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Prediction of Semi-Submersible's Motion Response by Using Diffraction Potential Theory and Heave Viscous Damping Correction

C. L. Siow[a], Jaswar Koto[a,b*], Hassan Abby[c], N. M. Khairuddin[a]

[a]Departement of Aeronautic, Automotive and Ocean Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Ocean and Aerospace Research Institute, Indonesia
[c]Marine Engineering and Naval Architecture Department, Engineering Faculty, Persian Gulf University, Iran

*Corresponding author: jaswar@fkm.utm.my

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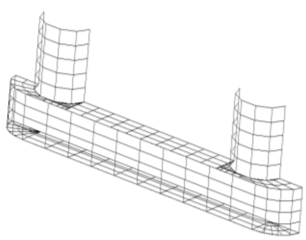
Graphical abstract



Abstract

This paper proposes a three dimensional diffraction potential theory with heave viscous damping correction to predict motion response of multiple hulls semi-submersible structure. The heave viscous damping correction was applied in this paper to avoid the execution return an infinity value for heave motion when the heave motion is dominated by damping term. On previous stage, this method was shown it capability to apply on single hull structure. However, some modification is required to able the single hull diffraction potential theory applied to multiple hull structure. Upon this stage, the modification was made into the meshing system in purposes to able the numerical coding calculate the response of semi-submersible structure. This paper also presented the comparison between the result calculate by diffraction potential theory, commercial software-Hydrostar and experiment result in the selected semi-submersible model. In the comparison, it is obtained that the tendency between the numerical results and the experimental result is agreed between each other.

Keywords: Multiple hulls; semi-submersible; motion response; diffraction potential; green function

1.0 INTRODUCTION

In a recent development, multiple hull structures such as semi-submersible structure and tension leg platform are popular structures often used in deep water oil and gas exploration. The reason for both structures become favour in the deep water is because both the structures have good response characteristic to the incident wave.

To study the motion response of multiple hull structure, numerical simulation approach often use as a research tool to evaluate the dynamic stability of the structure. The numerical analysis method for multiple hull structures is slightly different compared to single hull structure. Existing of hydrodynamic interaction effect in multiple hull structure can cause the response amplitude for the structures increased or decreased depending on the structures characteristic and environment condition such as incident wave frequency and incident wave angle.

In this study, semi-submersible structure is selected as an offshore structure model. To achieve objective of this research, a programming code was developed based on diffraction potential theory and it is written in visual basic programming language. By comparing the numerical result executed by using diffraction potential theory to experiment result, it is obtained that this theory able to predict the motion response for semi-submersible with acceptable accuracy most of the time, except for heave motion when the wave frequency near to the structure heave natural frequency [17].

In order to correct the over-predicting phenomenon made by the diffraction potential theory, this research was trying to increase the damping coefficient by adding viscous damping into the motion equation. From that study, the viscous damping is treated as extra matrix and can be added into the motion equation separately. The effect of this additional viscous damping to correct the heave motion response was also tested as the authors before [19]. From the study, it is observed that the existing of heave viscous damping was changed the tendency of heave damping at low frequency zone and this helped to avoid the diffraction potential theory to return an infinity heave response value when the wave frequency is closer to structure's natural frequency [19].

This study is proposed to expend the numerical method which previously use for single hull structures to able it apply for multiple hull structures especially for offshore structure such as semi-submersible. The discussion focuses on the meshing system which required modifying for multiple hull structures and the diffraction programming calculation procedure. After that, this paper also will discuss the comparison between then tendencies of the numerical result compared to the experimental result. The comparison showed that the diffraction potential theory with the heave viscous damping correction method is fixed well to the result obtained from motion experiment.

2.0 LITERATURE REVIEWS

Oscillating of floating structure caused by wind, wave and current affects loading and offloading operation systems. Hess and Smith, Van Oortmerssen and Loken studied on non-lifting potential flow calculation about arbitrary 3D objects [1, 2, 3]. They utilized a source density distribution on the surface of the structure and solved for distribution necessary to lake 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 is 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. Besides, Wu *et al*. also studied on the motion of a moored semi-submersible in regular waves and wave induced internal forces numerically and experimentally [4]. 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 analysed the excessive motion of moored semi-submersible [5]. They developed and employed two different time domain techniques due to mooring stiffness, viscous drag forces and damping. In the first technique, first-order wave forces acting on a structure which considered as a solitary excitation force and evaluated according Morison equation. In the second technique, they used mean drift forces to calculate slowly varying wave forces and simulate for slow varying and steady motions. Söylemez developed a technique to predict damaged semi-submersible motion under wind, current and wave [6]. He used Newton's second law for approaching equations of motion and developed numerical techniques of nonlinear equations for the intact and damaged condition in time domain.

Clauss *et al.* Analysed the sea-keeping behaviour of a semi-submersible in rough waves in the North Sea numerically and experimentally [7]. They used panel method TiMIT (Time-domain investigations, developed at the Massachusetts Institute of Technology) for wave and structure interactions in time domain. The theory behind TiMIT is strictly linear and thus applicable to moderate sea condition only.

An important requirement for a floating unit with drilling capabilities is the low level of motions in the vertical plane motions induced by heave, roll and pitch. Matos *et al*. were investigated second-order resonant of a deep-draft semi-submersible heave, roll and pitch motions numerically and experimentally [8]. One of the manners 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. They generated different number of meshes on the structure and calculated pitch forks.

Wackers *et al.* was reviewed the surface descretisation methods for CFD application with different code [9]. Besides, simulation of fluid flow Characteristic Around Rounded-Shape FPSO was also conducted by A. Efi *et al*. using RANs Method [10]. Jaswar *et al*. were also developed an integrated CFD simulation software to analyse hull performance of VLCC tanker. The integrated CFD simulation tool was developed based on potential theory and able to simulate wave profile, wave resistance and pressure distribution around ship hull [11].

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.* [12]. In continuing Hassan Abyn *et al*. also tried to simulate the motion of a semi-submersible by using HydroSTAR and then analysed the effect of meshing number to the accuracy of execution result and execution time [13]. Besides, C. L. Siow *et al.* also make a comparison on the motion of a semi-submersible when it alone to interaction condition by using previous experimental result [14]. Besides that, K. U. Tiau (2012) was simulating the motion of mobile floating harbour which have similar hull form as semi-submersible by using Morison Equation [15].

3.0 BASIC MATHEMATIC MODEL

3.1 Diffraction Potential

In this study, the diffraction potential theory was applied to obtain the wave force act on the semi-submersible structure. The regular wave acting on floating bodies can be described by velocity potential. The velocity potential normally written in respective to the flow direction and time as below:

$$\Phi(x,y,z) = Re\left[\phi(x,y,z)e^{iwt}\right] \quad (1)$$

$$\phi(x,y,z) = \frac{g\varsigma_a}{iw}\{\phi_0(x,y,z)+\phi_7(x,y,z)\} + \sum_{j=1}^{6} iwX_j\phi_j(x,y,z) \quad (2)$$

Where,

g	:	Gravity acceleration
ς_a	:	Incident wave amplitude
X_j	:	Motions amplitude
ϕ_0	:	Incident wave potential
ϕ_7	:	Scattering wave potential
ϕ_j	:	Radiation wave potential due to motions
j	:	Direction of motion

From the above equation, it is shown that total wave potential, ϕ in the system is contributed by potential of the incident wave, ϕ_0, scattering wave, ϕ_7 and radiation wave, ϕ_j. In addition, the phase and amplitude for both the incident wave and scattering wave is assumed to be the same. However, radiation wave potentials are affected by each type of motion of each single floating body inside system, where the total potential for radiation wave for the single body is the summation of the radiation wave generates by each type of body motions such as roll, pitch, yaw, surge, sway and heave.

Also, the wave potential $\emptyset$ must be satisfied with boundary conditions as below:

$$\nabla^2\emptyset = 0 \quad for\ 0 \le z \le h \quad (3)$$

$$\frac{\partial\emptyset}{\partial z} + k\emptyset \quad at\ z = 0 \quad (k = \frac{w^2}{g}) \quad (4)$$

$$\frac{\partial\emptyset}{\partial z} = 0 \quad at\ z = h \quad (5)$$

$$\emptyset \sim \frac{1}{\sqrt{r}}e^{-ik_0 r} \quad should\ be\ 0\ if\ r\ \infty \quad (6)$$

$$\frac{\partial\emptyset_7}{\partial n} = -\frac{\partial\emptyset_0}{\partial n}\ on\ the\ body\ boundary \quad (7)$$

3.2 Green Function and Wave Potential

By considering the wave potential only affected by structure surface, S_H, the wave potential at any point can be presented by following equation:

$$\emptyset(P) = \iint_{S_H} \left\{ \frac{\partial \emptyset(Q)}{\partial n_Q} G(P;Q) - \emptyset(Q) \frac{\partial G(P;Q)}{\partial n_Q} \right\} dS(Q) \quad (8)$$

Where $P = (x, y, z)$ represents fluid flow pointed at any coordinate and $Q = (\xi, \eta, \varsigma)$ represent any coordinate, (x, y, z) on structure surface, S_H. The green function can be applied here to estimate the strength of the wave flow potential. The green function in Equation (8) can be summarized as follow:

$$G(P;Q) = -\frac{1}{4\pi\sqrt{(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2}} + H(x-\xi, y-\eta, z+\zeta) \quad (9)$$

Where $H(x-\xi, y-\eta, z+\zeta)$ in Equation (9) represent the effect of free surface and can be solved by second kind of Bessel function.

3.3 Wave Force, Added Mass and Damping

The wave force or moment acts on the structure to cause the motions of structure can be obtained by integral the diffraction wave potential along the structure surface.

$$E_i = -\iint_{S_H} \phi_D(x,y,z) n_i dS \quad (10)$$

Where, ϕ_D is diffraction potential, $\phi_D = \phi_o + \phi_7$

Also, the added mass, A_{ij} and damping, B_{ij} for each motion can be obtained by integral the radiation wave due to each motion along the structure surface.

$$A_{ij} = -\rho \iint_{S_H} Re[\phi_j(x,y,z)] n_i dS \quad (11)$$

$$B_{ij} = -\rho w \iint_{S_H} Im[\phi_j(x,y,z)] n_i dS \quad (12)$$

n_i in Equation (11) to Equation (13) is the normal vector for each direction of motion, i = 1~6 represent the direction of motion and j = 1~6 represent the six types of motions.

3.4 Viscous Damping

The modified viscous damping from the equation provided by S. Nallayarasu and P. Siva Prasad [20] is shown as follows expression:

$$b_v = \nu\, [(M + A_{33}) w_n]\, C \quad (13)$$

Where b is heave viscous damping of the floating structure, ν is damping ratio for heave, M is the mass of the floating structure, A_{33} is heave added mass of floating structure and it is calculated from diffraction potential theory and w_n is heave natural frequency and C is the constant for the viscous damping.

The damping ratio, ν and heave natural frequency, ω at the Equation (13) can be found from heave decay experiment. Based on the result obtained from heave decay experiment, the logarithmic decrement method which defines the natural log of the amplitude of any two peaks can be used to find the damping ratio of an under-damped system. The equation for the logarithmic decrement, δ as follows

$$\delta = \frac{1}{n} \ln\left(\frac{x_0}{x_n}\right) \quad (14)$$

Where x_0 is the first peak amplitude and $x_n$is the n-th peak amplitude. After the logarithmic decrement, δ found, the damping ratio ν can be found from the following equation:

$$\nu = \frac{\delta}{\sqrt{\delta^2 - 4\pi^2}} \quad (15)$$

Besides, the heave decay experiment also can be used to obtain the damped natural frequency, w_d and heave natural frequency, w_n by following equation:

$$w_d = \frac{2\pi}{T} \quad (16)$$

$$w_n = \frac{w_d}{\sqrt{1-\varsigma^w}} \quad (17)$$

Where the variable T is period of heave oscillation motion or time required for two continue successive amplitude peaks.

By inserting the data obtained from heave decay experiment into Equation (13), the heave viscous damping will able to calculate and inserting into the motion equation as follows:

$$(M + A_{33})\ddot{X}_z + (B_{33} + b_v)\dot{X}_z + cX = F \quad (18)$$

Where the M is structure mass, A_{33} is heave added mass, B_{33} is linear damping from diffraction potential theory, b_v is the viscous damping defined at Equation (13), c is the heave restoring force, and F is the wave force contributed to heave motion.

■4.0 MULTIPLE HULL NUMERICAL METHOD

4.1 Rule for Meshing Data and Offset Data

In this study, the expansion of mono hull numerical method to multiple hull numerical method is made to meshing system. Interaction between hulls by radiation wave was ignored in this study. The purpose of this study is to discuss the possibility to produce the multiple hull numerical method bases on the mono hull method and the accuracy of diffraction potential theory to predict the motion response of multiple hull structure such as this selected semi-submersible.

In this numerical method, the right hand rule is applied. The panel coordinate must arranged follow this rule to ensure the execution of normal vector and it's direction is in the correct manner.

In addition, offset data covered the half breadth of the one side of hull is also required to execute the wave force on the structure. The offset data should be made separately for both the column and pontoon to avoid the programming code wrong reading the data and then generate wrong meshing on the structure.

The selected semi-submersible model in this study is constructed based on GVA 4000 type. Total panels used in the execution are 272 where 25 panels on each column and 222 panels on pontoon surface. The sample meshing constructed by this numerical method for the semi-submersible model is shown in Figure 1.

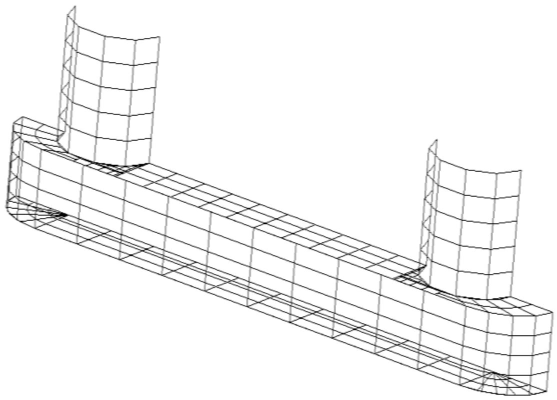


Figure 1 Meshing for semi-submersible model

4.2 Programming Flow Chart

In the general, this numerical method for multiple hull structure is almost similar with the mono hull method. The numerical method will only execute the wave force acting on one side of hull and then multiply the magnitude of force according to the number of hull for the selected structure.

As similar with other numerical method, this numerical method start with meshing generation and then execute the normal vector, centre point of each panel and area for each panel. After that, the program will construct matrix element for distribution of sources and normal dipoles over the panel.

Next, wave potential on each panel will solve by using green function and Bessel function. After that, radiation force and diffraction will be obtained. To continue, the total wave force acting on the structure to cause the motion can be obtained by summing up the total diffraction force on each panel. At the same time, added mass and damping of the structure at same wave condition can be obtained by summing up the real part of radiation potential and imaginary part of radiation potential.

To include the heave viscous damping in the calculation, the added mass value executed from the diffraction potential theory is required. Besides that, the structure heave decay experiment data, such as damping ratio, natural frequency is needed to provide to the programming manually. Based on the data, heave viscous damping can be obtained by using the Equation (13). In this numerical approach, the heave viscous damping is treated as an independent term which is calculated separately from the diffraction potential theory. The heave viscous damping is added directly into the motion equation which proposes to increase the damping magnitude as shown in Equation (18).

Lastly, the structure motion and it response to wave can be obtained by solving the coupled motion equation. The flow chart of this numerical method is shown in Figure 2.

■5.0 MODEL PARAMETER AND TEST DATA

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

Upon the model complete constructed, few tests were carried out to obtain the model particulars. Inclining test, swing frame test, oscillating test, decay test and bifilar test were carried out to identify the hydrostatic particular for the semi-submersible. The dimension and measured data for the model was summarized as in Table 1.

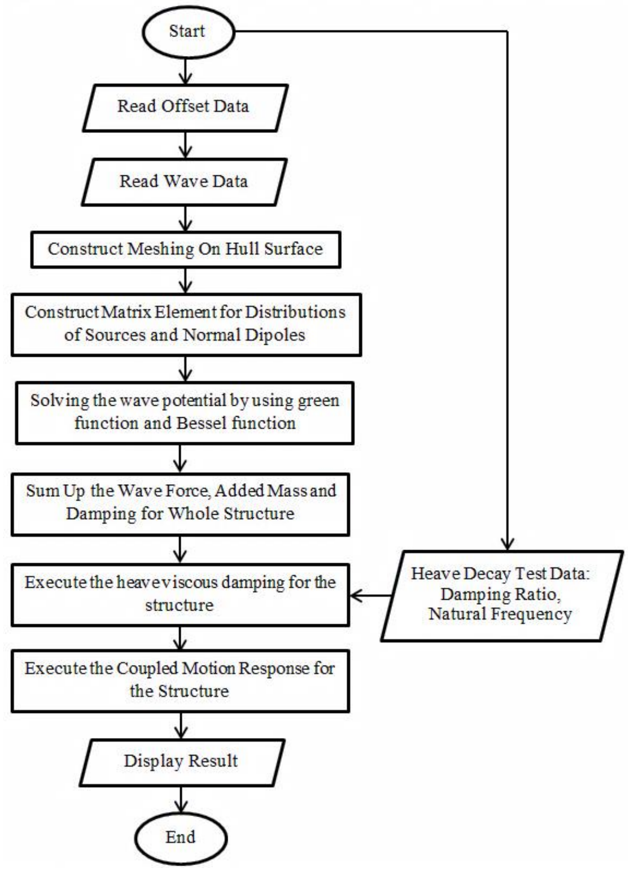


Figure 2 Flow chart for diffraction potential numerical method

Table 1 Principal particular of the structures

Length	0.954 m
Width	0.835 m
Draft	0.239 m
Displacement	0.043501 m^3
Water Plan Area	0.108082 m^2
Number of Columns	4
Pontoon length	0.954 m
Pontoon depth	0.09 m
Pontoon width	0.19 m
Pontoons centerline separation	0.645 m
Columns longitudinal spacing (centre)	0.651143 m
Column diameter	0.151286 m
GM_T	0.041 m
GM_L	0.058 m
K_{XX}	0.452 m
K_{YY}	0.385 m
K_{ZZ}	0.5 m

■6.0 RESULT AND DISCUSSION

In this part, the response amplitude of GVA 4000 semi-submersible structure in head sea condition was discussed. The result from the proposed numerical result was compared to the experimental result. The input for the numerical program was also adjusted to make the condition as close as the experimental condition. Due to the experiment carried out on the head sea condition, hence only surge, pitch and heave motion are discussed in this paper. To check the accuracy of this numerical method, the response amplitude calculated by this diffraction potential theory was compared to experiment result and the result executed by commercial software Hydrostar. To avoid the consideration of scaling effect, all results produced and compared in the model scale. The ratio of model scale to full scale is 1:70 as mentioned in the earlier part. The motion experiment is carried out at Towing Tank belong to Marine Technology Center, UTM with the wavelength from 1 meter to 9.4 meters [12, 17].

As shown in Figure 3 to Figure 5, the tendency of surge, pitch and heave motion response obtained by diffraction potential theory, Hydrostar software and experimental method is agreed between each other. In comparing to Hydrostar, the tendency of result obtained by the diffraction potential theory and Hydrostar is almost similar but only the magnitude of response at certain wave frequency is different. This finding is also proved that the programming code base on the diffraction potential theory is made in correct method and the assumption applies in the programming code is acceptable.

The Figure 3 shown the calculated surge response amplitude of the semi-submersible compared to Hydrostar and experiment result at the head sea condition. In general, tendency for all the results agreed among each other. From the Figure 3, it is obtained that the surge motion increase when the wavelength become longer. The experiment was carried out for the wavelength from 1 meter to 9.4 meters. All results obtained by different methods are agreed that the response of the semi-submersible at the wavelength around 9 meters start to flat-up. This also means that the surge motion for the semi-submersible start to follow the wave high proportionally if the wavelength is longer 9.4 meters.

From the Figure 3 also, it is obtained that the surge motion response for the semi-submersible by the diffraction potential method and Hydrostar are slightly lower compared to the result obtained from the experiment. However, the results from the diffraction potential theory and Hydrostar are acceptable in this situation since the tendencies are quite good fitted to the tendency of the result collected from motion experiment.

In the comparison of results obtained from diffraction potential theory with Hydrostar, it is obtained that both the methods give the similar result for wavelength below 6 meters. However, if the wavelength longer than 6 meters, it is obtained that the Hydrostar able to detect higher motion response compared to diffraction potential theory. Therefore, surge response calculated from Hydrostar is closer to the experiment result compared to the diffraction potential theory at this wave condition.

The pitch motion response for semi-submersible structure calculated by diffraction potential theory, Hydrostar and experiment method is shown in Figure 4. In the Figure 4, it is obtained that the tendency of pitch response calculated by the diffraction potential theory and Hydrostar is slightly different. The diffraction potential gives lower pitch response compared to Hydrostar in the comparison. By comparing to the experimental results, it can be obtained that the diffraction potential theory will able to predict the pitch motion response better at the shorter wavelength where the wavelength is below 4 meters. The Figure 4 also shown that the Hydrostar is over-predicted the pitch motion response for the semi-submersible when the wavelength is short.

When the wavelength longer than 5 meters, it can observed that the tendency of pitch motion response calculated by Hydrostar is better fixed to the experiment results compared to diffraction potential theory. The lower estimation of pitch response to the diffraction potential theory may cause by the ignored of drag effect. Therefore, the total pitch moment calculated by the diffraction potential theory is lower and then caused the predicted pitch response slightly lower compared to the pitch response predicted by Hydrostar and experiment method.

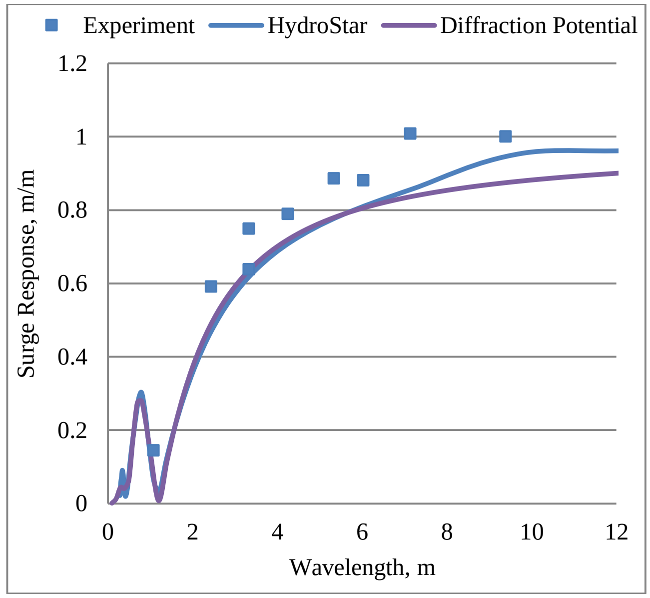


Figure 3 Surge motion response for semi-submersible model

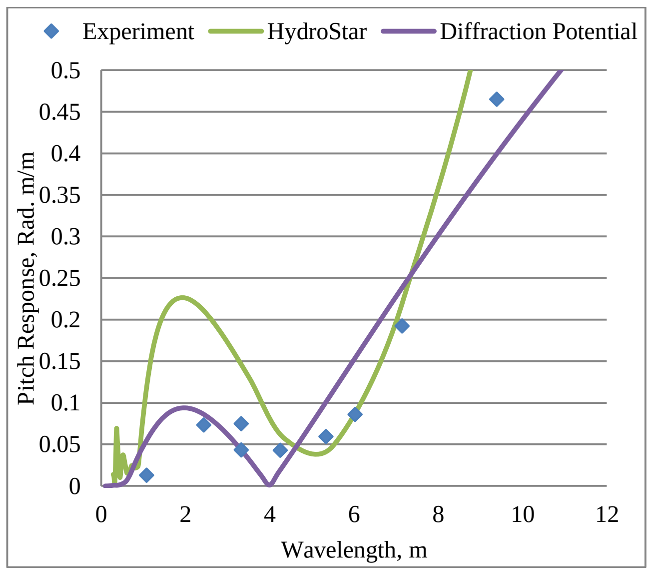


Figure 4 Pitch motion response for semi-submersible model

The heave motion response for the semi-submersible is shown in Figure 5. The comparison of the heave motion response estimated by all three methods obtained that the tendency of the result is slightly different between each other. In comparison to the experimental result, it is observed that the diffraction potential theory with heave viscous damping correction gives an acceptable accuracy in predict the heave motion response especially for wavelength below 6 meters. The heave viscous damping involved in the calculation by diffraction potential theory is proposed to avoid the motion response executed by the diffraction potential theory returned infinity value due to the very low damping estimated by the theory [19]. If the heave response is calculated from pure diffraction potential theory only, it can be observed the diffraction potential theory will return an infinity heave motion response at the wavelength around 9 meters [17].

In this study, the heave response calculated by the diffraction potential theory at the wavelength around 9 meters is reduced to the reasonable level due to the effect of heave viscous damping. However, it is still observed that the heave motion response calculated by the diffraction potential theory for wavelength longer than 6 meters is still no good fixed to the experimental result. This is because neglected of the drag effect on the diffraction potential theory causes the heave motion response calculated by this theory become no similar to the experimental method. The neglected of the drag effect in the execution was causing the damping and the drag force ignored in the calculation and then caused the wrong execution when the drag effect is dominated. From the study, the region where the heave motion dominates by damping term is located at the location where the wave frequency is close to the structure natural frequency [18]. Therefore, it can observe from the Figure 5 the tendency of the heave response calculated by the diffraction potential theory is no good fixed with the heave motion response when the wavelength longer than 6 meters.

Besides, the heave motion response calculated by Hydrostar is better fixed with the experimental result compared to the diffraction potential theory. Since the background of the Hydrostar is strongly developed base on potential theory, it is still suffering an overshooting of heave motion response prediction when the wave frequency is closer to structure heave natural frequency.

In comparing between the heave motion response tendencies estimated by diffraction potential theory to Hydrostar, it is observed that both the method gives the maximum peak response at the different wavelength. The maximum peak response obtained by Hydrostar is located at wavelength 7.0 meters while the diffraction potential theory is located at 9.5 meters. Besides that, the heave response by diffraction potential theory also gives a significant low heave response at the wavelength around 7.8 meters. This observation also tells that the wave force contributes to the heave motion calculated from the diffraction potential theory is lower than the actual at this wave condition. This observation may also happen due to the neglect of the drag effect in the diffraction potential theory. Therefore, it can be concluded that the weakness of the diffraction potential theory is caused by neglect of drag effect. This approach has caused this theory to become less accurate in predicting the semi-submersible heave response when the heave motion is dominated by damping or drag term.

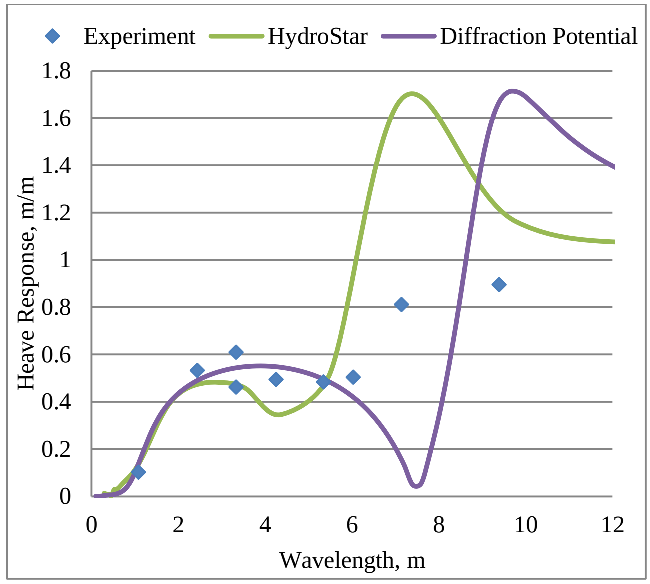


Figure 5 Heave motion response for semi-submersible model

7.0 CONCLUSION

In the conclusion, the three-dimensional diffraction potential method is possible to modify for analyse the wave force and motion response for multiple hull structure such as semi-submersible. From the comparison, it is observed that the motion response results tendency obtained from diffraction potential theory is agreed with experimental result which carried out at head sea condition. The tendency of the estimated motion response by diffraction potential theory is also quite similar to the motion response predicted by Hydrostar. However, the diffraction potential theory still suffers a larger error in predicting the heave motion when that heave motion is dominated by the drag effect. This observation shown that neglected the drag effect by diffraction potential theory in predicting the wave force and motion causes this theory become no accurate to predict motion response when the motion is dominated by damping.

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