shown in Fig.2 (a) and Fig. 2 (b). It is necessary to do both tests in order to obtain the parameters required by the simulation program and doing experiment. The Inclining Test obtains the GM value, the Swing Frame Test identifies the KG and the Oscillating and Bifilar Tests define the radius of gyration at planer (horizontal) and vertical axes.

Table 1 Principal particular of the Structures

Character	**TLP**	**Semi**	**unit**
Length	57.75	66.78	m
Width	57.75	58.45	m
Draft	21	16.73	m
Displacement	23941	14921	m^3
Water Plane Area	715	529.6	m^2
Number of Columns	4	4	-
Pontoon length	31	66.78	m
Pontoon depth	7.28	6.3	m
Pontoon width	9.73	13.3	m
Pontoon centreline separation	-	45.15	m
Column longitudinal spacing (centre)	-	45.58	m
Column diameter	-	10.59	m
GM_T	7.77	2.87	m
GM_L	7.63	4.06	m
K_{XX}	26.11	31.64	m
K_{YY}	26.46	26.95	m
K_{ZZ}	30.8	35	m
CG_Z	-6.37	-0.28	m

Matching the natural periods of motions of the model is of utmost importance to ensure the correctness of the model test set-up, it is a common practice to perform decay test to determine the natural periods of the model for every configuration [2]. Surge, sway, heave, pitch, roll and yaw decay tests for each test configuration with/without connectors were carried out by displacing the model in the appropriate directions or along the relevant axes, releasing and recording the displacement time histories. The tests are repeated when necessary to obtain reliable results. A motion test may be very sensitive to friction in the mooring lines and care was taken to minimize undue damping due to friction especially at the fairleads.



Inclining test

Swing and oscillating tests

Fig. 2(a) Model preparations

Bifilar test | Model construction

Fig. 2(b) Model preparations

The 6-DOF motions of the models when moored on springs are measured by the optical tracking system (Qualisys Camera) that uses a set of infrared cameras attached to the carriage to capture the positions of the reflective optical tracking markers placed on the model (Fig. 3). Software running on a PC calculates the 6-DOF motions of the body. Instruments were calibrated statically on a test bench by applying a series of known motions prior to test start up.

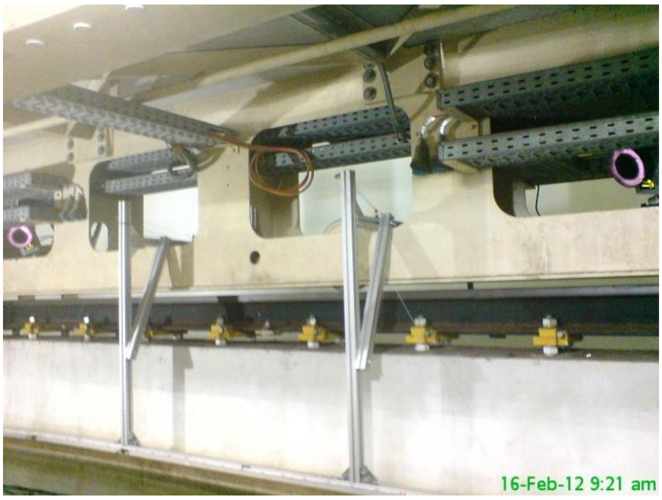


Fig. 3 Camera attached on tow carriage.

To directly measure the applied tension force on the model from the mooring springs, water-proof load cells are attached to the springs at the model fairlead locations to avoid any losses in force. The lightweight ring gauge load cells are sufficiently sensitive to provide a good signal for small mooring line tensions. The measured mooring line tensions are recorded by the Dewetron Data Acquisition System (DAQ). In order to obtain phase information, data recorded from different data systems were synchronized. For this purpose, the optical tracking system is used as the master. The external sync pulse is recorded on the DAQ thus enabling synchronized simultaneous data recording on both systems.

Soft lateral springs are attached to the TLP and semi-submersible to supply the horizontal component of restoring force of the prototype TLP tendons and semi-submersible moorings. These horizontal springs are used because when the TLP facilitate with tendons it restrict the vertical motion almost zero but tension leg mooring system allows for horizontal movement and tendon has the effect on horizontal motion. The stiffness considered here for providing the components of these restoring force. The TLP and semi-submersible are also connected to each other by two connectors to keep them close to each other. The spring ends at the model side are connected to load cells for measurement of the spring tension forces on the model. The other spring ends are clamped to the mooring posts attached to the carriage. The anchor locations for the springs are chosen so the mooring lines of the model make 45 degree angles with respect to the fairlead attachment points on the model. The spring pretension and spring stiffness to be applied are based on the horizontal stiffness required for the system to match the natural periods of the horizontal modes of motion (surge, sway) of the TLP and semi-submersible.

Since the vertical tendons, risers and moorings are not actually represented in the model tests, there will be less damping compared to the prototype, and this is expected to increase the motion amplitude at model scale. However, it is common practice to neglect damping from moorings, tendons and risers in floating structure tests in order to obtain conservative response estimates at the design stage and a similar philosophy is followed here.

For testing the TLP and semi-submersible models in a basin where the water depth is less than that required to include the full length of the tendons and moorings, almost horizontal springs set is considered for compensation of horizontal forces (Fig.4). If truncated tendons were used at, for example, 1-70th scale, the set-down would be greatly exaggerated. An alternative option would be to use a very small 1:200th scale model without truncation, but this would impose significant scale effects (Re<10,000) which could change the vortex shedding pattern around the body and unduly affect the results. For bluff bodies at Re>10,000, the vortex shedding is mostly independent of Reynolds number since the flow separates close to the column corners at both model scale and full scale [15]. The Strouhal number (St) is associated with the vortex shedding frequency and is a function of Re. Strouhal number is defined as a dimensionless proportionality constant between the predominant frequency of vortex shedding and the cylinder diameter(D) divided by the free stream velocity(U). In particular for smooth cylinders, the dependence of the Strouhal number defined as, on Reynolds number is well known. Minor fluid flow differences may come from the separation behavior around columns with rounded corners and this may cause the model scale flow to differ slightly from prototype unless the column radius is accurately modeled.

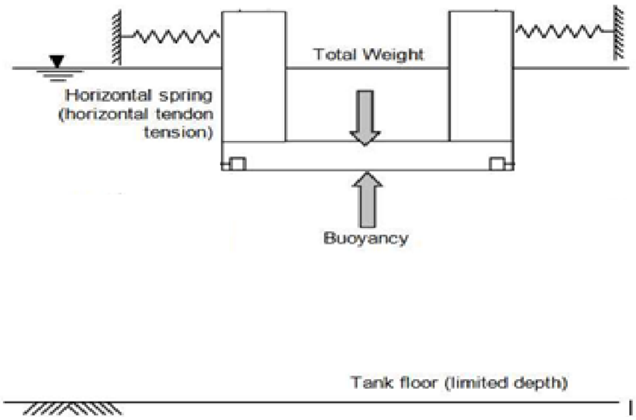


Fig. 4 Model test set-up in available water depth

Hydrodynamic interaction floating structures model test between TLP and semi-submersible was set up as shown in Fig. 5**Error! Reference source not found.**. Waves hit the TLP before the semi-submersible. The models were attached to the tow carriage on springs, and regular waves were generated by the wave-maker at the end of the towing tank (Fig. 6). At the start and end of these tests the model was carefully held to prevent large offsets due to sudden wave exciting forces which could damage the mooring springs. Measurement data collection commenced when the model had settled under a constant incident wave. The tank length was sufficient to ensure sufficient oscillations were recorded for each test before reflection occurred.

Owing to limitations in generating wave height and period by the wave making system, some periods were chosen to cover the natural period of the models, and wave slope was considered at 1/20, 1/40 and 1/60 to get an acceptable motion to record [16]. The set up is generally unique to a particular type of floating system and may not be appropriate for others. Separation distance of models is 21.7m in full-scale (Table 2).

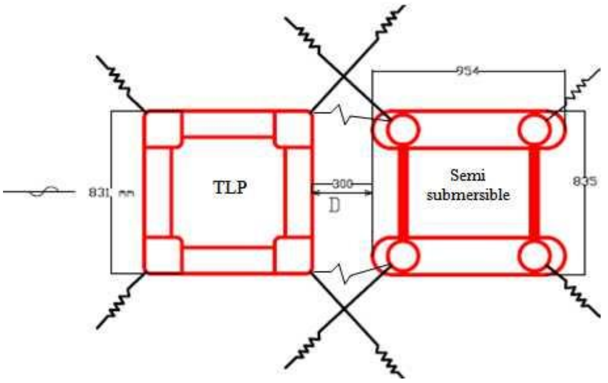


Fig. 5 Layout TLP and semi-submersible model experimental set up (Dimensions are in model scale).

Fig.6 TLP and semi-submersible set up into towing tank.

Table 2 Incident wave particulars

Distance (m)	ω (rad/s)	λ (m)	H(1/20) (m)	H(1/40) (m)	H(1/60) (m)
21.7	0.91	75	3.8		
	0.60	171	8.6		
	0.52	233	11.7	5.8	
	0.46	298		7.4	
	0.41	374		9.3	
	0.38	422		10.6	
	0.35	500		12.5	

	0.30	657			10.95

3. Results and Discussions

Figs. 7 ~ 12 depict time series of surge, heave and pitch motions, relative motions and relative distance between structures at wave frequency 0.52 rad/s, for two wave heights of 11.7m and 5.8m respectively in head sea condition. The 6-DOF motions of the models are measured by the optical tracking system (Qualisys Camera) that uses a set of infrared cameras attached to the carriage to capture the positions of the reflective optical tracking markers placed on the model. Relative distance between two structures in Fig. 7 and Fig. 8 show that they do not collide to each other as the distance between the structures are positive. The distance between the structures was taken 21.7 m which is based on authors proposed empirical formula for finding the minimum gap between the structures in waves [17]. Fig.9 to 12 show relative motion in the related frequency is higher than the motion of structures, so they show the motion of structures are out of phase. Experimental results in different frequencies show that with the decreasing of wave frequency the phase angle decreases, in other words less relative motion leads to the safer system.

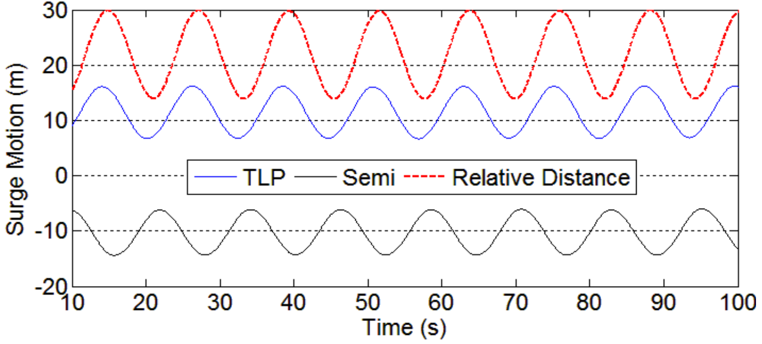


Fig. 7 Surge Motion of semi-submersible and TLP with their Relative Motion (Distance) at ω=0.52 rad/s, H=11.7m

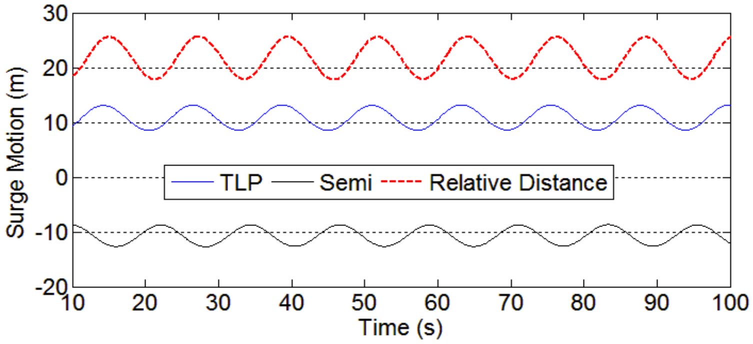


Fig. 8 Surge Motion of semi-submersible and TLP with their Relative Motion (Distance) at ω=0.52 rad/s, H=5.8 m

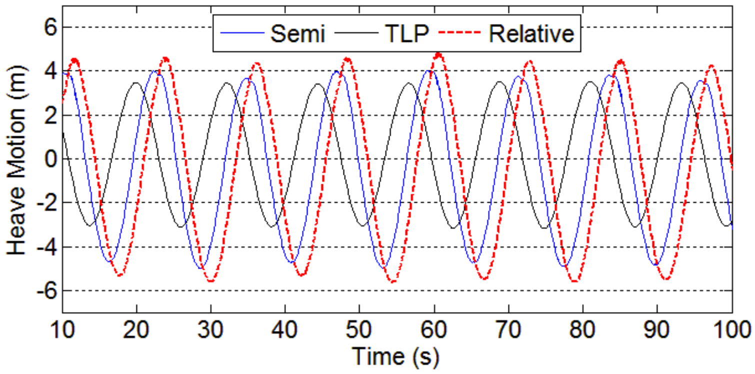


Fig. 9 Heave Motion of semi-submersible and TLP with their Relative Motion at ω=0.52 rad/s, H=11.7 m

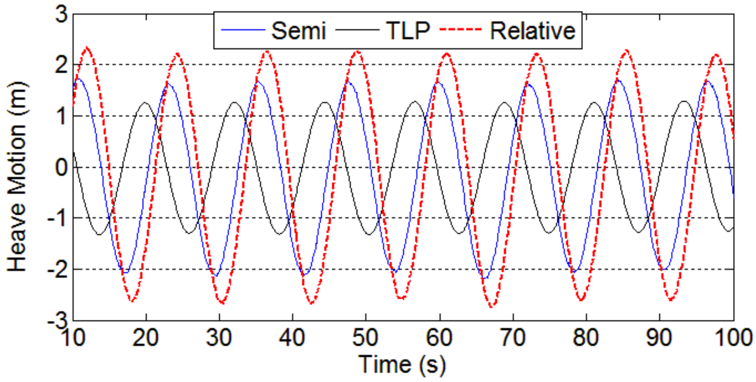


Fig. 10 Heave Motion of semi-submersible and TLP with their Relative Motion at ω=0.52 rad/s, H=5.8m

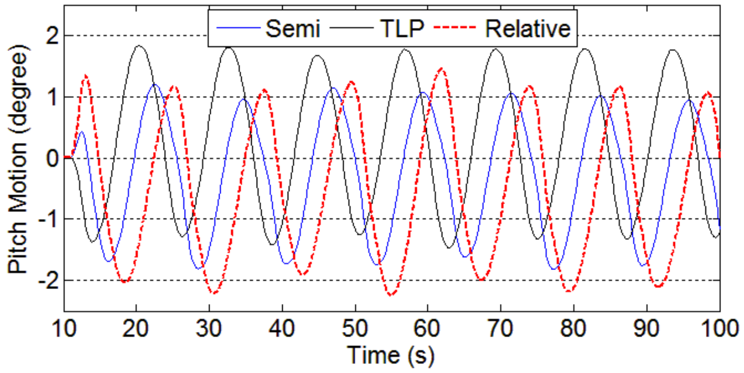


Fig. 11 Pitch Motion of semi-submersible and TLP with their Relative Motion at ω=0.52 rad/s, H=11.7m

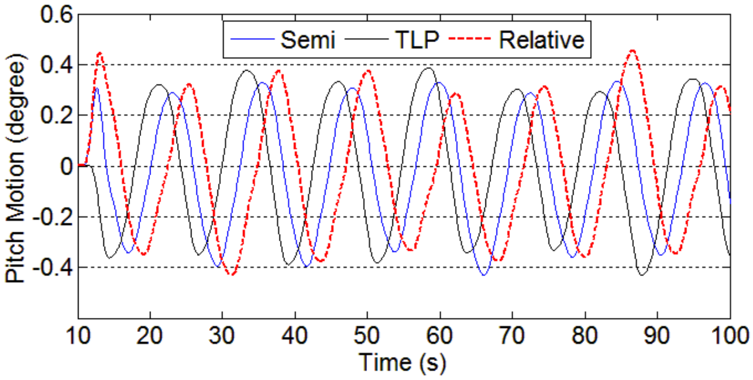


Fig. 12 Pitch Motion of semi-submersible and TLP with their

Relative Motion at ω=0.52 rad/s, H=5.8m

To obtain the experimental results in frequency domain and the response amplitude of operator (RAO=Ratio of motion amplitude to wave amplitude for linear motions and Ratio of motion amplitude to wave slope for angular motions), standard deviation of motion of models at different frequencies divided by standard deviation of incident wave height is derived using MATLAB. Fig.13 ~ 15 depict the surge, heave and pitch motions and relative motion of TLP and semi-submersible in a head sea condition. The data has been expressed in full-scale units, based on Froude scaling at the frequency range of 0.3 to 0.9 rad/s. The computational results obtained from a professional software (HydroStar) has also been plotted with experimental results and are shown in Figs. 14-16. The mesh configuration for which the computation has been carried out is given in Fig. 13. The number of panels is 824 for each structure. The optimum size of panel in panel method can be between 3 to 5 meters. The calculation time increases dramatically by increasing the mesh number. Increasing mesh number does not affect the accuracy of the calculated results except in the range of natural frequencies. **Abyn *et al.* (2014) [18]** showed that by increasing mesh numbers almost two times, calculation time increases about five times and by increasing panel number in four times it reaches up to twenty times.

Fig. 14 shows surge responses which slope down at frequency 0.3 rad/s to a minimum at 0.6 rad/s and then slope up on increasing frequency. Heave RAOs are depicted at Fig. 15. The largest values of semi-submersible heave motion and relative motion occur at low frequency, where the peak for TLP occurs at the resonance frequency of 0.35rad/s. Phase angles between semi-submersible and TLP motions at different frequencies lead to a change of the relative motion trend with respect to them. For example, the phase angles at 0.3rad/s and 0.46rad/s frequencies are almost 90 degrees. The heave relative motion has a good and reasonable trend. It is low at low and high frequencies but in the range of 0.1 to 0.8 rad/s, it has three peaks at frequencies 0.305, 0.39, 0.6 rad/s of which two of them take place at the natural frequencies of the TLP and Semi-submersible. Fig.15 shows pitch motion and relative motion RAOs, which decrease dramatically from a maximum at 0.3rad/s down to almost zero at 0.51rad/s, then levelling to around 0.1rad/s. For all motions, the trends of the results are same, however disagreements take place in the range of wave frequency 0.6 to 0.9 rad/s. This is due to the limitation of the experiment as explained in the previous section. As seen in the Table 2, the model test was carried out for two different slope (H/L=1/20 and 1/40) for incoming wave frequency 0.52 rad/s. There is a jump in the frequency 0.52 for experimental surge, heave and pitch motions for both the structures due to nonlinearity effects. This jump is clear and sensible in heave motion increase of 13.7% and 43.6% for semisubmersible and TLP. This jump is cancelled at relative motion which is one of concern and reaches to 4.1%. Increasing wave height with respect to wave length cause the nonlinearity and lead to increase the semisubmersible and TLP motions. This is shown in Fig. 15

In Fig 16 the pitch motion of the model test results are similar to the numerical calculation results with shifting in horizontal axis. This shifting in natural frequency comes from braces effect which was not simulated in HydroStar. The discrepancies between experimental results in the region of natural frequencies are because of the viscosity as the HydroStar software is based on potential wave theory which does not consider the viscosity. Experimentally, it is also difficult to measure the motions in natural frequency range. The non-linerity in the natural frequency range can be minimized in frequency domain method by incorporating a certain percentage of critical damping while computing motions. However the exact percentage is not yet established.

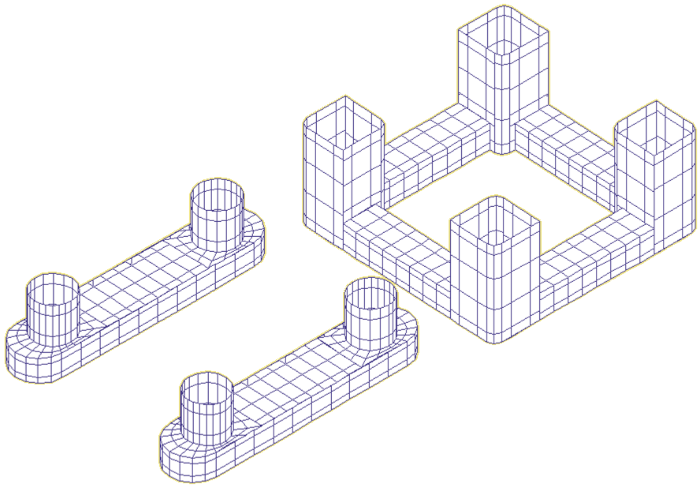


Fig. 13 Mesh arrangement of TLP and Semi-submersible

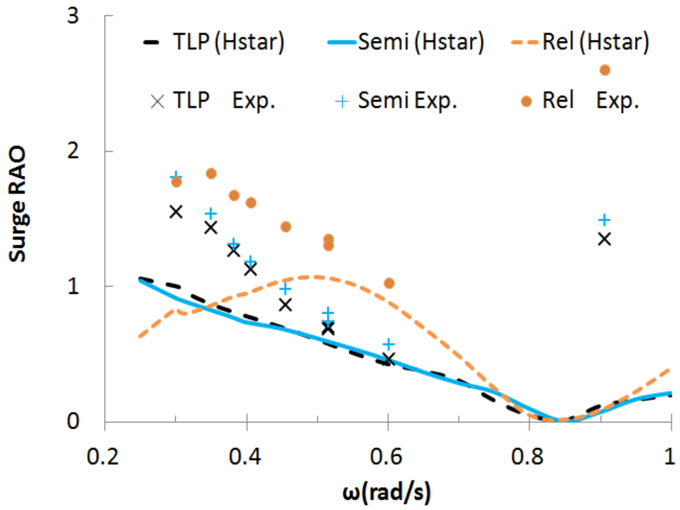


Fig. 14 Surge Motion RAO

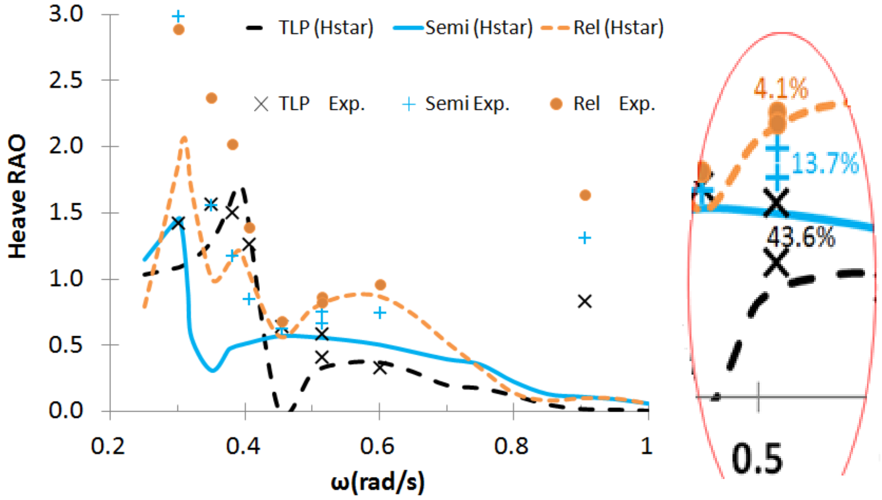


Fig. 15 Heave Motion RAO

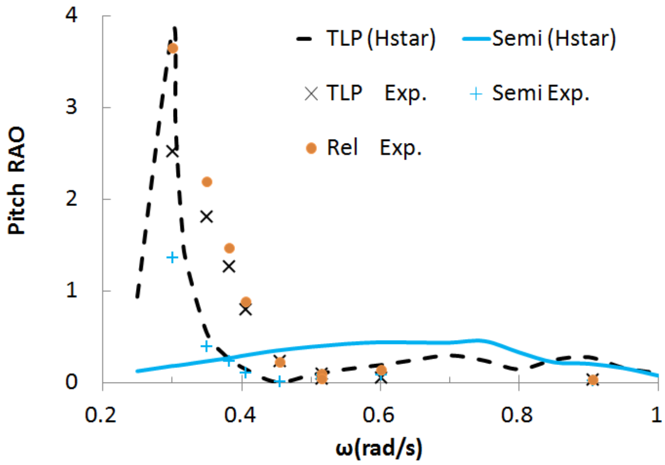


Fig. 156 Pitch Motion RAO

4. Conclusions

Motion of a floating structure has a significant influence on loading and offloading operations. For motion investigation, experimental tests are carried out.

In the research work, hydrodynamic interaction and relative motion of two moored structures are investigated experimentally and numerically. Due to limitation in water depth in the towing tank, only the horizontal forces of mooring lines are considered. From the analyses of the experimental and numerical results, it can be concluded that nonlinearity of the wave has an important effect on increasing the motion. Due to experimental limitation, the experiments were conducted in one depth and head sea condition only. In order to obtain comprehensive results and outcome, experiments should be carried out for various wave headings and water depths. The effect of tension leg is not considered except the horizontal effect of mooring. Thus future work should be carried out by incorporating the effect of Tension Leg.

5. Acknowledgment

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