Theoretical Study on Effect of Turret Location on Dynamic Response of Moored Twin Hulls FPSO System

Nik Mohd Khairuddin B. Nik Ismail, and Jaswar. Koto

Department of Aeronautics, Automotive and Ocean Engineering, Universiti Teknologi Malaysia, Malaysia
Ocean and Aerospace Research Institute, Indonesia
*Corresponding author: jaswar.koto@gmail.com

ABSTRACT

It currently no information is available for the comparison of the dynamic behaviour of the internal turret moored for twin hull FPSO system at different loading conditions with various turret locations under the action of wave. Hence, the present study investigated characteristics for a typical turret moored FPSO system by catenary anchor leg mooring (CALM) which subjected to sea waves, in order to get insight knowledge on its dynamic behaviour due to various turret locations with different loading conditions. The comparison of the dynamics behaviour to the FPSO and it mooring lines are important when choosing potential development and optimal options. This research will analysed and highlight the optimal turret location to the new potential concepts of twin hull FPSO. It also will highlight areas where effort is best focussed to mitigate the marine risks.

KEY WORDS: Moored Twin Hulls; FPSO; Turret Location; Dynamic Response.

1.0 INTRODUCTION

Offshore structures have been in use successfully for many years and rapidly developing. They serve the same purpose in the oil and gas production as well as the storage system. There are two common the type of offshore structure which are fix structure and floating structure. These floating structures include Tension Leg Platform (TLP), Semi-submersible platform, Floating Storage and Offloading (FSO), and also Floating Production Storage and Offloading (FPSO).

Since the offshore drilling are being discovered in deep sea area the fixed structure are not practical because it have significant heave, pitch and yaw motions in large wave. Good stability characteristic as a drilling platform was make the floating structure attempt to replace traditional fixed jacket platforms. These movable structures have the maneuverability ability to be used in several fields, but the cost effectiveness is the main advantages of movable structures.

FPSO is vessel used by the offshore industry for the processing and storage of oil and gas. A FPSO vessel is transportable platform which designed to receive oil or gas produced from nearby platforms or subsea template, process it, and store it until oil or gas can be offloaded onto a tanker or transported through a pipeline. FPSOs are preferred in frontier offshore regions as they are easy to install, and do not require a local pipeline infrastructure to export oil and gas.

The vessels often take the form of traditional tankers. In addition to dedicated vessels that are designed for FPSO, oil and gas tankers can be converted to an FPSO vessel which also makes them an economical and flexible option. The vessels are moored in place either via a single point or by spread mooring which involves the vessel being anchored via multiple points on the sea floor. This allows them to operate in both deepwater and ultra deepwater environments which are designed to take into account local weather situations and can even be detached from moorings which make them ideal in extreme weather conditions.

Turret is a typical single point mooring system for FPSO. Turret also is the major component used for station keeping in harsh environments; heavy sea, high winds and strong current which the risers coming from seabed are connected. The most important function of turret is weathervaning which allows vessel to rotate freely around turret.

Floating production vessel have the principal characteristic of remaining at substantially stable position, presenting movements when they experience environmental forces such as the wind, waves and currents. In floating structure design, it is important to
determine its motion and behavior when subjected to waves (Sharma et al. 2010).

According to the research from T.R Kannah and R. Natarajan (2006), it has been illustrated that the position of the turret location plays a vital role to determine the behavior of the FPSO and also its mooring lines forces when subjected to environmental impact. Throughout this research, it tries to investigate the influence of turret location to the dynamic behavior and the mooring lines force of the floating production system. This study is made to access the optimum operational capability of the FPSO system due to the dynamic behaviour and mooring lines force condition.

This research is tried to improve the response prediction by using diffraction potential theory by involving drag effect from the Morison equation in the calculations. The main objective is too carried out the hydrodynamic response of the twin hull FPSO using the correction method that has been done by Siow et al., (2014b) thus applied to moorings and risers as top end excitation for the dynamic response analysis.

2.0 LITERATURE REVIEW

It has been forecasted that between 2013 and 2017, 91 billion dollar will be spent on floating production systems, an increase of 100 percent over the preceding five year period (Westwood, 2013). With global economic growth in 2014 projected to increase to 3.5 percent from 2.9 percent in 2013, world oil demand is forecast to rise by one million barrels per day, compared with 900 000 barrels per day in year 2013 (Cochran, 2014). This massive growth in the floating production sector has come as a result of the rapid evolution that gives the impact to the future development of FPSO.

IEA (2012) forecasted that oil and gas demand will rise from 3.3 trillion cubic meters in 2010 to 5.0 trillion cubic meters in 2035, an increase of 50 percent. This situation has driven the market for FPSO to fulfill the demand. As a result of this situation, the new concept of twin hull FPSO has emerged. This novelty is achieved by joining together two FPSO which the process facilities along with the storage and crew living quarters are located on deck. This twin hull concept allows adequate space for the process facilities with the necessary space between sections of equipment to satisfy safety requirements, while providing sufficient oil and gas storage capacity.

The environmental loads on moored structures, namely due to wind, current, and waves, are of a main concern when determining vessel motions and evaluating mooring design (C. G. Soares, et al. 2005). Turret-moored FPSO systems are sensitive to the effect of waves, wind and current. In the recent years, considerable research is being carried out on turret moored FPSO system operating at offshore locations. An internal turret moored FPSO system is an attractive concept for both production facilities and offshore storage (T.R Kannah and R. Natarajan, 2006).

In an internal turret moored FPSO system, the turret structure is built inside the tanker’s hull and it is attached to the sea-bed by catenary anchor leg mooring (CALM). The spider part of the turret located at the vessel keel level includes bearings, allowing the vessel to rotate freely around its mooring legs in response to changes in environmental excitation and system dynamics. In the case of internal turret moored FPSO system, the vessel motions and mooring forces are mainly governed by the location of the turret so as to maintain optimal operating conditions.

Many research have been done up to now about the single point mooring for monohull FPSO. Thiagarajan and Finch (1998, 1999) conducted an experimental investigation of the vertical motions of a turret moored FPSO in wave using different positions of the mooring along the length of the model. The results show that the mooring location affects the vertical motions and accelerations of the FPSO. Bemtisas and Papoulia (1986) conducted the study on the yaw and stability of single point mooring. Yaw of turret moored vessels in regular waves was investigated Liu et al. (1999). O’Donoghue and Linfoot (1992) performed the model test in irregular waves and reported the effect of turret position and mooring load characteristics. Jiang et al. (1995) extensively reported the horizontal motions and mooring line loads of single point moored tanker. Cho (2012) and Cho et al. (2013) studied the motion behavior and stability of turret moored floating body and two bodies including sloshing. Recently, Seok et al. (2013) conducted the model test and stability analysis for a turret moored Floating Storage Regasification Unit (FSRU). Model tests are performed in regular waves. The results of model test show that the possibility of large yaw in irregular wave can be predicted by the regular wave tests.

Based on the review of these existing literatures, it is found that no information is available for the comparison of the dynamic behaviour of the internal turret moored for twin hull FPSO system at different loading conditions with various turret locations under the action of wave. Hence, the present study investigation has been programmed for a typical turret moored FPSO system by catenary anchor leg mooring (CALM) which subjected to sea waves, in order to get insight knowledge on its dynamic behaviour due to various turret locations with different loading conditions. The comparison of the dynamics behaviour to the FPSO and it mooring lines are important when choosing potential development and optimal options. This research will analyses and highlight the optimal turret location to the new potential concepts of twin hull FPSO. It also will highlight areas where effort is best focussed to mitigate the marine risks.

This research is targeted to propose a correction method which applicable to linear diffraction theory in order to evaluate the motion response of selected moored floating structure. The linear diffraction theory estimate the wave force on the floating body based on frequency domain and this method can be considered as an efficient method to study the motion of the large size floating structure with acceptable accuracy. The effectiveness of this diffraction theory apply on large structure is due to the significant diffraction effect exist on the large size structure in wave (Kvittem et al., 2012).

In this study, twin hull FPSO will select as an offshore structure model since this structure is one of the new concept structure used in deep water oil and gas exploration area. To achieve this objective, a programming code will develop based on diffraction potential theory and it is written in visual basic programming language. By comparing the numerical result predicted by using diffraction potential theory to experiment result, it is obtained that the motion prediction by diffraction potential theory has an acceptable accuracy mostly, except for
heave motion when the wave frequency near to the structure natural frequency (Siow et al., 2013a and Siow et al., 2014a).

As presented in a previous paper, the diffraction potential theory is less accurate to predict the structure heave motion response when the wave frequency closer to structure natural frequency. At this situation, the heave response calculated by the diffraction potential theory will be overshooting compare to experiment result due to low damping executed by the theory and then follow by the large drop which give and underestimating result compare to experiment result before it is returned into normal tendency (Siow, et al., 2013a).

In order to correct the over-predicting phenomenon made by the diffraction potential theory, the previous research was trying to increase the damping coefficient by adding viscous damping into the motion equation (Siow et al., 2014a). From that study, the viscous damping is treated as extra matrix and added into the motion equation separately. This addition viscous damping was estimated based on the equation provided by Nallayarasu and Prasad (2012).

By adding the extra viscous damping into the motion equation, it can be obtained that the significant over-predicting of heave motion when wave frequency near to the floating structure natural frequency was corrected and it is close to the experimental result compared to executed result by diffraction potential theory alone (Siow et al., 2013a). However, the under-predicting of the heave response by diffraction potential theory in a certain wave frequency region still remaining unsolved by adding the viscous damping to the motion equation as discussed in the previous study (Siow et al., 2013a).

Siow, et al., (2014b) conducted the researches which focus on the effect drag force and viscous damping in estimate the semi-submersible heave response using diffraction potential theory. To able the numerical solution to calculate the extra drag force and viscous damping, they applied the drag term in Morison equation. Accuracy of the modification solution also checked with the previous semisubmersible experiment result which carried out at the towing tank belongs to UniversitiTeknologi Malaysia (Abyn, et al., 2012a and Siow, et al., 2014b). The experiment is conducted in head sea condition and slack mooring condition for wavelength around 1 meter to 9 meters. In the comparison, they obtained that the non-agreed heave response tendency near the structure natural frequency predicted by diffraction potential theory can be corrected by involving the drag effect in the calculation.

3.0 PARTICULARS OF TWIN HULL FPSO

As mentioned, the twin hull FPSO construct by joining together two FPSO which the process facilities along with the storage and crew living quarters are located on deck. Figure 3.5 and Table 3.1 showed the description and principal particulars of twin hull FPSO that will be consider in this research.

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
<th>Prototype</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dead weight</td>
<td>≈250000</td>
<td>tonnes</td>
</tr>
<tr>
<td>2</td>
<td>Length</td>
<td>270.7</td>
<td>m</td>
</tr>
<tr>
<td>3</td>
<td>Breadth</td>
<td>44.3</td>
<td>m</td>
</tr>
<tr>
<td>4</td>
<td>Depth</td>
<td>21.7</td>
<td>m</td>
</tr>
<tr>
<td>5</td>
<td>Fully loaded draught</td>
<td>16.7</td>
<td>m</td>
</tr>
<tr>
<td>6</td>
<td>Spacing between hull</td>
<td>30</td>
<td>m</td>
</tr>
<tr>
<td>7</td>
<td>Diameter of turret</td>
<td>21.5</td>
<td>m</td>
</tr>
<tr>
<td>8</td>
<td>Type of mooring</td>
<td>CALM</td>
<td></td>
</tr>
</tbody>
</table>

4.0 MODEL EXPERIMENT APPROACH

In the experimental approach the first part deals with the model preparation. In model preparation some test will perform to check the natural period of the twin hull FPSO, to confirm the KG of the structure and others. Those tests are inclining test, swing test, decay test and spring calibration test. In another way it can be said that the model preparation is to validation of the loading of the structure. The model was ballasted with additional weights to achieve the 40%, 70% and 100% DWT respectively at different turret locations as shown in Figure 3.4. The second part deals with the experiment to analyze force oscillation test and the third part is wave excitation test to analyze the force and moment acting on the structure. The last part is motion test. Wave will be used for the test. From the experiment the dynamics force of twin hull FPSO as well as its mooring line force acting on the body motion has measured at corresponding wave frequency. Part of
The motion test has provided the value to find the RAO of FPSO. The experimental approach gives the following information:

i. Model preparation to determine the particular of the twin hull FPSO.
ii. Force oscillations test to obtain the exciting force on structure in regular waves.
iii. Wave excitations test to obtain the force and moment acting on the structure.
iv. Motion test to obtain the RAO of the twin hull FPSO in regular waves.
v. Analysis of the force and moment oscillations test as well as motion test will provide the hydrodynamics behavior.

The result obtained from experiment illustrated the behavior of the structure at every particular wave frequency.

Figure 2: Different Positions of Turret Structure of an Internal Turret Moored Twin Hull FPSO System.

5.0 THEORETICAL STUDY OF TWIN HULL FPSO

5.1 Diffraction Theory

According to linear potential theory, the potential of a floating body is a superposition of the potentials due to the undisturbed incoming wave $\Phi$, the potential due to the diffraction of the undisturbed incoming wave on the fixed body $\Phi_d$, and the radiation potentials due to the six body motion $\Phi_j$. The total potential can be written by:

$$\Phi = \sum_{j=1}^{6} \Phi_j + \Phi_w + \Phi_d$$

(1)

Also, the potential must be satisfied with boundary condition below:

- **The continuity equation,**

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$

(2)

holds in fluid domain.

- **Sea bed boundary condition,**

$$\frac{\partial \Phi}{\partial z} = 0 \quad \text{at} \quad z = -h_0$$

(3)

in which $h_0$ is the distance from the origin of the earth-bound coordinate system, $O(x, y, z)$, to the sea bed.

- **Free surface boundary condition,**

At the mean free surface:

$$\frac{\partial \Phi}{\partial z} + \frac{\partial^2 \Phi}{\partial \xi^2} = 0$$

(4)
Kinematic boundary condition on the oscillating body surface, on the wetted part of the oscillating hull of the structure (in its mean position):

\[
\frac{\partial \Phi}{\partial n} = \mathbf{v} \cdot \mathbf{n}
\]  

(5)

in which \(\mathbf{v}\) is the velocity of a point on the hull of the body and \(\mathbf{n}\) is the normal vector of the hull, positive into the fluid.

1. The body motion and diffraction potentials have to satisfy a radiation condition which states that at great distance from the body these potentials disappear.

In regular waves a linear potential \(\Phi\), which is a function of the earth-fixed coordinates and of time \(t\), can be written as a product of a space-dependent term and a harmonic time-dependent term as follows:

\[
\Phi(x, y, z; t) = \Phi_0(x, y, z) \cdot e^{-i \omega t}
\]  

(6)

According to Tuck (1970), a convenient formulation can be obtained by writing:

\[
\Phi = -i \omega \sum_{j=0}^6 \Theta_j \zeta_j
\]  

(7)

where \(j = 0\) represents the undisturbed incoming wave, \(j = 1, \ldots, 6\) are associated with each of the motion modes of the body and \(j = 7\) represents the diffracted wave. The space-dependent part of the velocity potential \(\Theta_0\), associated with an undisturbed long-crested regular wave in water of constant depth \(h\) is given by:

\[
\Theta_0 = \frac{\zeta_0}{i \omega} \cdot \cosh(k(h_0 + z)) \cdot e^{ikx(\cos \mu + y \sin \mu)}
\]  

(8)

Where,

- \(\zeta_0\) = amplitude of undisturbed wave (m)
- \(k\) = wave number at shallow water (rad/m)
- \(\mu\) = wave direction (rad); zero for a wave travelling in the positive x-direction
- \(\omega\) = wave frequency (rad/s)
- \(h_0\) = distance from the origin, \(O\), of the earth-fixed axes to the sea bed (m)
- \(h\) = water depth (m)

The complex potential \(\Phi\) follows from the superposition of the undisturbed wave potential \(\Theta_0\), the wave differtential \(\Theta_j\), and the potentials \(\Theta_j\) associated with the \(j\)-modes of motion of the body \((j = 1, \ldots, 6)\):

\[
\Phi = -i \omega \left\{ \Theta_0 + \Theta_1 \zeta_0 + \sum_{j=2}^6 \Theta_j \zeta_j \right\}
\]  

(9)

The fluid pressure follows from the Bernoulli equation:

\[
p(x, y, z; t) = -\rho \frac{\partial \Phi}{\partial t}
\]  

(10)

The first order wave exciting forces \((k = 1; 2; 3)\) and moments \((k = 4; 5; 6)\) in the \(k\)-th direction are:

\[
X_k = -\int_S \rho n_k dS_0 = -\rho \omega^2 \zeta_0 e^{-i \omega t} \sum_{j=0}^6 \Theta_j \zeta_j dS_0
\]  

(11)

and the oscillating hydrodynamic forces and moments in the \(k\)-th direction are:

\[
F_k = -\int_S \rho n_k dS_0 = -\rho \omega^2 \sum_{j=1}^6 \zeta_j e^{-i \omega t} \sum_{j=0}^6 \Theta_j \zeta_j dS_0
\]  

(12)

In which,

- \(S_0\) = mean wetted surface of the body
- \(n_k\) = direction cosine of surface element \(dS_0\) for the \(k\)-mode

The added mass and damping (coupling) coefficients are defined as follows:

\[
a_{kj} = -Re \left[ \rho \int_S \Theta_j n_k dS \right]
\]  

(13)

\[
b_{kj} = -Im \left[ \rho \omega \int_S \Theta_j n_k dS \right]
\]  

(14)

5.2 Morison Equation

Morison equation is a semi-empirical equation for the inline force on a body in oscillatory flow. The Morison equation is used to estimate the wave loads in the design of oil platforms and other offshore structures.

The Morison equation is the sum of two force components (Morison et al., 1950) an inertia force in phase with the local flow acceleration and a drag force proportional to the (signed) square of the instantaneous flow velocity. The inertia force is of the functional form as found in potential flow theory, while the drag force has the form as found for a body placed in a steady flow.

\[
F = F_i + F_d |u|
\]  

(15)

\[
F = \rho C_m V |u| + \frac{1}{2} \rho C_d |u|^2
\]  

(16)

where, \(F\) is wave force, \(F_i\) is inertia force, \(F_d\) is drag force, \(C_m\) is inertia coefficient, \(C_d\) is drag coefficient, \(|u|\) and \(u\) is water particle velocity normal to the structure, \(u\) is particle acceleration normal to the structure, \(\rho\) is seawater density and \(V\) is volume of the structure.

The force coefficients \(C_m\) and \(C_d\) are dependent on Renoyd, \(Re\) number, roughness parameter, interaction parameter and Keulegen and Carpenter, \(KC\) number. The inertia term of Morison equation was used to calculate the wave exciting force and moment on the semi-submersible as the drag force was assumed insignificant (Chakrabarti, 2007). The water particle kinematics was determined by the following equations:

Horizontal water particle velocity,

\[
u = \frac{\pi H \cos \theta}{T \sin \theta} \cos \theta
\]  

(17)
Horizontal water particle acceleration,
\[ \ddot{u} = \frac{2\pi N \sinh kx}{T \sinh \frac{kx}{2}} \sin \theta \]
where, \( s = y+d \), \( \theta = kx - \cot \), \( k \) is wave number (2\( \pi \)/\( L \)), \( T \) is wave period, \( y \) is height of the point of evaluation of water particle kinematics, \( x \) is point of evaluation of water particle kinematics from the origin in the horizontal direction, \( t \) is time instant at which water particle kinematics is evaluated, \( L \) is wave length, \( H \) is wave height and \( d \) is water depth.

### 5.3 Drag Term of Morison Equation
The linear drag term due to the wave effect on floating structure is calculated using Drag force equation as given by Morison equation:
\[ F_D = \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_x - X_x \right) - \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_z - X_z \right) \]
where, \( \rho \) is fluid density, \( A_{proj} \) is projected area in Z-direction, \( C_D \) is drag coefficient in wave particular motion direction, \( \phi_x \) is velocity of particle motion at Z-direction in complex form and \( X_x \) is structure velocity at Z-direction.

In order to simplify the calculation, the calculation is carried out based on the absolute velocity approach. The structure-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 4.35 is shown as follows:
\[ F_D = \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_x - X_x \right) - \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_z - X_z \right) \]

By ignoring all the term consist of \( \phi_z \), equation 4.36 can be reduced into following format:
\[ F_D = \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_x - X_x \right) - \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_z - X_z \right) \]

The above equation 4.37 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, then nonlinear drag term is then expanded in Fourier series. By using the Fourier series linearization method, equation 4.37 can be written in the linear form as follow:
\[ F_D = \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_x - X_x \right) - \frac{1}{2} \rho A_{proj} C_D \left( \dot{\phi}_z - X_z \right) \]
where, \( V_{max} \) is the magnitude of complex fluid particle velocity in Z-direction. From the equation 4.38, it can be summarized 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 Sjöbris (2012), the linearize term is given by:
\[ m \ddot{X}_x + \left( 2 \pi \rho A_{proj} C_D \frac{V_{max}}{\pi} \right) \dot{X}_x + kx = F_p + \frac{1}{4} \rho A_{proj} C_D \left( \dot{\phi}_x - X_x \right) \]
where, \( m \) is mass, \( k \) is restoring force, \( m_a \) is heave added mass, \( b_p \) is heave diffraction damping coefficient, \( F_p \) is heave drag force calculated from diffraction potential method, \( \frac{1}{3} \rho A_{proj} C_D \frac{V_{max}}{\pi} \) is viscous damping and \( \frac{1}{4} \rho A_{proj} C_D \frac{V_{max}}{\pi} \) is drag force based on drag term of Morison equation.

### 5.4 Equation of the Motion for the Whole System
The motion equation for a floating structure with attached stinger can be written, in the time domain, as:
\[ M \ddot{\theta}(t) = \bar{F}_c(t) + \bar{F}_m(t) \]
where, \( \bar{F}_c(t) \) is hydrodynamic forces on the vessel and \( \bar{F}_m(t) \) is Morison load on mooring lines elements.
\[ \bar{F}_c(t) = \bar{F}_p + \bar{F}_d \]
where, \( \bar{F}_p(t) \) is diffraction force calculated from diffraction potential method and \( \bar{F}_d(t) \) is drag force based on drag term of Morison equation.

The mass matrix of the total system is defined by \( M \). The accelerations \( \ddot{\theta}(t) \) are solved in a time stepping procedure, and the motion \( \theta(t) \) follow from integration. If the mooring line is rigidly connected to the vessel, the vessel motion vector contains six rigid body motion components. The Morison load on slender (tubular) elements is given:
\[ \bar{F}_m(t) = \frac{1}{2} \rho D C_m \bar{u}(t)|\bar{u}(t)| \]
where, \( C_m \) is inertia coefficient, \( C_D \) is drag coefficient, \( \bar{u}(t) \) is particle water particle velocity normal to the structure, \( \bar{u}(t) \) is particle acceleration normal to the structure, \( \rho \) is seawater density and \( D \) is diameter of the mooring line.

### 6.0 CONCLUSION
This chapter emphasized the formula and the mathematical that has been used in this research. The formula and mathematical theory has been modeled to analyze the output of the method approach.

ACKNOWLEDGMENT
The authors are very grateful to Universiti Teknologi Malaysia and Ocean and Aerospace Research Institute, Indonesia for supporting this study.
REFERENCES


