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Theoretical Review on Prediction of Motion Response using Diffraction Potential and Morison

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ABSTRACT

This paper reviewed the capability of the proposed diffraction potential theory with Morison Drag term to predict the Round Shape FPSO heave motion response. From both the self-developed programming code and ANSYS AQWA software, it can be observed that the diffraction potential theory is over predicting the Round Shape FPSO heave motion response when the motion is dominated by damping. In this study, Morison equation drag correction method is applied to adjust the motion response predicted by diffraction potential theory. This paper briefly present the procedure to integrate the Morison equation drag term correction method with the diffraction potential theory and then, the proposed numerical method was applied to simulate the Round Shape FPSO heave motion response. From the comparison, it can be concluded that Morison equation drag correction method is able to estimate the FPSO heave response in the damping dominated region and provides more reasonable motion tendency compare to the diffraction potential theory without consider the drag effect in the calculation.

KEY WORDS: *Wave Response, Diffraction Potential, Damping Correction, Morison Theory.*

NOMENCLATURE

$\Phi(x,y,z)$	VelocityPotential in x, y, z directions
$G(P;Q)$	GreenFunction
F_D	Drag Force
R	Horizontal Distance
K	Wave Number

1.0 INTRODUCTION

This paper is targeted to review the accuracy of correction methods applied at the diffraction potential theory in order to evaluate the motion response of offshore floating structure.The diffraction potential theory estimates wave exciting forces on the floating body based on the frequency domain and this method can be considered as an efficient one to study the motion of large size floating structure with acceptable accuracy. The accuracy of the diffraction potential method to predict the structures response was also detailed studied. The good accuracy of this diffraction theory applied to large structures is due to the significant diffraction effect that exists in the large size structure in wave [4].

In this study, the motion response of a selected Round Shape FPSO is simulated by self-developed programming code based on diffraction potential theory with Morison damping correction method. The accuracy of this programming code was checked with the previous semi-submersible experiment result which carried out at the towing tank belong to Universiti Teknologi Malaysia [5].

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

As presented by Siowet al. [6], their finding found that the diffraction potential theory is less accurate to predict the floating structure heave motion response when the wave frequency is close to the structure's natural frequency. In this situation, the heave response calculated by the diffraction potential theory is significantly higher compared to experimental result due to the low damping represented by the theory [9].

In order to improve the heave motion predict by the diffraction potential theory, Siow et al. tried to increase the damping coefficient by adding viscous damping into the motion equation. In his study, the viscous damping is treated as an extra matrix and can be added into the motion equation separately [6]. Besides,Siow et.al. also tried to integrate the linearized Morison drag equation with diffraction potential theory. The linear Morison drag equation would modify both the damping term and exciting force in the motion equation compared to the viscous damping correction method which only modified the damping term in motion equation. The accuracy of the modification solutions are also checked with the semi-submersible experiment result which was carried out at the towing tank of the UniversitiTeknologi Malaysia [10].

The 6-DOF Round Shape FPSO motion result calculated by this method and the comparison of result between the proposed methods with experiment result was published by Siow et.al in year 2015 [11]. In this paper, thetheoretical numerical calculation result of Round Shape FPSO using Diffraction Potential and Morison was reviewed. The result was compared to the original diffraction potential calculation method and the result obtained from ANSYS Software. Since the diffraction potential theory is only modified to the heave motion equation, hence the discussion in this paper only focused to the heave motion response.

2.0 NUMERICAL CALCULATION

2.1 Diffraction Potential

In this study, the diffraction potential method was used to obtain the wave force act on the Round Shape FPSO also the added mass and damping for all six directions of motions. 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:

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

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

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 in the system is contributed by the potential of the incident wave, scattering wave and radiation wave. In addition, the phase and amplitude of both the incident wave and scattering wave areassumed to be the same. However, radiation wave potentials are affected by each type of motions of each single floating body in the system, where the total radiation wave potential from the single body is the summation of the radiation wave generates by each type of body motions such as surge, sway,heave,roll, pitch and yaw,

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

$$\nabla^2\emptyset = 0 \quad for\ 0 \le z \le h \tag{3}$$

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

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

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

$$\frac{\partial\phi_7}{\partial n} = -\frac{\partial\emptyset_0}{\partial n}\ on\ the\ body\ boundary \tag{7}$$

2.2 Wave Potential

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

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

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

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

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

2.3 Wave Force, Added Mass and Damping

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

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

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.

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

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

$n_i$in eq. (10) to eq. (12) is the normal vector for each direction of motion, i = 1~ 6 represent the direction of motion and j = 1~6 represent the six type of motions

2.4 Drag Term of Morison Equation

The linear drag term due to the wave effect on submerge model is calculated using Drag force equation as given by Morison equation:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z - \dot{X}_z| (\dot{\phi}_Z - \dot{X}_z) \tag{13}$$

Where ρ is fluid density, A_{Proj} is projected area in Z direction, C_D is drag coefficient in wave particular motion direction, $\dot{\phi}_Z$ is velocity of particle motion at Z-direction in complex form and $\dot{X}_z$ is structure velocity at Z-direction

In order to simplify the calculation, the calculation is carried out based on the absolute velocity approach. The floating model dominates term is ignored in the calculation because it is assumed that the fluid particular velocity is much higher compared to structure velocity. Expansion of the equation (13) is shown as follows:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| \dot{X}_z - \frac{1}{2}\rho A_{Proj} C_D |\dot{X}_z| \dot{\phi}_Z + \frac{1}{2}\rho A_{Proj} C_D |\dot{X}_z| \dot{X}_z \tag{14}$$

By ignoring all the term consist of $|\dot{X}_z|$, equation (14) can be reduced into following format.

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| \dot{X}_z \tag{15}$$

The above equation (15) is still highly nonlinear and this is impossible to combine with the linear analysis based on diffraction potential theory. To able the drag force to join with the diffraction force calculated with diffraction potential theory, the nonlinear drag term is then expanded in Fourier series. By using the Fourier series linearization method, equation (15) can be written in the linear form as follow:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} \dot{X}_z \tag{16}$$

Where, V_{max} in equation (16) is the magnitude of complex fluid particle velocity in Z direction. From the equation (16), it can summarize that the first term is linearize drag force due to wave and the second term is the viscous damping force due to the drag effect.

According to Christina Sjöbris, the linearize term $\frac{8}{3\pi}V_{max}$ in the equation (16) is the standard result which can be obtained if the work of floating structure performance at resonance is assumed equal between nonlinear and linearized damping term [8].

The linearize drag equation as shown in equation (16) now can be combined with the diffraction term which calculated by diffraction potential theory. The modified motion equation is shown as follows:

$$(m + m_a)\ddot{X}_z + \left(b_p + \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max}\right)\dot{X}_z + kx = F_p + \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z) \tag{17}$$

Where m is mass, k is restoring force, m_a, b_p, F_p is heave added mass, heave diffraction damping coefficient and heave diffraction force calculated from diffraction potential method respectively. $\frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max}$ is the viscous damping and $\frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z)$ is the drag force based on drag term of Morison equation.

2.5 Differentiation of Wave Potential for Morison Drag Force

To obtain the drag force contributed to heave motion, the wave particle velocity at heave direction must be obtained first. This water particle motion is proposed to obtain from the linear wave potential equation. From the theoretical, differential of the wave potential motion in Z-direction will give the speed of water particle motion in the Z-direction.

As mentioned, the drag force in Morison equation is in the function of time; therefore, the time and space dependent wave potential in the complex form should be used here. The wave potential in Euler form as follows:

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz + iKR + i\alpha} \tag{18}$$

The expending for the equation (18) obtained that

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz} \cdot [\cos(KR) + i\sin(KR)] \cdot [\cos\alpha + i\sin\alpha] \tag{19}$$

Rearrange the equation (19), the simplify equation as follows

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz} \cdot [\cos(KR + \alpha) + i\sin(KR) + \alpha] \tag{20}$$

Differentiate the equation (20) to the Z-direction, the water particle velocity at Z-direction is shown as follows:

$$\phi_Z(x,y,z) = \frac{\varsigma g}{w}(-K)e^{-Kz} \cdot [\cos(KR + \alpha) + i\sin(KR) + \alpha] \tag{21}$$

Since this numerical model is built for deep water condition, hence it can replace the equation by $Kg = w^2$ and the equation (21) is becoming as follow:

$$\phi_Z(x,y,z) = \varsigma w e^{-Kz} \cdot [\cos(KR+\alpha) + i\sin(KR+\alpha)] \quad (22)$$

In the equations (18) to (22), ς is the wave amplitude, g is the gravity acceleration, w is the wave speed, K is wave number, R is the horizontal distance referring to zero coordinate, α is the time dependent variable.

The horizontal distance, R and the time dependent variable, α can be calculated by the following equation

$$R = Kx\cos\beta + Ky\sin\beta \quad (23)$$

$$\alpha = wt + \epsilon \quad (24)$$

In equation (23) and equation (24), the variable β is wave heading angle, ϵ is the leading phase of the wave particle velocity at the Z-direction and t is time.

To calculate the drag forces by using the Morison equation, equation (22) can be modified by following the assumptions below.

First, since the Morison equation is a two dimensional method, therefore the projected area of the Z-direction is all projected at the bottom of structure.

Second, as mentioned in the previous part, this method applies the absolute velocity method and the heave motion of model is considered very small and can be neglected; therefore, the change of displacement in Z-direction is neglected.

From the first and second assumption, the variable z at equation (22) is no effected by time and it is a constant and equal to the draught of the structure. By ignore the time series term, and thenthe equation (22) can be become as follow:

$$\phi_Z(x,y,z) = \varsigma w e^{-Kz} \cdot [\mathrm{Cos}(KR) + i\,\mathrm{Sin}(KR)] \quad (25)$$

2.6 Determination of Drag Coefficient

Typically the drag coefficient can be identified from experimental results for the more accurate study. In this study, the drag coefficient is determined based on previous empirical data. To able the previous empirical used in this study, the Round Shape FPSO assumed as a vertical cylinder. Second, the laminar flow condition is applied to calculate the drag damping and drag force so it is match with the assumption applied in diffraction potential theory. The drag coefficient applied in the calculation of motion response of Round Shape FPSO as listed in Table 1 and the reference of the dimension used in calculate the drag coefficient is showed in Figure 1.

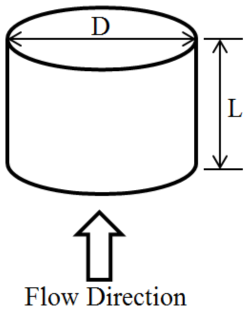

Figure 1: Dimension of Vertical Cylinder and flow direction

Table 1 Drag Coefficient for Cylinder with the flow direction in vertical direction [12]:

Aspect Ratio, AR $Length, L / Diameter, D$	Drag Coefficient, C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

3.0 MODEL PARTICULARS

The objective of this paper is reviewing the heave motion response of new designed Round Shape FPSO estimated by the diffraction potential theory with Morison drag correction method. The designed Round Shape FPSO modelhas the diameter at the draft equal to 1.018meters and draught of 0.2901meters. The model was constructed from wood following the scale of 1:110 (Table 1).

Upon the model complete constructed, inclining test, androll decay test were conducted to identify the hydrostatic particular of the Round Shape FPSO model. The dimension and measured data of the model was summarized as in Table 2.

Table 2: Particular of Round Shape FPSO

Symbol	**Model**
Diameter (m)	1.018
Depth (m)	0.4401
Draught(m)	0.2901
Free board(m)	0.150
Displacement (m^3)	0.2361
Water Plan Area (m^2)	0.8139
KG (m	0.2992
GM (m)	0.069

In this study, the proposed numerical method was applied to execute the heave motion response of Round Shape FPSO. The panel method developed based on diffraction potential theory with Morison damping correction as presented at part 2 in this paper required to generate a number of meshes on the model surface in order to predict the distribution of wave force act on this Round FPSO model. To reduce the execution time, symmetry theory is applied in the calculation and total number of panels generated for execution in each symmetry side is525 (1050 for whole model) for immerse part. The sample of mesh ofRound Shape model used in the numerical calculation is shown in Figure 2.

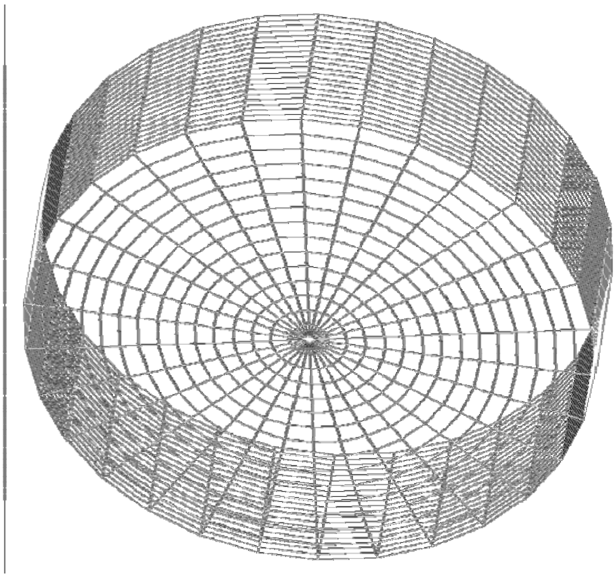

Figure 2: Meshing for Round Shape FPSO model

4.0 ROUND SHAPE FPSO HEAVE RESPONSE

The heave RAO calculated by the diffraction potential theory, the corrected diffraction potential theory by the Morison drag term and ANSYS Diffraction method are presented in Figure 3. From Figure 3, it can be seen that the diffraction potential theory with linearized Morison drag correction is predicted lower heave motion response amplitude compared to the diffraction potential theory without any correction and the ANSYS Diffraction method.

The tendency of the heave response calculated by the diffraction potential theory with and without viscous damping correction is similar between each other. The higher prediction of the heave motion of the Round Shape FPSO by diffraction potential theory is due to the small prediction of the heave damping by this theory alone. In compared to the result calculated by the ANSYS software, the diffraction potential theory without any correction function return the same result as the result predicted by ANSYS software. The observation also proved that the self-developed diffraction potential coding is developed based on the diffraction potential theory correctly. Since the linear potential theory is ignored the viscous effect in the calculation, so both the diffraction potential theory and the ANSYS software would predict the heave response of the Round Shape FPSO with higher amplitude. The maximum response amplitude of the Round Shape FPSO predicted by both the ANSYS and diffraction potential theory is same and has the value of 2.43 at wavelength 3.5 meters.

On the other hand, by involved the drag effect in the calculation, the predicted maximum heave response of the Round Shape FPSO was reduced from 2.43 to 1.74. The peak response amplitude was existed in the same wavelength either the drag effect is included in the calculation. The predicted tendency of the heave response by the diffraction potential theory, diffraction potential theory with Morison drag correction method and ANSYS AQWA software is showed similar between each other. In this calculation, the drag term of the linearized Morison equation has contributed to increase the damping and exciting force in the motion equation as shown in eq. 17. The good prediction of the drag effect by using Morison drag equation in this method was contributed to correct the weakness of the diffraction potential theory when this theory is applied to predict the heave motion of the Round Shape FPSOat damping dominate region. This is because the drag effect becomes significant at damping dominating region while the diffraction potential theory was neglected the drag effect in its prediction hence, causes the predicted motion amplitude become significant higher. By involving the drag effect in the calculation, the peak response predicted by the diffraction potential method would be reduced. Also, by compared to the experiment result, the peak heave motion response of the Round Shape FPSO is closer to the peak heave motion response predicted by experiment method [12].

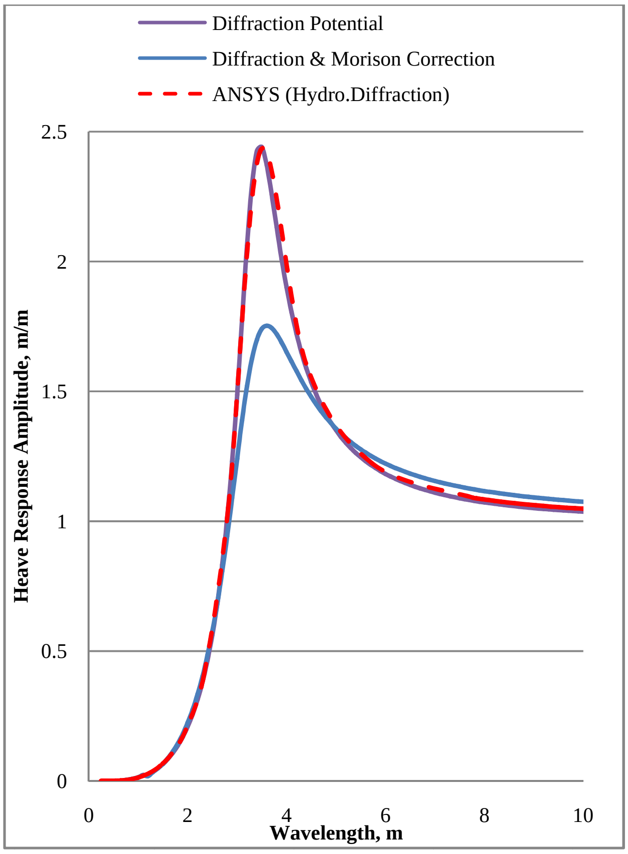

Figure3Heave motion response predicted by Diffraction Potential theory, Diffraction Potential Theory with Morison Drag Correction method and ANSYS AQWA software.

5.0 CONCLUSION

In conclusion, this paper reviewed the tendency of heave motion response predicted by the proposed diffraction potential theory with Morison drag term correction method. In the beginning, the FPSO heave motion response predicted by the self-developed programming was compared to the predicted result by ANSYS AQWA. The comparison showed that the self-developed diffraction potential coding have the same performance as ANSYS AQWA software where both method provided same tendency of result and almost similar response amplitude at any wavelength. After that, the study was focused in compared the effect of the drag effect in the motion response prediction. By involved the Morison drag term in the calculation, the peak heave response predicted by the diffraction potential theory with Morison Drag correction method is lower compared to the diffraction potential theory and ANSYS AQWA. This shown that by involved the drag effect in the calculation would help to avoid the diffraction potential theory predict the FPSO heave motion response with the significant higher magnitude in the damping dominate region.

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