Concept of Gap Distance in Motion Interaction between Multiple Floating Bodies

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Paper History

Received: 15-December-2013
Received in revised form: 18-December-2013
Accepted: 20-December-2013

ABSTRACT

Conceptual study on gap distance between multiple floating structures system was related to the effect of wave particle motion on structure motion. The evaluation on the gap distance between floating structures is an important study for multiple floating structures system especially for deep water liquefied natural gas, LNG exploration because the small gap distance between floating structures is needed to guarantee the effectiveness of LNG transfer. This conceptual study only discussed the effect of wave particle motion to the varying of gap distance between structures based on theoretical point of view. The expected result was generated by simple harmonic motion equation but it is no been validate in this paper. The expected result shown that the wave length and the structures initial gap distance give a significant effect to the minimum gap distance can be achieved by two floating structures. The mentioned minimum gap distance in this paper mean minimum distance between two floating structures achieved due to surge motions induced by wave. In addition, the comparison to various selected case found that at the condition where one structure face wave crest and other structure face wave trough will caused closest minimum gap distance between floating structures but minimum gap distance will be the largest if both structures face wave crest and wave trough at simultaneously. Therefore, proper selection of initial gap distance for different ocean condition can help to avoid crashing happen on structures when experience wave induced motion.

KEY WORDS: *Gap Distance, Floating Structures, Motion*.

NOMENCLATURE

LNG Liquefied Natural Gas

1.0 INTRODUCTION

Offshore floating structures are often arranged close to each other to complete as a system. Multiple floating structures such as tandem and side-by-side arrangements have been an important research area in the offshore industries recently. Study of the gap distance in multiple floating bodies becomes an important to ascertain the safety of the bodies' arrangement.

Response of structures to environment at open water is an important criterion to be evaluated to ensure the system operates safely. The comparison between single floating structures with multiple structures was made by Siow et.al shows that the hydrodynamic interaction effect may cause the floating structures to experience larger motion amplitude in all six types of motion [13]. This phenomenon can cause accidents on floating structures such as crash between structures. Therefore, multi structures operation should give more attention during design and it requires more accurate analysis of hydrodynamic interactions between closely moored structures [6].

In this research, influence of wave to the minimum distance between structures is discussed. The mentioned minimum gap distance in this paper mean minimum distance between two floating structures achieved due to surge motions induced by wave. To simplify the discussion, the tandem arrangement is considered here. Thus, only the surge motion is only the effect to causes the change of gap distance between floating structures. At the end of discussion, this conceptual study shown that the initial gap distance and wave length will give significant effect to the minimum gap distance of two floating structures.

2.0 LITERATURE REVIEW

Matos et.al commented that the vertical plane motions induced by heave, roll and pitch should be kept adequately low to guarantee the safety of the floating structure, risers and umbilical pipes and other important facilities use in oil production [22]. The operability and safety of floating bodies operation are greatly determined by the relative motions between them. So, the accurate motion prediction of two bodies included all the hydrodynamic interaction is greatly important [10].

Motions of floating structures can be analysed by applying strip theory and potential theory. A number of notable studies were carried out to study hydrodynamic interaction phenomena such as Ohkusu[12] and Kodan[9].

Hess and Smith [5], Van Oortmerssen[17] and Loken[11] studied on non-lifting potential flow calculation about arbitrary 3D objects. They utilized a source density distribution along the structure surface and solved for distribution necessary to lake the normal component of the fluid velocity zero on the boundary. Also, Wu et.alwere studied the motion of a moored semi-submersible in regular waves numerically and experimentally. In their mathematical formulation, the moored semi-submersible was modeled as an externally constrained floating body in waves, and derived the linearized equation of motion [18].

Yilmaz and Incecik analysed the excessive motion of moored semi-submersible. They developed two different time domain techniques due to mooring stiffness, viscous drag forces and damping; the mathematic models are strong nonlinearities in the system. In the first technique, first-order wave forces acting on a structure which considered as a solitary excitation force and evaluated by using the Morison equation. In the second technique, mean drift forces were used to calculate slow varying wave forces and simulate slow varying and steady motions [19]. Söylemez developed a technique to predict damaged semi-submersible motion under wind, current and wave. An approaching equation of motion based on Newton's second law was used in the research to develop a nonlinear numerical technique for both intact and damaged condition in time domain [14].

Besides, the hydrodynamic interaction effect was studied by Kashiwagi. He introduced a hierarchical interaction theory in the framework of linear potential theory used to study hydrodynamic interactions between a large numbers of columns supporting flexible structure. He also furthers the research to investigate wave drift force and moment on two side by side arranged ships by using Higher-order boundary element method (HOBEM). His research obtained that the hydrodynamic interaction force is more predominant in the motion equation in the shorter wavelength region due to resonant phenomena. Kashiwagi was also concluded that the intensity of the interaction force is dependent upon the ratio of the wavelength to the separation distance between two adjacent cylinders. After that, Kashiwagiwas also investigated the applicability of wave interaction theory apply to simulate the small gap length condition. The study obtained that the wave interaction theory able to predict the motion accurately if the separation between the structures is satisfied with the addition theorem of Bessel functions [8].

Besides, Choi and Hong were also applied HOBEM to analysis hydrodynamic interactions of multi-body system [3]. Clauss et al. analyzed the sea-keeping behavior of a semi-submersible in rough waves in the North Sea by numerical and experimental method. They used 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 to moderate sea condition only [4].

On the other hand, Spyros was also purposed a design oriented semi-analytical method to solve the radiation problem and evaluate the hydrodynamic and interaction coefficients [15]. An analytical solution to solve hydrodynamic diffraction problem of arrays of elliptical cylinders were also introduced by Ioannis and Spyros [7]. In the research, he obtained that the variation of hydrodynamic loading on the interaction cases is in relative to the wave heading angle. Besides, the effect of structures numbers affects to hydrodynamic interaction was also covered by Tajali et.al [16]. Their research results indicated that by increase the number of pontoons can cause the peak frequency and peak amplitude for all motion increase.

A numerical method also employed by Zhu et.al to study the effect of gap in multiple box shape structure system. In that study, the potential for incident wave and scattering wave were ignored, the motion of the structures is assumed only affected by radiated wave [21]. The gap distance was ranged from 1% of breadth to 50% of breadth. The simulation showed that the hydrodynamic interaction between floating structures can caused by the surge, sway and heave motion; however, only sway motion shows a strong interaction at certain resonance wave number. And then, Zhu et.al was also carried out a research on hydrodynamic resonance phenomena of three dimensional multiple floating structures by applying linear potential theory in time domain. The gap was limited to 1% compared to the breadth. The research found that peak force response on floating bodies at resonance frequency is same between frequency domain technique and time domain technique. This proved that the time domain technique can be an alternative to investigate hydrodynamic interaction phenomena between floating bodies in small gap [21].

Zhao et.al was carried out a study of hydrodynamic interaction between FLNG vessel and LNG carrier which arranged in side by side arrangement. They were observed that the hydrodynamic interactions give more influence to the surge, sway and yaw motions. In addition, they also discovered that the interaction between structures able to affect the load on the structures connection systems [20].

In addition, few experimental tests were carried out to obtain the motion response of structures. A model test related to interaction between semi-submersible and TLP was carried out by Hassan Abyn et al. [1]. In continue Hassan Abyn et.al also tried to simulate the motion of semi-submersible by using HydroSTAR and then analyze the effect of meshing number to the accuracy of execution result and execution time [2]. Besides that, K.U. Tiau was simulating the motion of mobile floating harbor which have similar hull form as semi-submersible by using Morison Equation [23]. To investigate the interaction effect to structure motions, C. L. Siow et.al were made a comparison on the motion of semi-submersible when it alone to interaction condition by using experimental result [13].

From the series of reviews, it can obtain that a lot of effort was made by many researchers to study the hydrodynamic interaction phenomena. The literature review also shown that the previous research on this area carried by other researchers are preferred to study on the effect of hydrodynamic interaction to wave forces acting of structures, change of hydrodynamic coefficient and structures motion in response to wave. To prevent the crashing occur in multiple structures system, this research is focused in analyses the change of gap distance due to structures motions. Thus, the main proposed of this research is developed a concept to relate the gap distance between two floating bodies to its motion induced by wave.

3.0 WAVE INDUCED HORIZONTAL PLANE MOTION

In this study, the structures are considered arranged in tandem arrangement. Thus, the distance between structures is predicted influence by surge motion of the structures. Influence from wave to structures' distance can be explained by wave theories. The expression for wave potential as follows:

$$\phi = -\frac{ga\cosh k(d+z)}{w}\cos(kx - wt) \quad (1)$$

By differential the velocity potential in x direction and z direction, the velocity component can be obtained are:

Horizontal velocity component

$$u = \frac{\partial\phi}{\partial x} = \frac{gak}{w}\frac{\cosh k(z+d)}{\cosh kd}\sin(kx - wt) \quad (2)$$

Vertical velocity component

$$w = \frac{\partial\phi}{\partial x} = -\frac{gak}{w}\frac{\sinh k(z+d)}{\cosh kd}\cos(kx - wt) \quad (3)$$

In addition, the wave particle motion is assumed to have a fixed point (x_0, z_0) in the wave and the new coordinates of wave particle can be represented by ξ and ζ as shown in figure 1.

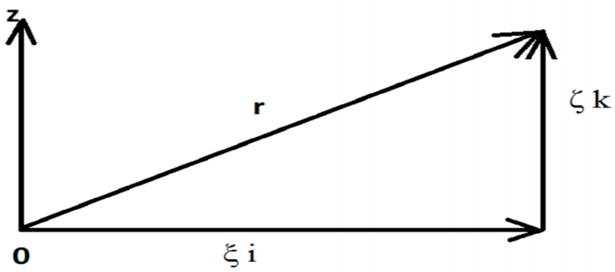

Figure 1: Wave particle motion

The coordinates can be defined by the following:

$$\xi = \int_0^t \frac{\partial\phi}{\partial x}\,dt \;\; and \;\; \zeta = \int_0^t \frac{\partial\phi}{\partial z}\,dt \quad (4)$$

Thus the position vector to describe wave particle motion is

$$r = \xi\, i + \zeta\, k \quad (5)$$

$$r = \frac{a}{\sinh(kd)}[\cosh(kz_0 + kd)\cos(kx_0 - wt) + \sinh(kz_0 + kd)\sin(kx_0 - wt)\,k] \quad (6)$$

From the above equation, it is shown that the value of kd inside the hyperbolic function determines the shape of the particle paths of wave at different water depth.

This paper is focused on deep water condition because only floating structures are applicable for offshore industry at this area. Therefore, the equation can be simplified. In deep water condition,

$$\sinh(kd) \cong \cosh(kd) = \frac{e^{kd}}{2} \;\; and \;\; \tanh(kd) \cong 1$$

Thus,

$$r = ae^{kz_0}[\cos(kx_0 - wt)i - \sin(kx_0 - wt)\,k] \quad (7)$$

The variable ξ and ζ at the equation describes a circular path of the water particle. At deep water condition, ξ = ζ so that it can assume the water particles move in a circle at the free surface and the radius is equal to wave amplitude.

At theoretical of view, the particles in the water typically would execute a circular motion as a wave passed. Likewise, the water particle also assumes without significant net advance in their position. As illustrated in the figure 2, the direction of particle motion will follow wave direction as the crest of the wave passes, but move backward as the trough of the wave passes. This particle motion is oscillate at the same position when the next peak arrives.

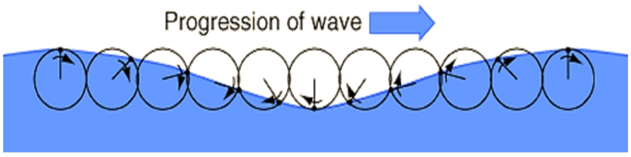

Figure 2: The water particle motion along wave passes. [ref:http://hyperphysics.phy-astr.gsu.edu/hbase/waves/imgwav/circonwave.gif]

In this study, the surge motion of the structures induces by wave is assumed affected by the water particle motion. The magnitude of wave particle motion and the motion direction was pushing both the structures to move closer or farther from each other from its original distance between structures.

4.0 GAP DISTANCE BETWEEN STRUCTURES

The gap distance between floating structures is assumed effected by the relative motion between two floating structures. To simple the study, let assumed the floating structures are arranged in tandem arrangement. Therefore, only surge motion is considered to influence the gap distance between floating structures. Since, the motion of the floating structures is assumed induced by the wave particle motion, it can concluded that the change of gap distance between structures is highly influence by the wave particle motion.

The figure 3 shown two floating structures arranged in a separate distance, *l*. Hence, the same wave will arrive at the in front structure to induce the motion before it is proceeded to induce the motion at behind structures. Therefore, leading phase between two structures is existed due to the time required by the wave travel from one structure to another structure.

From the theoretical point of view, the leading phase between structures can be calculated if the separate distance between structures and the wave length, λ is known. The equation to calculate the leading phase between structures as follow:

$$\alpha = \frac{l}{\lambda} \times 2\pi \tag{8}$$

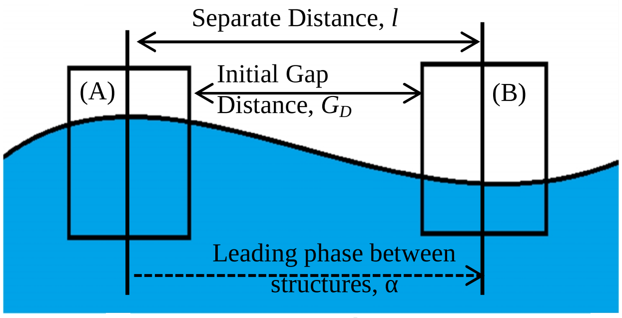

Figure 3: Progressive wave and Structure interaction.

The equation (8) shown that the leading phase between structures, α is in the ratio of structures separation distance, l to the wave length, λ.

To obtain the wave potential acting to the structures (A) and (B), the wave potential represent in equation (1) can be modified by assuming the position-x for structure (A) is zero and position-x for structure (B) is equal to separate distance, l, hence the term $kx = \alpha$. The wave potential act on structures (A) and (B) can be rewritten as follow.

$$\phi_A = -\frac{ga \cosh k(d+z)}{w} \cos(-wt) \tag{9}$$

$$\phi_B = -\frac{ga \cosh k(d+z)}{w} \cos(\alpha - wt) \tag{10}$$

From the equation (10), it is obtained that wave arrived on structure (B) always leading by an phase, α. Therefore, the motion on the structure (B) will always have a leading phase of α compare to structure (A). In this case, the surge motion of the floating structures can be represented as following equation.

$$X_A(t) = \bar{X}_A \sin(-wt + \beta_A) \tag{11}$$

$$X_B(t) = \bar{X}_B \sin(\alpha - wt + \beta_B) \tag{12}$$

Where $X_A(t)$ and $X_B(t)$ is the surge motion for structure (A) and structure (B), $\bar{X}_A$ and $\bar{X}_B$ is the surge amplitude for structure (A) and structure (B), β_A and β_B is the leading phase between wave to structure motion for structure (A) and structure (B), α is the leading phase between structures, w is the wave speed in rad/seconds and t is the time in seconds.

Next, the change of gap distance between two floating structures can be calculated based on the relative motion of the floating structures. The gap distance between two floating structures, $G(t)$ in tandem arrangement can be calculated by considered the original gap distance, G_D, surge motion of both structures. The simplified equation as follows,

$$G(t) = G_D + [X_A(t) - X_B(t)] \tag{14}$$

$$G(t) = G_D + [\bar{X}_A \sin(-wt + \beta_A) - \bar{X}_B \sin(\alpha - wt + \beta_B)] \tag{15}$$

From the equation (14), it is obtained that the individual surge motion of the floating structures will contribute to the change of gap distance between floating structures when the wave progress pass through the floating structures.

5.0 DISCUSSION

As mentioned, the wave particle motion is the factor contributes to the surge motion of floating bodies. Also, the radius of wave particle motion is influence by wave length. On the other hand, the equation (15) shown that the change of gap length in time domain, $G(t)$ can be estimated by consider the individual structure's surge motion and leading phase. The relative motion between structures which influence by the leading phase between structures, α is the main factor to causes the gap distance between structures varying in time.

In continue to study the effect of wave length and structures arrangement to the change of gap distance in time, $G(t)$, total five casesare highlighted in this paper there are the ratio of wave length, λ to the separate distance between structures, l equal to 4, 2, 4/3, 1 and 2/3.

To make the comparison between the changes of gap distance between floating structures for the five selected cases, few assumptions is applied here. First, let assume the motion response for both the floating structure is always the same regardless any wave frequency and let the surge RAO is 0.1 for all cases. Second, both the structures are assumed as a same type of structures hence the effect of the motion to wave leading phase, β_A and β_B is ignorable. Third, the original gap distance, G_D is half of theseparate distance, l. Let assumed that the separate distance between floating structures, l is 1 unit, then the change of gap distance between floating structures in respected to the initial separate distance between floating structures, G_D is shown as at figure 4 to figure8.

From figure 4 to figure 8, the comparison of relative surge motion and change of gap distance between two floating structures are shown. In this conceptual comparison, all initial gap length is settled to 0.5 and the surge amplitude for both structures are always 0.1. Due to the change of wave length in all the presented five cases, this study obtained that the minimum gap distance can be achieved by floating structures is difference compare to each other.

In these comparison, the closest gap distance can be achieved is falling on cases λ=*2l* and λ=*2/3l*. The similarity for these two case are the leading phase between two floating structures can be represented by the equation $\alpha = 360^0 N + 180^0$ where *N = 1, 2, 3* … is the number of complete wave length within the distance of two structures. Both the case λ=*2l* and λ=*2/3l* have the value of *N=0* and *1* respectively. Hence, the leading phase between structures are 180^0 and $(360+180)^0$ respectively. At these cases, if one floating structure receive wave crest, then another floating structure will face wave trough. Due to wave particle motion as discussed in this paper, against direction of wave particle motion causing the floating structures move in opposite direction respective to each other and then lead to the closest gap distance and the most far gap distance compared to other cases at the constant surge amplitude.

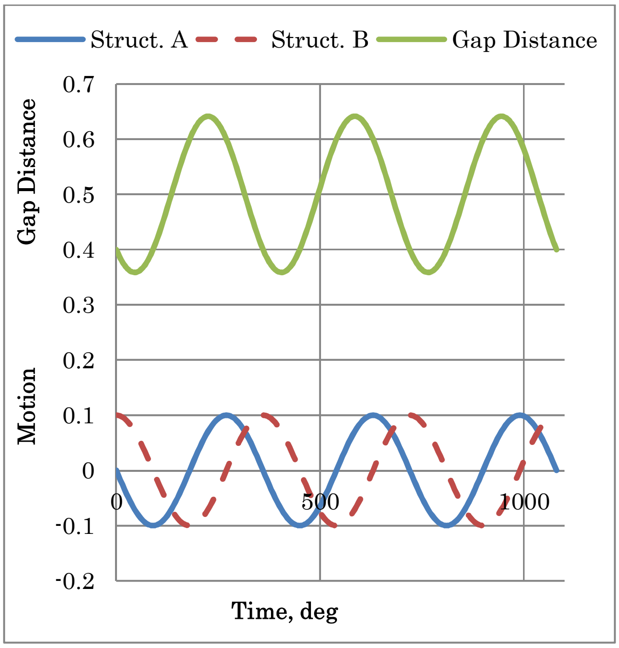

Figure 4: Surge motion of structures and distance between structures for $\lambda=4l$.

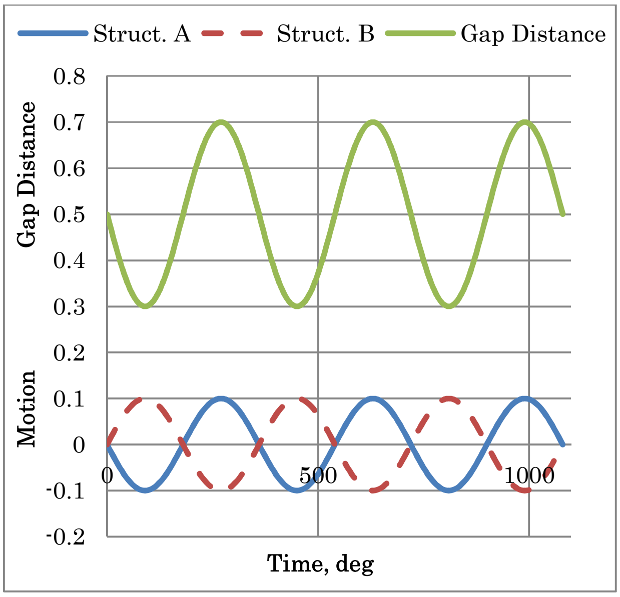

Figure 5: Surge motion of structures and distance between structures for $\lambda=2l$.

On the other hand, if the wave length is same as gap distance between structures, the minimum gap distance will be the largest compare to other cases. As shown in figure 7, it is no varying in gap distance based on the assumption and calculation by using equation (15). At this condition, both the floating structures will facing wave crest and wave trough at the same time. This causing both floating structures move in same direction and magnitude due to the direction wave particle motion as discussed in this paper. This phenomenon causes the gap distance between floating structures experience a minimum changing compare to other cases.

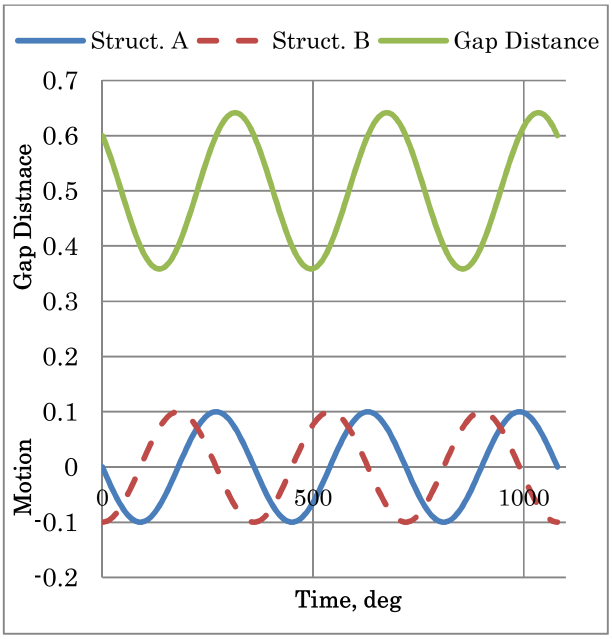

Figure 6: Surge motion of structures and distance between structures for $\lambda=4/3l$.

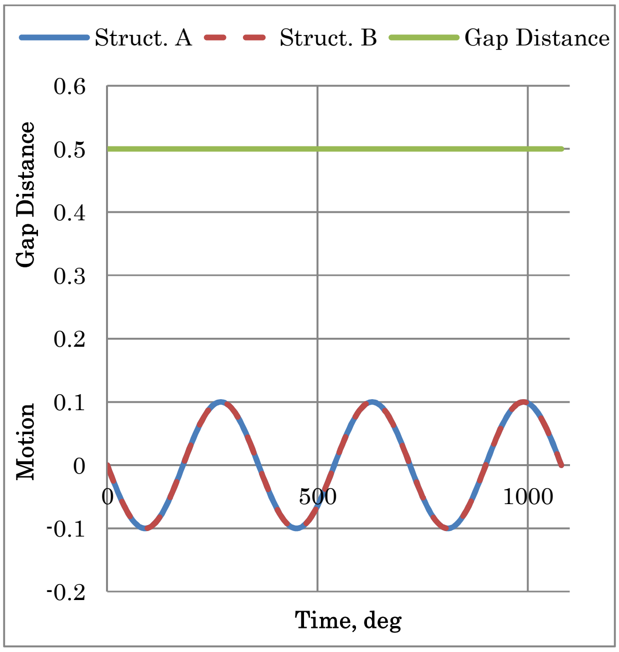

Figure 7: Surge motion of structures and distance between structures for *λ=l.*

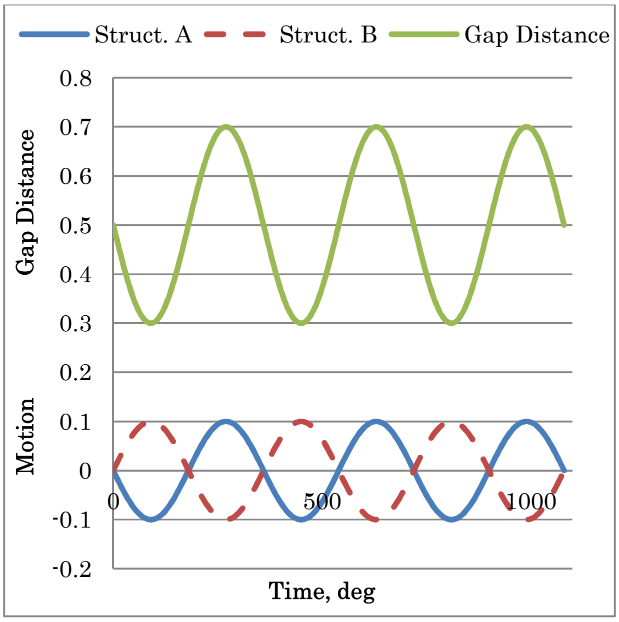

Figure 8: Surge motion of structures and distance between structures for *λ=2/3l.*

6.0 CONCLUSION

The concept of gap distance between floating structures was presented in this paper. The factor of varying of gap distance between floating structures is related to the wave particle motion. Due to the effect of the direction of wave particle motion, the minimum gap distance between floating structures can be different for different wave length. This is because the wave length is the main factor to decide either both the floating structures will face a wave crest or wave trough at same time or against. And then, this phenomenon can lead to the change of motion direction for both floating structure where this change can give a significant effect for the minimum gap distance between floating structures. From this preliminary study, the minimum gap distance between floating structures is the largest compare to other cases if both floating structures experience wave crest or wave trough simultaneously. In opposite, the closest gap distance will obtained if one structure experience wave crest while other structure experience wave trough.

However, actual condition is more complicated compared to this conceptual study. This is because the structures motion's response is varying depend on the wave frequency. The change of motion response will causes the amplitude of surge motion changed and this will lead to the change of gap distance between floating structures. Besides that, hydrodynamic interaction between floating structures is one of the complicated phenomena which can give a significant effect on the structures' motion. Hence, the effect of hydrodynamic interaction between floating structures to the gap distance between structures has to investigate to ensure the workability of this presented concept. In order to evaluate the gap distance between floating structures to ensure the safety of the structures arrangement, experiment test may carry out to obtain the change of gap distance between floating structures in more realistic condition.

ACKNOWLEDGEMENT

The authors would like to acknowledge Universiti Teknologi Malaysia and Ocean and Aerospace Research Institute, Indonesia.

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