Study on Pitch Motion of Three Floating Structures

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ABSTRACT

This paper discuss on the pitch motion due to the hydrodynamic interaction of three floating structures for different gap distances, 25 m and 50 m, and wave directions at 0 degree. In the study, commercial software, ANSYS AQWA software which practices the use of linearized wave theory is used to analyze the added mass, radiation damping and motion responses for the interaction between structures, where a 134 m diameter of round-shaped FPSO is used as a reference structure with a 97.6 m diameter round-shaped FPSO and LNG vessel. From the results, RAO at the gap distance of 50 m produced larger responses compare to RAO at the gap distance of 25 m..

KEYWORDS*:* *Round-Shape Floating Production Storage Offloading; Hydrodynamic Interaction; Gap Distance; Wave Directions.*

NOMENCLATURE

RAO	Response Amplitude Operator
FPSO	Floating Production Storage Offloading

1.0 INTRODUCTION

Since the demand for oil and gas increased in recent years, there is a huge impact on the growing offshore industry where there are a lot of construction of offshore structures are built and designed not only used to support the exploration of oil and gas, but they are also acting as a base for drilling, production and storage of oil and gas. The exploration for hydrocarbons started from the land to shallow waters (< 350 m) extended to deep water (< 1500 m) and now involves into ultra-deep water (> 1500 m). The development of oil and gas area regarding the offshore structures which considered as a challenge in the past has become a common thing nowadays where the effects of hydrodynamic interaction on the motion of the offshore structures have to be carefully taken into consideration for their safe operation.

There are many situations where it is important to understand the hydrodynamic interaction that occurs as a result of the motion between the multiple bodies of offshore structures. As an example, in general, there are many offshore operations involving the use of two or more floating structures in which they are placed close to each other to transfer the oil and gas during offloading. From this activity, the motions of each other are affected due to the hydrodynamic interaction in waves. As a result of the large motions between the two floating bodies can cause disturbance to the offloading system and collision to each body. It is important to understand, study and analyze the hydrodynamic interaction effect that occur due to the motion of the multiple bodies of offshore structure in order to trace the problem and minimize the serious implications that may be occurring.

There are many methods that have been used in order to analyze the motion of the floating structures due to the hydrodynamic effect. A common method that is usually has been performed to study the motion of the structure is by conducting an experiment using the model test in towing tank. In this research, three types of analysis are conducted; single body of offshore structure, two bodies of offshore structures and three bodies of offshore structures. The models which consist of two different rounds-shaped floating, productions, storage and offloading (FPSO) and liquefied natural gas (LNG) vessel from the previous research are used for the hydrodynamic analysis. The use of commercial software which is ANSYS Hydrodynamic Diffraction (AQWA) is utilized in order to predict the effect of the gap or distance between the bodies of offshore structures on the wave forces.

2.0 LITERATURE REVIEW

There are many researches have been done regarding to hydrodynamic interaction effect on multiple bodies of offshore structures. The researches have been done analytically and numerically in order to solve the problems regarding the hydrodynamic analysis between multiple bodies. Some previous researches have been used as a guideline to the present researches.

For the hydrodynamic behavior of a single body of offshore structure, Saad et al. (2009) [18] used a mono-hull production platform in real environmental conditions which is in Brazilian waters. They also compared the data obtained from the field measurements with the results from the numerical simulations as well as the results acquired from model tests performed during the design phase. The hydrodynamic behavior of the mono-column showed satisfactory results and valid even though there are quite conservative to those related to the higher period amplitude. Cueva et al. (2010) [7] presented the numerical and experimental models for motion evaluation by using a circular shaped floater which is also a mono-column structure. The results for both numerical and experimental evaluations are presented in terms of Response Amplitude Operators (RAOs) for heave and pitch/roll motions. The results obtained for both numerical and experimental models are quite satisfactory except that there are slight differences and they are still valid.

There are many researches have been done regarding the problem of hydrodynamic interaction between multiple bodies and strip theory and potential theory are normally used to analyze the motions of the floating structures. Ohkusu (1974) [17] adopted strip theory to analyze the ship’s motion around large floating structure. The results described clearly the effects of position of a smaller body in opposition to a large body. Ohkusu’s method is extended by Kodan (1984) [14] to investigate the hydrodynamic interaction between two parallel structures in oblique waves. In order to support the validity of strip theory, he compared his investigation with model experiment but neglecting the speed effect and the results obtained are satisfactory with the experimental results. Fang and Kim (1986) [8] also utilized the strip theory to predict the motion between two ships due to hydrodynamic effect in oblique sea. Their method is different with previous researcher where the speed effects are taken into account, however, some deficiencies popped up due to the assumptions of two-dimensional.

Van Oortmerssen (1979) [22] solved the hydrodynamic interaction problem between two floating structures in waves by using the three-dimensional linear diffraction theory to solve. The results obtained for the numerical calculation achieve an agreement with the data obtained from the experiment but the speed effects are not considered as well as he did not applied his method to the ship configuration. Loken (1981) [15] used three-dimensional sink-source method to investigate the wave-induced motion and wave-drifting forces and moment on several close vessels in waves and the results obtained were satisfactory but the results for resonance region were quite unsatisfactory. Wu et al. (1997) [23] reviewed numerically and experimentally on the motion of a moored semi-submersible in regular waves and the wave-induced internal forces in the semi-submersible. For numerical method, the linearized equations of motions of the semi-submersible which is modelled as an externally constrained floating body are obtained in a common reference system fixed on the body. The results between the numerical and experiment in the practical wave-frequency range achieved very good agreement.

As the ability to compute is evolved, three-dimension approach to solve the hydrodynamic problems has become popular. Choi and Hong (2002) [5] employed a higher-order boundary element method (HOBEM) or wave Green function to analyze numerically the hydrodynamic interactions of multi-body system for twin barges and FPSO-shuttle systems. The results obtained show that there are rapid changes in hydrodynamic loads and responses along the wave frequencies caused by the hydrodynamic interaction. M. Kashiwagi and Q. Q. Shi (2010) [12] investigated numerically the wave interaction theory of four identical box-shaped floating bodies to compute the pressure distribution and integrated forces on body surfaces using the separation distance between the multiple floating bodies. The results obtained from the wave interaction theory are compared to HOBEM because the results obtained from HOBEM are accurate with respect to the separation distance between bodies. Clauss et al. (2002) [6] analyzed numerically and experimentally the sea keeping behavior of a semi-submersible in rogue wave. A panel-method program is used for wave or structure interactions in time-domain which is TiMIT (Time-domain investigation developed at the Massachusetts Institute of Technology) to evaluate the motions of the semi-submersible. The results showed good agreement with model test despite the fact that TiMIT theory is strictly linear and applicable for moderate sea conditions only.

Zhou Xianchu et al (1997) [24] applied the linear potential theory to investigate the hydrodynamic interaction between two vertical cylinders in water waves where the diffraction wave and radiation waves are considered. It is found that the incident angle which is the angle between the incident wave direction and the line joining two cylinder centers is depended on the magnitude of wave excited forces on cylinders. M.S. Kim and M. K. Ha (2002) [13] studied the motion responses between two offshore floating structures due to hydrodynamic interaction by using linearized three-dimensional potential theory with various heading waves. They used three-dimensional source distribution method for twelve coupled linear motion responses and elative motions of the barge and the ship in oblique waves to solve the numerical calculation. The results obtained provide a good correlation with the experimental results. Zhu et al. (2008) [9] applied time domain method to research the influence of the separation distance on the wave forces for hydrodynamic resonance of three-dimensional multiple floating structures. The results obtained from the time domain method for the peak force response on each floating body show similar resonant phenomena and hydrodynamic interaction when compared with frequency domain method, thus the time domain method is said as practically efficient.

M. T. Ali et al (2010) [1] investigated the first order wave exciting forces and motion responses due to hydrodynamic interaction between two unequal-sized freely floating three-dimensional rectangular boxes in regular waves using 3-D source distribution method through different wave headings angles and separation distances (gaps). The results obtained show that the magnitude of the amplitude of motion responses and wave exciting forces for the smaller box can be increased or decreased depending on the wave heading while high peak frequencies is obtained as the gaps between two floating rectangular boxes is reduced. Z. Tajali et al. (2011) [21] carried out the hydrodynamic analysis of a floating multiple bodies of floating pier interacting with incident waves in the frequency domain. They used three-dimensional diffraction theory to predict the dynamic response of modules in irregular waves. The pier is modeled as a rigid body platform and pontoons are connected to each body of the floating piers by hinge. The results showed that for a fixed length of the pier, the amplitude of heave and pitch motions increased as the number of pontoons increased.

Siow et al (2013) [20] study the hydrodynamic interaction between Tension Leg Platform (TLP) and semi-submersible and the characteristics of multiple floating bodies when placed near to each other in regular waves. The experiment tests were carried out to find out the effect of hydrodynamic interaction to the motions of the structures. They applied Fourier Transform method to get the data in frequency domain by converting the data in time domain. The result shows that the hydrodynamic interaction will occur due to the scattering wave and radiation wave generated by another floating body which can cause the increase to the magnitude of the motions of the structures.

Siow et al. (2013) [21] proposed the method of three-dimensional diffraction potential methods to predict the motion response of multiple hulls semi-submersible structures as well as the use of three-dimensional green functions to estimate the wave velocity potential at each panel on semi-submersible surface. They only modified the meshing system in order to make it able to be applied to multiple hull structures. Good agreement between numerical and experimental results is obtained even though the numerical result obtained is slightly under-predicted compared to experimental results in most cases.

Siow et al. (2014) [22] included the viscous damping in the calculation to improve the heave damping magnitude in the motion equation due to over-estimated in heave motion from the previous study. The total damping is revised with the addition of viscous damping to the linear damping from diffraction theory. As a result of this revision, the involvement of viscous damping helps in correcting a part of heave motion response and reducing over-predicted error of heave damping magnitude.

Siow et al. (2014) [23] did another improvement by involving the drag effect in the calculation of diffraction potential theory and viscous damping. In order to correct the insufficient of diffraction potential theory, the nonlinear drag term in Morrison equation that is linearized using Fourier series linearization method is inserted in the motion equation. Hence, a satisfied result of heave response especially in damping is obtained.

3.0 PRINCIPAL THEORY

3.1 Motions of Floating Body

At sea, a floating structure experienced the motions responses due to waves where the motions are divided into 6 degrees-of-freedom in which three of them are linear while the other three are rotational about the three principal axes as in Figure 1.

The linear motions are surge (x-axis), sway (y-axis) and heave (z-axis) while the rotational motions are roll (x-axis), pitch (y-axis) and yaw (z-axis). From the six motion responses, heave, roll and pitch are considered as oscillatory motions since they are moving about a neutral point while for surge, sway and yaw, they do not return to their original equilibrium unless they are forced by exciting forces or moments.

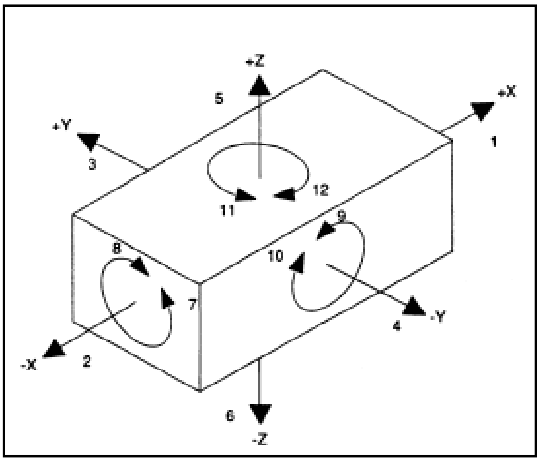

Figure 1: Six Degree-of-Freedom of a Floating Body

The equation of motion of a floating body can be expressed as

$$(m_j + a_{jj})\ddot{x}_{j(t)} + b_{jj}\dot{x}_{j(t)} + c_{jj}x_{j(t)} = f_{j(t)} \tag{1}$$

where x is displacement, $\dot{x}$ is velocity, $\ddot{x}$ is acceleration and f is exciting force. The displacement can be expressed as

$$x_{j(t)} = x_{jo}\cos(\omega t - \varepsilon_j), \tag{2}$$

the velocity, can be expressed as

$$\dot{x}_{j(t)} = -x_{jo}\omega\sin(\omega t - \varepsilon_j), \tag{3}$$

the acceleration can be expressed as

$$\ddot{x}_{j(t)} = -x_{jo}\omega^2\sin(\omega t - \varepsilon_j), \tag{4}$$

and the exciting force can be expressed as

$$f_{j(t)} = f_{jo}\cos(\omega t) \tag{5}$$

where; m_j is the mass of the system, a_{jj} is the hydrostatic reaction in phase with acceleration (added mass), b_{jj} is the hydrostatic reaction in phase with velocity (damping coefficient), c_{jj} is the stiffness, x_{jo} is the amplitude of the motion, f_{jo} is the amplitude of the force and ε_j is the phase angle.

3.2 Concept of Interaction of Floating Bodies

3.2.1 Diffraction Wave Potential

Based from potential flow theory, the fluid flow around the bodies can be described by velocity potential by satisfying the conservation of mass and momentum equations using Laplace's equation. It is assumed that the fluid flow around bodies as incompressible, inviscid which is frictionless and irrotational where the fluid particles are not rotating due to the viscous effects which are limited to the boundary layer. The velocity potential can be defined as$\Phi(x,y,z)$. The velocity potential can be divided into three parts; incident wave Φ^I, scattered wave Φ^S and radiation waveΦ^R.

$$\Phi(x,y,z) = \Phi^I(x,y,z) + \Phi^S(x,y,z) + \Phi^R(x,y,z) \qquad (6)$$

Eq. 6 can be simplified as

$$\Phi(x,y,z) = \frac{gA}{i\omega}\{\emptyset_I(x,y,z) + \emptyset_S(x,y,z)\} + \sum_{k=1}^{6} \omega X_k \emptyset_R(x,y,z) \qquad (7)$$

where, g is the gravitational acceleration (9.81 m/s^2), A is the amplitude of the incident wave, $\emptyset_I$ is the incident wave potential, $\emptyset_S$ is the scattering wave potential, $\emptyset_R$ is the radiation wave potential due to the motions, X_k is the amplitude of the motions and k is the direction of the motion.

The diffraction wave is the scattered wave from the fixed body caused by the incident wave. The radiation wave represents the wave propagated by the oscillating body in calm water. The diffraction wave and radiation wave can cause a significant effect on the bodies of floating structure in deep water.

It is assumed that the phase and amplitude for both the incident wave and diffraction wave are the same but the radiation wave is affected by each type of motions of each single floating body in the system. As a result, the total potential for radiation wave for a single body is the summation of the radiation waves generated by each type of motions of body which are surge, sway, heave, roll, pitch and yaw.

$\emptyset_I$ which is the incident wave potential can be written as

$$\emptyset_I(x,y,z) = -\frac{igA}{\omega}\frac{\cosh[k_0(z+h)]}{\cosh kh} e^{ik_0(x\cos\alpha + y\sin\alpha)} \qquad (8)$$

where, α is the angle where the incident waves propagate relative to x-axis.

The scattering wave potential, $\emptyset_S$, due to the continuous surface of fluid can be represents as

$$\emptyset_S(x,y,z) = \frac{1}{4\pi}\iint_S \sigma_S(a,b,c)\, G(x,y,z;a,b,c)\, ds \qquad (9)$$

$$\emptyset_S(x,y,z) = -4\pi u_n(x,y,z) \qquad (10)$$

where, $\sigma_S(a,b,c)$ is the source of the strength function, $G(x,y,z;a,b,c$ is the Green's function, (x,y,z) is the coordinates of the field and (a,b,c) is the coordinates for thesource point

Diffraction wave potential $\emptyset_D$ can be obtained from the sum of incident wave potential and scattering wave potential.

$$\emptyset_D(x,y,z) = \emptyset_I(x,y,z) + \emptyset_S(x,y,z) \qquad (11)$$

The diffraction wave potential $\emptyset_D$ must be satisfied with the boundary conditions:

- Laplace's equation:

$$\nabla^2\emptyset_D = 0 \text{ for } 0 \le z \le h$$

- Free-surface condition:

$$\frac{\partial\emptyset_D}{\partial z} + K\emptyset_D = 0 \text{ at } z = 0 \text{ where } K = \frac{\omega^2}{g}$$

- Bottom boundary condition:

$$\frac{\partial\emptyset_D}{\partial z} = 0 \text{ at } z = h$$

- Radiation condition:

$$\emptyset_D \sim \frac{1}{\sqrt{r}} e^{-ik_0 r} \text{ should be 0 if } r \text{ is } \infty$$

- Body boundary condition:

$$\frac{\partial\emptyset_D}{\partial n} = -\frac{\partial\emptyset_I}{\partial z} \text{ on the boundary}$$

Thus,

$$\emptyset_D(x,y,z) = Re\left[\frac{gA}{i\omega}\{\emptyset_I(x,y,z) + \emptyset_S(x,y,z)\}e^{-i\omega t}\right] \qquad (12)$$

The boundary conditions for the radiated wave potential are the same with the boundary conditions for incident wave potential. For radiated wave potential which is related to the motions of the body can be given as

$$\emptyset_R(x,y,z) = \sum_{k=1}^{6} \omega X_k \emptyset_R(x,y,z) \qquad (13)$$

The radiated wave potential due the motions of the body can be obtained from as shown below

$$2\pi\emptyset_R(x,y,z) + \sum \emptyset_R(a,b,c) \iint_{S_B} \frac{\partial G(x,y,z,a,b,c)}{\partial n} dS$$
$$= \sum \emptyset_R(a,b,c) \frac{\partial\emptyset_R(a,b,c)}{\partial n} \iint_{S_B} G(x,y,z,a,b,c) dS \qquad (14)$$

where, S_B is the wet body surface of the floating body

3.2.2Green Function and Wave Potential

The wave potential at any point can be shown by eq. (15) in consideration of the wave potential can only be affected by structure surface, S_H:

$$\emptyset(P) = \iint_{S_H}\left\{\frac{\partial\emptyset(Q)}{\partial n_Q} G(P;Q) - \emptyset(Q)\frac{\partial G(P;Q)}{\partial n_Q}\right\} dS(Q) \qquad (15)$$

where, $P = (x,y,z)$ is the fluid flow pointed at any coordinate and $Q = (\xi,\eta,\zeta)$ is any coordinate, (x,y,z), on the structure surface, S_H.

In order to estimate the strength of the wave flow potential, the Green function in eq. (15) can be utilized as follows:

$$G(P;Q) = \frac{1}{4\pi\sqrt{(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2}} + H(x-\xi, y - \eta, z - \zeta) \qquad (16)$$

where,   is the effect of the free surface.

3.2.3Added Mass and Damping

For each motion, the added mass,   and damping,   can be obtained by using the integration of the radiation wave due to each motion along the surface of the structure as shown as following:

(17)

(18)

where,   is the normal vector for each direction of motion,   and ,   is the direction of motions and   is the type of motions.

4.0 SIMULATION SETUP

Simulation of hydrodynamic interaction of three floating bodies was arranged as shown in Figure.2. The simulation was carried out at different wave directions as follows: 0^0, 45^0, 90^0, 135^0 and 180^0 headings using parameters of environmental conditions at Kikeh field as shown in Table.1.

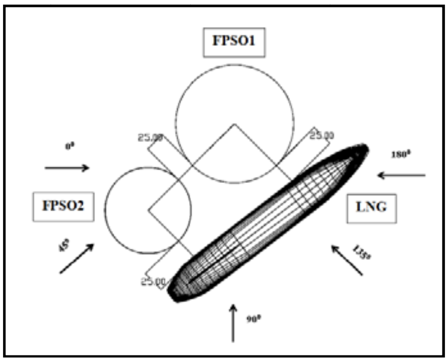

Figure 2: Wave Direction at 0^0, 45^0, 90^0, 135^0 and 180^0 headings

Table 1: Environmental Condition in Kikeh Field

Description	Value	Unit
Sea Water Characteristics		
Water Depth	1320	m
Water Density	1025	kg/m^3
Wave Characteristics		
Type	Range of Directions, No Forward Speed	
Wave Range	-180^0 to 180^0 (-PI to PI)	
Interval	45^0	
Number of Intermediate Directions	7	

The FPSO's and ship are analyzed using commercial software which is Rhinoceros for design and ANSYS AQWA Hydrodynamic Diffraction and ANSYS AQWA Hydrodynamic Time Response. Figure.3 shows drawn of FPSO-1, FPSO-2 and ship by Rhinoceros viewed from top, front, and right sides. Table.2 and Table.3 show principal dimensions of FPSO and ship, respectively.

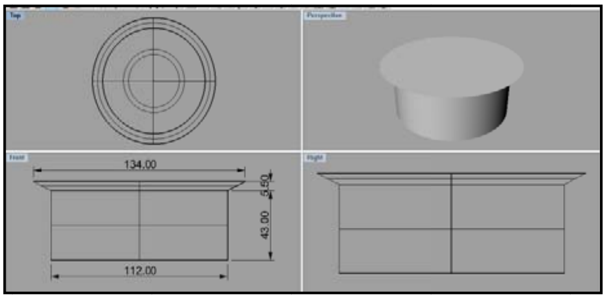

Figure 3.a: View of FPSO-1 from top and front

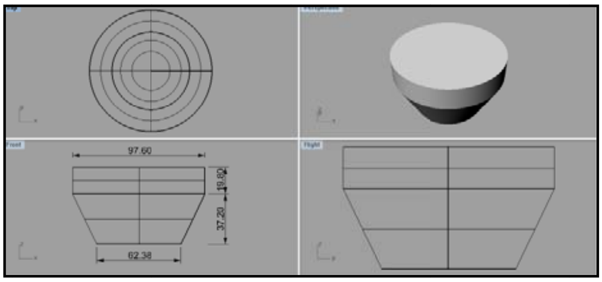

Figure 3.b: View of FPSO-2 from top and front

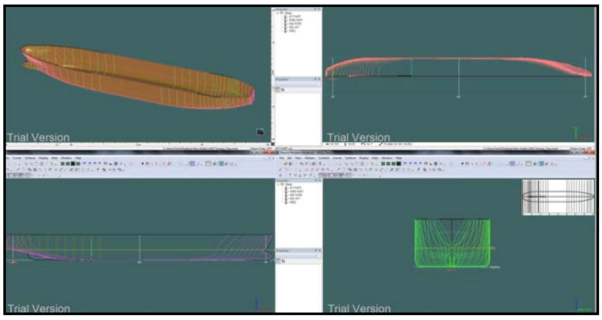

Figure 3.c: View of ship from top, front and side

Table 2: Principal Dimensions of FPSO

Parameter	FPSO-1	FPSO-2
Diameter at Upper Deck (m)	134.00	97.60
Diameter at Base (m)	112.00 m	62.38
Draught (m)	32.00	37.20

Table 3: Principal Dimensions of LNG ship

Parameter	LNG
Length	270.70 m
Breadth	44.30 m
Draught	11.13 m

5.0 RESULTS AND DISCUSSION

The results in relation to the hydrodynamic analysis of single body, two bodies and three bodies of offshore structures for added mass, damping coefficients and RAO are analyzed for every added mass, damping coefficients and RAO for each direction are presented by using graphical method the data that has been extracted from ANSYS AQWA Hydrodynamic Diffraction and ANSYS AQSA Time Response. These results will be discussed on the differences between the motion of single body, two bodies and three bodies of offshore structures due to hydrodynamic interaction.

5.1Added Mass

Figure 4 shows the results of added mass on pitch motion against frequency for FPSO-1 with FPSO-1 with FPSO-2, FPSO1 with LNG and FPSO-1 with FPSO-2 and LNG for two different gap distances which are 25 m and 50 m respectively. The figure show that the added mass has the same trend despite there are small differences in between due to more interaction between numbers of floating structures are involved in smaller gap distance. The trends for the added mass at 25 m gap distance is different with the trend for the added mass at 50 m gap distance where the values of added mass decreases rapidly at the resonant frequency as the gap distance increases. As a result, this shows that gap distance and presence of other structures can give different effects to the values of added mass for the hydrodynamic interaction between two and three floating structures.

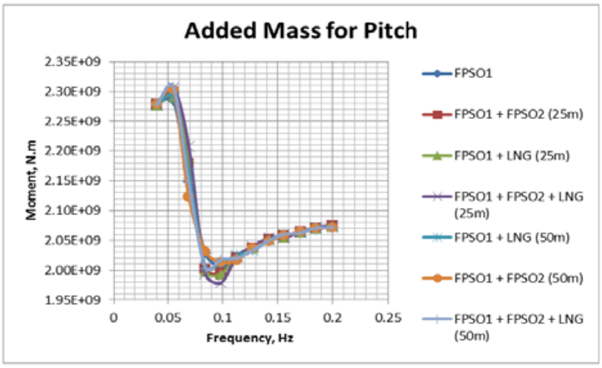

Figure 4: Added mass on pitch motion

5.2 Radiation Damping Coefficient

Figure 5 shows the results of radiation damping on pitch motion against frequency for FPSO-1 with FPSO-1 with FPSO-2, FPSO-1 with LNG and FPSO-1 with FPSO-2 and LNG for two different gap distances which are 25 m and 50 m respectively.

From the figures, all the radiation damping pitch motion have experienced same trend though there are small differences in the values obtained. Apart from that, the radiation damping for three floating structures have the highest values on pitch motion compare to others especially at the gap distance 25 m due to the motion effects of two other structures experienced by one structure. The trends for the radiation damping at 25 m gap distance are slightly different compare to the trend for the radiation damping at 50 m gap distance in which the radiation damping values drop down rapidly at the resonant frequency as the gap distance increases. Therefore, gap distance and presence of other structures plays important roles in affecting the radiation damping values for the hydrodynamic interactions between two and three floating structures.

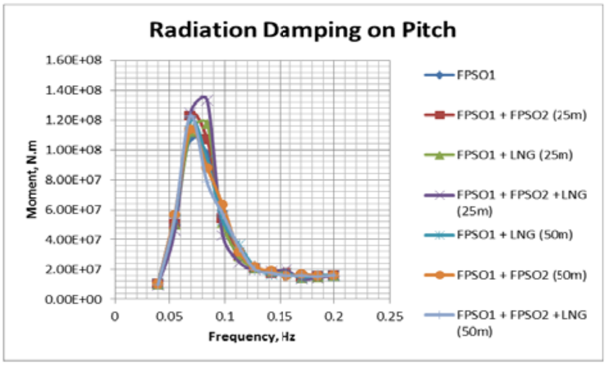

Figure 5: Radiation Damping on Pitch Motion

5.3 Response Amplitude Operators (RAO)

Figure 6 shows the results of RAO on pitch motion against frequency at 0° heading for FPSO-1 related to FPSO-1 and FPSO-2, related to FPSO1 and LNG and related to FPSO-1, FPSO-2 and LNG for two different gap distance which are 25 m and 50 m respectively. The pitch motion, there are slight differences between the motion responses of the structures at 25 m and 50 m in which the motion responses at 50 m are higher than the motion responses at 25 m. Although there are small differences on pitch motion with the presence of neighboring structures, there are slight motion responses between multiple floating structures for the direction of wave at 0° heading and it is proved there are hydrodynamic interactions between multiple floating structures.

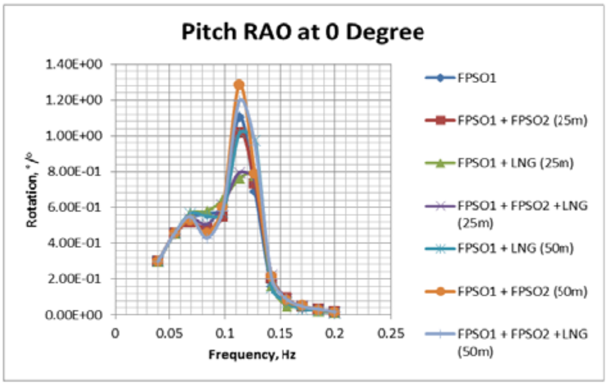

Figure 6: Pitch RAOs at 0 Degree

6.0 CONCLUSION

In this study, the simulation of three floating bodies of offshore structures has been conducted interaction using ANSYS AQWA software in order to investigate the effect of hydrodynamic interaction for different gap distances, 25 m and 50 m, and wave directions at 0 degree.

For the results of added mass and radiation damping, more reactions have been experienced by the structure at the gap distance of 25 m where the values of added mass and radiation damping are large compare to the results of added mass and radiation damping at the gap distance of 50 m. The wave directions do not affect the added mass and radiation damping since all the results at every direction are the same. RAO at the gap distance of 50 m produced larger responses compare to RAO at the gap distance of 25 m.

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