Theoretical Study for Predicting Response Water Column in a Moonpool

O Turbaningsih and H I Nur

1Department of Marine Transportation Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia.

Abstract. Moonpool commonly installed in production barge, drilling vessel, pipe laying vessel, survey vessel and offshore diving vessel. Moonpool is an opening vertical wall through the deck from top to bottom of the vessel. The main purpose of using moonpool is to perform lifting/lowering of subsea equipment. It considers as the most effective subsea handling method, but it has disadvantages with oscillation of water column inside moon pool. The purpose of this study is to understand the correlation between response water column inside the moonpool with environmental load and the motion of the floating structure during operational time or transit condition. During transit condition, the forward speed of the barge is zero, the excitation force only caused by incoming waves and barge heave motion. The study started by defining the barge vertical movement and all the forces acting in the body of moonpool to obtain simplified harmonic equation for water column motion and plotting the result using MATLAB software. The amplitude of heave barge and water column piston mode is strongly influenced by environmental conditions, in this case the significant wave height and also the dimension of the moonpool area since it is giving additional added mass into the motion. The large amplitude of the water column likely to occur if critical frequency is in the range of wave excitation. Thus, to prevent any over flowing condition during lowering/lifting operation via moonpool, the limiting sea-state condition should be identified for the designated location.

1. Introduction

In business practice, marine offshore operation can be categorized as offshore facilities operation and vessel operation. Many vessels have been specifically designed to meet the technical and functional to serve the operational purposes such as exploration, maintenance and construction works in the ocean. The offshore vessels mainly classified as offshore exploration and drilling vessel, offshore support vessels, construction/special purpose vessel and offshore productions vessel. The efficiency of marine offshore operation is depending to the ability for handling the project equipment. The handling methods that commonly use in offshore practice can be broadly group into side handling, stern handling, open handling, and moonpool [1]. Moonpool commonly installed in drilling vessel, pipe laying vessel, survey vessel and offshore diving vessel. Moonpool is an opening vertical wall through the deck from top to bottom of the vessel. The main purpose of using moonpool is to perform lifting and lowering of subsea equipment, riser and pipeline installation, ROV launching and diving bell handling. By using moonpool, the operator has full control over the load while its being lifting or lowering from the sea. The equipment such as diving bell or drilling hammer can be launched using the lifting arrangement system built in the vessels safer than side or stern handling without affecting much to the ship stability. Figure 1 shows the illustrations on how the lifting operation via moonpool.

![Figure 1. Illustration for vessel with lifting arrangement via moonpool [2].](image)

Table 1 show the advantages and disadvantages for equipment handling towards moonpool [2][3].
Table 1. The advantages and disadvantages of handling equipment via moonpool.

| Advantages                                      | Disadvantages                                      |
|-----------------------------------------------|---------------------------------------------------|
| Protection of equipment from environmental forces, thus the limiting sea-state can be increased during the operation. | Water plugs within moonpool can result in flooding on vessel deck and large loads on equipment in moonpool. |
| Minimise installation cost and intervention operation (during equipment installation) | The equipment has higher risk to hit the cursor frame during lowering/lifting operation |
| Moonpool close to vessel roll and pitch axis which minimise dynamic force | Size limitation of equipment |

The offshore field operators required to keep the operability of subsea equipment as high as possible to reduce shut down cost. It is advisable to avoid any sea-state condition that may potentially damage subsea equipment. To date, the sea state limit has been increased by using module handling systems that enables launch and recovery through moonpool placed near the centre of roll and pitch axis of the vessel [4]. The water motions inside the moonpool have two type of natural modes [5] which are sloshing modes (back and forth movement) and piston modes (heave motion). The piston mode is very dominant. During resonant condition, the water elevation inside the moonpool is higher than usual, which able to cause flooding on the vessel deck. The lifting/lowering equipment operation much likely happened during transit condition. The vessel will be either perform dynamic positioning, anchored or using single point mooring system depend on the locations. During stationary waves, large water motion likely happened if vertical excitation resulting from the ship motions and waves is matched with natural frequency of the water column [6].

The excitation caused by the pressure difference in bottom of moonpool. The pressure variation is depending on the wave forces and cross section of the moonpool which called as FWH (wave exciting force). This force is well known as Froude Krylov wave force. This force can be calculated from incident wave potential with consideration of interaction force between added mass and damping coefficient [7]. Heave motion is the most dominant motion among the six type of motions acting in the floating structures. One of research investigated that the strongest excitation of the moonpool was caused by the forced heaving, depending on the oscillation amplitude and its damping[7]. Theoretical approach was performed to determine simplified equation to predict the heave response in moonpool during stationary waves. The study investigates the main parameter affecting the piston mode in the moonpool.

The purpose of this study is to understand the correlation of response water column inside the moonpool to the environmental condition and the floating structure movement. The main outcome of this study is to generate simplified equation to predict response of water column inside moonpool in relative to sea water elevation and vertical motion of the floating structure. This equation can be used to check the limiting environmental factor that considered still safe to perform lifting/lowering equipment through moonpool.

2. Work methodology

The theoretical approach to define the water column response was performed in the two stages, first calculating heave response in the floating structures and then include it as an input to determine the water column equation of motion. The floating structure modelled in this study based on barge shape. Figure 1 shows the flowchart for the work methodology in this study.
Figure 2. Work methodology flowchart.

The study will be based on the parameter shows at Table 2.

Table 2. Barge details and environmental data used in the study.

| Parameter Description | Value         |
|-----------------------|---------------|
| Barge Length (m)      | 227.0         |
| Barge Width (m)       | 42.0          |
| Water depth (m)       | 100           |
| Moonpool dia. (m)     | 10; 20; 30    |
| Draft (m)             | 8; 12; 18     |
| Hs (m); Tp(s) (1-year)| 2.9; 9.1      |
| Hs (m); Tp(s) (10-year)| 4.1; 10.3   |
| Hs (m); Tp(s) (100-year)| 5.3; 11.1 |

The simplified equation described in this study is based on the following assumption:
- The wave theory for deep water is applied.
- Ideal fluid, where fluid is inviscid, incompressible and irrotational.
- Flow of the fluid is uniform and constant over time.
- The long wave theory is applied.
- The floating structure being simulated is barge type without moonpool
- Only vertical motion of the barge taken into consideration
- The volume of the barge is calculated by the total volume minus the moonpool volume.
- Wave excitation force calculated is combination of Froude Krylov force and diffraction force.
- If length overall barge far less than wave length, the diffraction force is negligible, the additional forces to be counted for is radiation force, where radiation damping equal to zero and added mass $m_{ij}$ is equal to $m_{ji}$.
- Added mass at the moonpool calculated using slender body theory, where the added mass is obtained from the 3-dimensional integration of 2D added mass cuts.

Understanding the six degree of freedom in the floating structure is important. Figure 3 shows the rotational and translational movement in every axis.
Figure 3. Six degree of freedom in floating structure.

Note: 1=surge, 2=sway, 3=heave, 4=pitch, 5=roll, 6=yaw

where, $M_{ij}$ is matrix mass component, $A_{ij}$ is added mass component, $C_{ij}$ is restoring hydrostatic force component, $F_{ij}$ is excitation force amplitude.

$$M_{jk} = \begin{bmatrix} M_{11} & 0 & 0 & 0 & M_{j6} & 0 \\ 0 & M_{22} & 0 & -M_{j6} & 0 & 0 \\ 0 & 0 & M_{33} & 0 & 0 & 0 \\ -M_{j6} & 0 & 0 & I_{44} & 0 & -I_{46} \\ 0 & 0 & 0 & 0 & I_{55} & 0 \\ M_{j6} & 0 & 0 & 0 & 0 & I_{66} \end{bmatrix}$$  \hspace{1cm} (1)

$$A_{jk} = \begin{bmatrix} A_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{66} \end{bmatrix}$$  \hspace{1cm} (2)

General equation for floating structure motion stated in Equation (3).

$$\sum_{j=1}^{6} [ (M_{ij} + A_{ij}) \dot{X}_j + B_{ij} \dot{X}_j + C_{ij} \dot{X}_j ] = F_{ij} \epsilon^{int} \hspace{1cm} (3)$$

3. Theoretical study of response water column in a moonpool

This study of response water column is started by examining the forces acting on the barge influenced by the actual environmental data on site.

3.1. Heave motion equation for the barge

Basic assumption required to evaluate sea loads and motions acting on the ships. The governing equation applied for fluid incompressible and inviscid with constant density [8] use Laplace formula where $\nabla^2 \Phi = 0$ is:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$  \hspace{1cm} (4)

Kinematic boundary condition for fixed body in a moving fluid [8] as follow:

$$\frac{\partial \Phi}{\partial n} = 0; \text{ on body surface} \hspace{1cm} (5)$$

The pressure in the water surface is equal to constant atmosphere pressure in the free surface, thus, the kinematic boundary condition applied as follows:

$$g \zeta + \frac{\partial \Phi}{\partial t} + \frac{1}{2} \left( \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} \right) = 0$$  \hspace{1cm} (6)

By linearizing Equation (6) and assume that the ship in transit condition, no forward speed and current is zero [8]. The dynamic boundary condition become:

$$g \zeta + \frac{\delta \Phi}{\delta t} = 0 \text{ on } z = 0 \hspace{1cm} (7)$$
Hydrodynamic forces acting on the barge can be calculated using pressure area method. Barge vertical motion on can be calculated using strip theory. The wave excitation force calculated using Froude Krylov theory. The potential velocity used in the analysis:

\[ \Phi(x, z, t) = \frac{g}{\rho} e^{kz} \cos(\omega t - kx) \]  

The excitation force on barge calculated using Froude Krylov:

\[ F_t = \int f(x) n \, dS = \int f(x) \frac{1}{2} \rho g \zeta \sin(\omega t - kx) \, dx \]  

where, \( f(x) = 0 \) for other variables.

\[ F = \frac{1}{A_{33}} \rho g \zeta B \quad e^{kD} \left[ \frac{1}{2} \sin kL_b \sin \omega t \right] \]  

where, \( A_{33} \) is Froude Krylov force, \( B_w \) is barge width, \( L_b \) is barge length, \( D \) is barge draft, \( P \) is pressure in the bottom of the barge, and \( \zeta \) is sea water elevation.

Added mass of structure, \( A_{33} \) is depending on its shape, since barge is rectangular shape, the added mass \( A_{33} \) value can be taken from Lewis graphics [8] as 0.75 \( \rho B_w D \) which resulted following equation:

\[ A_{33} = L_b A_{33} \quad 2D = 0.75 \rho B_w D L_b \]  

Radiation force is affected by the added mass and the damping coefficient in the structures. The radiation force can be formulated as follows:

\[ F_R = -A_{33} Z_3 \quad \frac{3}{2} - B_{33} Z_3 = -0.75 \rho B_w D L_b Z_3 \]  

where, \( B_{33} \) is heave damping, in this scenario the heave damping is considered as zero.

When a body is free floating, the restoring force will follow hydrostatic and mass considerations [8] as shows in the following equation:

\[ F_H = -\rho g \int z \, n \, dS = -\rho g A_{wp} Z_3 = -\rho g B_w L_b Z_3 \]  

where, \( F_{\text{Hi}} \) is restoring forces (hydrostatic force) and \( C_{33} = \rho g B_w L_b \) is restoring moment coefficient.

The heave motion is following Newton II principle where \( \sum F = m \cdot a \) as shows as follows:

\[ M Z_3 + (M + A_{33}) Z_3 + C_{33} Z_3 = F_{\text{Ex}}(t) \]  

where, \( M \) is total mass of the barge (kg), \( A_{33} \) is added mass, \( C_{33} \) is restoring moment coefficient, \( F_{\text{Ex}}(t) \) is barge excitation force, \( Z_3 \) is heave motion barge.

Natural period calculated using this equation:

\[ \omega_n = \sqrt{\frac{M + A_{33}}{I_{33}}} + \rho g B_w L_b = 0 \]  

\[ \omega_n = \left( \frac{1}{M + A_{33}} \right) + \left( \frac{1}{\rho g B_w L_b} \right) = \left( \frac{1}{g} \right) \]  

\[ T = 2\pi \sqrt{\frac{D + 0.75 BD}{\rho B_w L_b}} \]  

In heave motion, damping assumed to be 0, which is called as forced vibration system.

\[ (M + A_{33}) Z_3 + C_{33} Z_3 = F_{\text{Ex}}(t) \]  

(23)

\[ \frac{1}{2} \rho B_w L_b \]  

(22)
\[ F_{E3} = \rho g \zeta_a B_w L_b \]  
\[ Z_{E3} = \frac{\rho g B_w L_b}{\omega} \sin \omega t = \zeta_a \sin \omega t \]  

(24)  

(25)

3.2. Piston mode in a moonpool

The response water column is studied during transit time where the barge forward speed is 0, so there is no flow separation and the excitation force acting is based on Froude Krylov theory. The symbol \( \Omega \) in Figure 4 state the fluid domain, \( S_f \) is the free surface, \( S_B \) is the fluid body limitation and \( S_0 \) is the fluid limitation between wall tank and seabed.

\[ \text{Figure 4. Surface control [8].} \]

The governing equation applied in the fluid domain \( \Omega \) is:

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

(26)

The kinematic boundary condition at the free surface in the \( S_B \) plane body is:

\[ \frac{\partial \zeta}{\partial t} = \frac{\partial \Phi}{\partial z} \]  

(27)

The dynamic boundary condition, the pressure in the water surface is equal to the constant atmospheric pressure in the free surface shown as the following:

\[ P + \rho gy + \frac{1}{2} (u^2 + v^2 + w^2) = \text{Constant} \]  

(28)

\[ P = P_0, \text{ on } S_f \]  

(29)

The kinematic boundary condition in the Equation 42 become:

\[ g \zeta + \frac{\partial \Phi}{\partial t} = 0, \text{ for } z = 0 \]  

(30)

The total energy \( E \) in the volume \( \Omega \), consist of potential energy and kinetic energy, shown as follow:

\[ E(t) = \rho \int \left( \frac{1}{2} V^2 + gz \right) d\tau \]  

(31)

\[ \frac{\partial E(t)}{\partial t} = \rho \int \left( \frac{\partial \Phi}{\partial \tau} \left( \frac{\partial \Phi}{\partial t} \frac{\partial \Phi}{\partial \tau} \right) - \left( \frac{P - P_0}{\rho} + \frac{\partial \Phi}{\partial t} \right) U \right) ds \]  

(32)

The fluid speed applied as follows:

\[ u_n = \frac{6\Phi}{6n}, \text{ on } S_f \text{ and } S_B \]  

(33)

The Equation (32) become

\[ \frac{\partial E(t)}{\partial t} = \rho \int \left( \frac{P - P_0}{\rho} \right) U ds - \rho \int \frac{\partial \Phi}{\partial t} \frac{\partial \Phi}{\partial n} ds \]  

(34)

\[ \rho \int \left( \frac{P - P_0}{\rho} \right) U ds = \int_{\delta}^{\delta} f(P - P)Z ds \]  

(35)
The forces acting in a moonpool is Froude Krylov, radiation forces and hydrostatic forces. The Froude Krylov for inertia force in circular moonpool as per follows:

$$ F = \oint \left( -\rho \frac{\partial^2 \mathbf{F}}{\partial t^2} \right) \, dS = \oint \rho g \zeta e^{i k z} \sin(\omega t - kx) \, dS = \rho g \zeta A e^{-kD} \sin(\omega t - kx) \quad (37) $$

The radiation force caused by the added mass and damping of the structure. The radiation forces equation as per below:

$$ F_{R}(t) = \oint R \mathbf{F}(t) = \int_{-R}^{R} \rho \mathbf{v} \, dS = \int_{-R}^{R} \rho \mathbf{v} \, dx = \rho \pi R^3 \left( R \text{ is moonpool radius} \right) \quad (38) $$

The force acting in the body of moonpool in control volume system is gravitation force and inertia force caused by the heave motion $Z_3$.

$$ F_H = \oint \rho g dV = -\rho g A \int_{V}^{Z} \mathbf{z} \, dV = -\rho g A (Z + Z_3) \quad (45) $$

The heave motion is following Newton II principle where $\sum F = m \cdot \alpha$, all the forces acting in the structures equal to mass times it accelerations.

$$ \sum F_Z = F_I + F_H + F_R + F_{FR} \quad (46) $$

$$ (\rho AD) Z = -A_z (Z_3 + Z) - B_z Z - \rho g A (Z + Z_3) + \rho g \zeta A e^{-kD} \sin(\omega t - kx) \quad (47) $$

$$ (\rho AD) Z + A_z (Z_3 + Z) + B_z Z + \rho g A (Z + Z_3) = \rho g \zeta A e^{-kD} \sin(\omega t - kx) \quad (48) $$

$$ (M + A_z) Z - B_z Z - CZ = F(t) \quad (49) $$

$$ F(t) = \rho g A \zeta e^{-kD} \sin(\omega t - kx) - A_z Z_3 - \rho g A Z_3 \quad (50) $$

Where: $M$ is mass of water column in moonpool ($\rho AD$), $B$ is damping calculated by $\frac{\rho g R}{m} \left( \frac{C^2}{Z_3} \right)$, $C$ is hydrodynamic stiffness ($\rho g A$), $Z$ is water column elevation in a moonpool, $Z_3$ is heave motion in
barge, $A$ is moonpool area. The natural frequency in a moonpool during no un-damping, formulated as:

$$
\omega = \left( \frac{\rho g A}{\rho AD + A_Z} \right)^\frac{1}{2} = \left( \frac{\rho g A}{\rho AD + R C A D} \right)^\frac{1}{2} \left( \frac{g}{D + R} \right)^\frac{1}{2}
$$

(51)

The water column response is depended on the force excitations. The force excitation is directly proportioned with wave amplitudes. The amplitude for response water column in a moonpool is:

$$
X = \frac{F(t) \sin(m t - \alpha)}{2} \left( 1 + \frac{\lambda}{\delta_{m n}} \right) \left( 1 + \frac{\lambda}{\delta_{m n}} \right)
$$

(52)

$$
X = X_{m n} \sin(\omega ft - \alpha)
$$

(53)

The water column response is depending on the wave excitation force acting on the body. This excitation force is directly proportionated with the wave amplitude. Table 3 shows the water column response relative to the sea water elevation and heave barge response.

| 1-year return period | 10-year return period | 100-year return period |
|---------------------|-----------------------|------------------------|
| Heave amplitude: 0.57 m | Heave amplitude: 0.95 m | Heave amplitude: 1.22 m |
| Water column amplitude: 2.08 m | Water column amplitude: 3.12 m | Water column amplitude: 4.03 m |

The response of water column in a moonpool in Table 3 is relative to heave barge amplitude and seawater elevation based on environmental data 1-year, 10-year and 100-year return period based on moonpool with diameter 10 meters. It clearly shows that elevation water column in moonpool will be getting higher if the seawater level outside the floating structure is increased. The maximum amplitude of piston mode occurred during 100-year storm environmental condition. For the further analysis, we will use the 100-year storm data. The study investigates the influence of vessel draft and moonpool sizing to the water column elevation inside the moonpool shows in Table 4 and Table 5.

| 10-year return period | 100-year return period |
|----------------------|------------------------|
| Moonpool dia. = 10m  | Moonpool dia. = 18m    |
| Water column amplitude: 4.03 m | Water column amplitude: 5.5 m |
| Moonpool dia. = 25m  |                        |
| Water column amplitude: 7.80 m |                     |
Table 5. The response of water column during several barge draft condition.

| Draft (m) | Heave amplitude (m) | Water column amplitude (m) | Barge heave amplitude (m) |
|----------|---------------------|----------------------------|---------------------------|
| 8        | 2.40               | 3.85                        | 0.71                       |
| 12       | 1.22               | 4.03                        |                           |
| 18       |                    | 5.28                        |                           |

During loaded condition or deeper draft, the water column elevation will be higher. The draft of the barge is giving additional weight to the floating structure total masses. The natural frequency of moonpool is inversely proportional with the floating structure draft.

4. Verification of result and discussion

The harmonic motion equation in this study will be verified using studies performed by Matusiak [10] and DNV [3]. Further analysis to investigate the response water column will be using irregular waves theory. The motion response of the floating structure in irregular wave theory using wave spectrum Pierson Moskowitz as shown in the Equation below:

$$S_\omega = \frac{\pi^4}{2\omega^2} \exp \left(-\frac{m}{\omega_p}\right)$$  \hspace{1cm} (54)

Sea water elevation calculated based on consideration long wave theory and random waves formulated as follow [8]:

$$\zeta = \sum_{j=1}^{N} A_j \sin(\omega_j t - k_j x + \epsilon_j)$$ \hspace{1cm} (55)

The steady state response of the floating structure in each wave direction shown as:

$$\sum_{j=1}^{N} A_j |H(\omega)| \sin(\omega_j t - k_j x + \epsilon_j)$$  \hspace{1cm} (56)

where, $H(\omega)$ is transfer function or amplitude response per unit of amplitude wave and $\epsilon_j$ is the random phase within $0$ and $2\pi$.

$$|H(\omega)| = K_s \left[ (K_s - m\omega) + c_1 \omega \right]^{\frac{2}{2}}$$  \hspace{1cm} (57)

DNV [3] simplified the formula to calculate the fluid motion inside moonpool as per below:

$$\frac{\partial X}{\partial t} + C_{11}(X-X_s) + KX = F(t)$$  \hspace{1cm} (58)

$$\frac{-\omega^2M + 2i\omega C_{11} + K}{\omega^2} X + \sum_{j=1}^{N} A_j g \left( e^{s_1}\sqrt{A_j} \right)$$  \hspace{1cm} (59)

$$F(t) = \rho F_K A + A_3 X_s = \rho A X_s g + \epsilon_{ KD - \omega^2 \sqrt{A_j}}$$  \hspace{1cm} (60)

$$X = \frac{\sum_{j=1}^{N} A_j g + C_{11}}{\omega^2M + 2i\omega C_{11} + K}$$  \hspace{1cm} (61)

The other study is based on Jerzy Matusiak [10]. The force working in the bottom of moonpool consist of the reaction $F_R$ due to water flux, force $F_D$ due to dynamic pressure, hydrostatic force $F_H$, radiation force $F_R$, and Froude Krylov force $F_{FK}$ stated as below:
\[
F_{SB} = \int f \, dS = F_R + F_D + F_H + F_A + F_{FK} \quad (63)
\]

\[
F_{SB} = \rho S \left[ \dot{z} \{ \dot{z} \} - \frac{1}{2} \left( \dot{z} \right)^2 + g(T - z) \right] - A \left( \dot{z} + \dot{z'} \right) + S \left[ P + P_{FK} (z, t) \right] \quad (64)
\]

The added mass calculated using:

\[
A_i = \frac{2}{3} \rho m R^3
\]

The only force acting on body of moonpool is gravitational force and inertia force due to ship heave motion \( z_3 \):

\[
F_{FSF} = \int f \, dS = -S_{FSF} \rho g V = \rho A (g + z_3') \int_0^{T+z} dh = \rho A (g + z_3') (T + z) \quad (65)
\]

Since the forwards speed is zero during transit period, the harmonic equation for vertical motion in the moonpool become:

\[
\rho A g(T - z_3) - A_0 (\ddot{z} + \dot{z}_i) + \rho A \ddot{z} + \rho A \ddot{z} + \rho A g z_3 = P_{FK} (z, t) \quad (66)
\]

\[
\rho A (D + z) (\ddot{z}) + \rho A \ddot{z} + \rho A g z_3 = P_{FK} (z, t) - A_2 \dddot{z}_3 - \rho A g z_3 \quad (67)
\]

Table 6 shows the comparison of parameter in the calculation of response water column in moonpool.

| Description                  | Moopool Study | DNV RP H103 | Jerzy Matusiak |
|------------------------------|---------------|-------------|----------------|
| Mass of barge (kg)           | 9.78.10^8     | 9.78.10^8   | 9.78.10^8      |
| Stiffness of barge (kg/s^2)  | 9.58.10^7     | 9.58.10^7   | 9.58.10^7      |
| Natural frequency (rad/s)    | 0.16          | 0.16        | 0.16           |
| Excitation force F(t)        | \( A z' \)    | \( A z' \)  | \( A z' \)     |
| Equivalent mass in the moonpool (kg) | \( \rho A z' A \) | \( \rho A z' A \) | \( \rho A z' A \) |
| Stiffness (kg/s^2)           | \( 7.89.10^5 \) | \( 7.89.10^5 \) | \( 7.89.10^5 \) |
| Damping                      | \( 3.45.10^5 \) | \( 2.5\sqrt{KM} \) | \( 1.62.10^5 \) |

Based on the above result, the highest damping factor resulted from studies by DNV. DNV using the linearized damping as critical damping ratio multiplied by the damping of structure-dependent damping in the moonpool, so that the amplitude of the water column in the moonpool based on DNV resulted the smallest amplitude for the response water column. Damping factor will reduce the water elevation trapped inside the moonpool. Figure 5 shows the comparison of response water column in a moonpool based on this study, DNV [3], and Matusiak [10] and Table 7 shows its statistical parameter. The highest water elevation inside the water column is based on the authors’ study.
The water column motion is almost symmetrical with respect to the still water level. Based on the statistical parameter analysis (zero up and down crossing) the max elevation is 25.70m and peak period 16.51 s. The water column elevation inside the moonpool able to present the overflowing water that may cause flooding on deck when the water oscillation in the moonpool occurred.

5. Conclusion

Based on the study, the parameters that influenced the amplitude of piston motion in the moonpool such as follow:
- Oscillation water column in a moonpool is relative motion to the ship movement.
- Amplitude of heave barge and water column piston mode is strongly influenced by environmental conditions, in this case the significant wave height. Thus, in the marine offshore operation, the limitation for sea state should be identified for the designated offshore location.
- The study on barge with 227m(length) x 42m(width) x 12m(draft) and moonpool diameter 10m, the highest water column amplitude obtained during 100-year return period with seawater amplitude 2.6m, barge heave motion 1.22m and response water column in a moonpool is 4.03m. This shown that the water column inside the moonpool always have higher elevation compare to the seawater elevation outside the barge.
- The moonpool area is in linear with the added mass, thus the bigger moonpool area will increase water column elevations inside moonpool.
- To reduce the amplitude of water column in a moonpool, damping device is required.

For the future works, the heave motion will be more accurate if the floating structure with moonpool is modelled to obtain more accurate response. The current analysis, it assumed that the fluid is inviscid, for further analysis should be done for viscous fluid to consider friction factor.
between fluid and the moonpool wall. For the more accurate marine lifting operation modelling, it is recommended to analyse the hydrodynamics forces acting on the object lifted through moonpool.

6. References

[1] Kuo C 1978 A Controlled Handling Method for Effective Offshore Support Operations OTC 3318 (Offshore Technology Reference)

[2] Revheim E 2012 Moonpool Operations on Havila Subsea – improvement study (Norway: University of Stavanger) p 14

[3] Det Norske Veritas 2011 DNV RPH103 Modeling and Analysis of Marine Operations (Det Norske Veritas) pp 50-57

[4] Stald TC 2011 Assessment of critical factors when running and retrieving Framo pump modules through moonpool (Norway: University of Stavanger) p 42

[5] Molin B 1999 On the piston mode in moonpools International Workshop on Water Waves and Floating Bodies p 1

[6] Gaillarde G, Cotteleer A. 2001 Water motion in moonpools empirical and theoretical approach (Netherland: Maritime Research Institute Netherlands MARIN)

[7] Aalbers AB 1984 The Water Motion in Moonpool Ocean Engineering 11(6) pp 557–79.

[8] Faltinsen, O 1990 Sea Loads on ship and Offshore Structure (United Kingdom: Cambridge University Press) pp 10-48

[9] Newman JN 1980 Marine Hydrodynamics (Cambridge: The MIT Press) pp152

[10] Matusiak J 1997 Water Column Motion in A Moonpool of a Ship (Rakenteiden Mekanikka Vol.30)

Acknowledgments

Both authors would like to acknowledge for all the support given by Department of Marine Transportation Engineering, ITS. Apart from that, the first author wishes to thanks the lecturers in Ocean Engineering, ITB for the guidance during her studies.