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Three Dimensional Radiated Water Wave with a Submerged Cylinder in Presence of Circular Plate

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***Abstract:** This work deals with the problem of radiated by wave interaction with a couple of submerged cylinders in water which can be considered as a wave energy device and the problem arising from the rotational motion of submerged upper cylinder which one contains in the device. In this work, we approach theoretically to solve the problem based on the method of separation of variables and we derive the radiated velocity potentials numerically based on linear wave theory and eigenfunctions are introduced for each region by using free surface condition. Then we calculate the hydrodynamic coefficients due to rotational of the upper cylinder by using Bernoulli's equation of pressure by neglecting the atmospheric pressure and unknown constants are calculate by using matched conditions between the regions Finally, we present all numerical results graphically for different radii of the cylinders*

***Keywords:** linear, rotational, virtual boundary, device, submerge.*

I. INTRODUCTION

The estimation of hydrodynamic properties on a submerged structure is very important to design a wave energy device. To examine the hydrodynamic properties of oscillating structures, different techniques are used, for example, Finite element method and some analytical method. Till today, many researchers have applied different techniques, for example, multipoles method, eigenfunction expansion technique, to an investigation of hydrodynamic properties of oscillating structures.

In [2] studied wave load on a floating vertical cylinder and they present a mathematical technique to solve the problem due to radiation and diffraction. In [3] considered the problem of wave interaction with a rectangular structure placed above a step type ocean floor and they calculated the induced force on the structure due to wave loads on the structure. In [4] discussed the radiation problem due to surge motion by a pair of submerged cylindrical structure and they derived the hydrodynamic coefficient as well as presented graphically. In [5] developed a diffraction problem arise from the wave interaction with a submerged cylinder in water and they presented the pitch, heave and surge results due to the influence of the cylinder length. In [6] analyzed the diffraction problem due to wave loading on a vertical cylinder. In [8] solved the diffraction problem of the wave interaction with a rectangular oscillating structure and discussed the effect of bottom still on the structure. In [9], [10] analyzed the hydrodynamic problem of linear water wave interaction with a device of consisting a couple of cylinders and present analytical results of the forces for different radii of the floating cylinder. Also, in [11] formulated the problem of wave loads on a pair of the vertical cylinders and gave importance to hydrodynamic properties due to radiation and diffraction for the pair of cylinders. In [12] present the influence of a bottom obstacle on WOC in a channel.

II. FORMULATION OF THE MODEL

A. Radiation problem

The Cartesian coordinate system (x, y, z) of the geometry as indicated in Fig. 1. The origin is O at the free surface of water and $z-$axis is positively upwards. The region of the fluid bounded by $-l_1 < z < 0, -\infty < x < \infty$ which is assumed to be filled by the homogenous and incompressible fluid of uniform density ρ. Also, it consists a pair of cylinders having radii R' and $R''(\geq R)$. The region occupied by the upper cylinder is $r \leq R', 0 \leq \theta \leq 2\pi, -l_4 \leq z \leq -l_5$ and the region occupied by the lower cylinder is $r \leq R'', 0 \leq \theta \leq 2\pi, -l_2 \leq z \leq -l_3$. .

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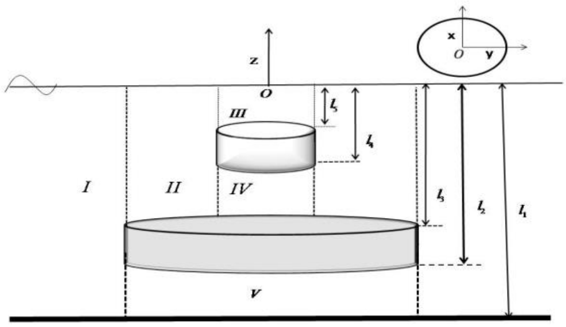

Fig. 1. Structural device

Bases on linearized wave theory, the irrotational motion of velocity potential is of the following form

$$\phi(r,\theta,z,t)=\mathrm{Re}[\varphi(r,\theta,z)e^{-i\omega t}], \quad (1)$$

Where (r,θ,z) represent the usual cylindrical coordinate, Re[.] be the real part and the time-independent velocity potential $\varphi(r,\theta,z)$ satisfies the following three dimensional Laplace's equation in cylindrical coordinate:

$$\frac{\partial^2\varphi}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi}{\partial r}+\frac{1}{r^2}\frac{\partial^2\varphi}{\partial\theta^2}+\frac{\partial\varphi}{\partial z^2}=0.$$
(2)

B. Governing equations

The radiated potential ϕ_r for the roll motion is given by (as in [9])

$$\phi_r=-i\omega\varphi_{r2}(r,z)\cos\theta \quad (3)$$

From the above equations (2) and (3), we deduced the following boundary conditions with the governing equation:

$$\frac{1}{r}\frac{\partial\varphi_{r2}}{\partial r}+\frac{\partial^2\varphi_{r2}}{\partial r^2}+\frac{\partial\varphi_{r2}}{\partial z^2}-\frac{\varphi_{r2}}{r^2}=0 \quad ,$$
(4)

$$\frac{\partial\varphi_{r2}}{\partial z}=0,\quad (z=-l_1) \quad (5)$$

$$\frac{\partial\varphi_{r2}}{\partial z}-\frac{\omega^2}{g}\varphi_{r2}=0,\quad (z=0) \quad (6)$$

$$\frac{\partial\varphi_{r2}}{\partial r}=\begin{cases}0, & (-l_2<z<-l_3, r=R'')\\ (z-z'), & (-l_4<z<-l_5, r=R')\end{cases} \quad (7)$$

$$\frac{\partial\varphi_{r2}}{\partial z}=0,\quad (z=-l_4, r<R'; z=-l_2, r<R'') \quad (8)$$

$$\lim_{r\to\infty}\sqrt{z_1 r}\left(\frac{\partial\varphi_{r2}}{\partial r}-iz_1\varphi_{r2}\right)=0, \quad (9)$$

where $(0,0,z')$ is the centre of rotation. The fluid regions are denoted by I, II, III, IV and V, as shown in Fig. 1 and the potentials due to radiation are described by $\varphi_{r2}{}^{I}, \varphi_{r2}{}^{II}, \varphi_{r2}{}^{III}, \varphi_{r2}{}^{IV}$ and $\varphi_{r2}{}^{V}$ in the respected regions.

III. MATCHING CONDITIONS

Along the boundary $r=R''$ to preserve continuity, we have

$$\varphi_{r2}^{I}=\varphi_{r2}^{II}\quad (-l_3\le z\le 0) \quad (10)$$

$$\varphi_{r2}^{I}=\varphi_{r2}^{V}\quad (-h_1\le z\le -l_2) \quad (11)$$

$$\frac{\partial\varphi_{r2}^{I}}{\partial r}=\begin{cases}\dfrac{\partial\varphi_{r2}^{II}}{\partial r} & (-l_3\le z\le 0)\\ 0 & (-l_2\le z\le -l_3)\\ \dfrac{\partial\varphi_{r2}^{V}}{\partial r} & (-h_1\le z\le -l_2)\end{cases}$$
(12)

Along the boundary $r=R'$, we have

$$\varphi_{r2}^{II}=\begin{cases}\varphi_{r2}^{III} & (-l_5\le z\le 0)\\ \varphi_{r2}^{IV} & (-l_3\le z\le -l_4)\end{cases}$$
(13)

$$\frac{\partial\varphi_{r2}^{II}}{\partial r}=\begin{cases}\dfrac{\partial\varphi_{r2}^{III}}{\partial r} & (-l_5\le z\le 0)\\ (z-z') & (-l_4\le z\le -l_5)\\ \dfrac{\partial\varphi_{r2}^{IV}}{\partial r} & (-l_3\le z\le -l_4)\end{cases} \quad (14)$$

IV. SOLUTION TO THE PROBLEM

In this section, we derive the analytical solution of the above boundary value problem by using the method of variables separation. Therefore the radiated velocity potentials are

$$\varphi_{r2}^{I}=\sum_{j=0}^{\infty}C_n\frac{W_1(_j r)}{W_1(a_j R'')}\cos[a_j(z+l_1)], \quad (15)$$

$$\varphi_{r2}^{II}=\sum_{j=0}^{\infty}\left[D_j\frac{V_1(b_j r)}{V_1(b_j R')}+E_j\frac{U_1(b_j r)}{U_1(b_j R')}\right]\cos[b_j(z+l_3)]$$

(16)

$$\varphi_{r2}^{III}=\sum_{j=0}^{\infty}F_j\frac{R_1(c_j r)}{R_1(c_j R')}\cos[c_j(z+l_5)], \quad (17)$$

$$\varphi_{r2}^{IV}=\left[G_0 r+\sum_{j=1}^{\infty}G_j\frac{I_1(\alpha_j r)}{I_1(\alpha_j R')}\cos[\alpha_j(z+l_3)]\right], \quad (18)$$

$$\varphi_{r2}^{V}=H_0 r+\sum_{j=1}^{\infty}H_j\frac{I_1(\beta_j r)}{I_1(\beta_j R'')}\cos[\beta_j(z+l_1)] \quad (19)$$

where C_j, D_j, E_j, F_j, G_j and H_j are denoted for the constant which are called unknown coefficients and a_j, b_j, c_j, α_j and β_j are called eigenvalues and these are given by following equations:

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$$\begin{cases} a_j = -iz_1 & \omega^2 = gz_1 \tanh\left(z_1 l_1\right),\ j=0 \\ \omega^2 = -ga_j \tan\left(a_j l_1\right) & j = 1, 2, \ldots \end{cases} \quad (20)$$

$$\begin{cases} b_j = -iz_2 & \omega^2 = gz_2 \tanh\left(z_2 l_3\right),\ j=0 \\ \omega^2 = -gb_j \tan\left(b_j l_3\right) & j = 1, 2, \ldots \end{cases} \quad (21)$$

$$\begin{cases} c_j = -iz_3 & \omega^2 = gz_3 \tanh\left(z_3 l_4\right),\ j=0 \\ \omega^2 = -gc_j \tan\left(c_j l_4\right) & j = 1, 2, \ldots \end{cases}$$

(22)

$$\alpha_j = \frac{j\pi}{l_3 - l_4} \qquad j = 0, 1, 2, \ldots$$

(23)

$$\beta_j = \frac{j\pi}{l_1 - l_2} \qquad j = 0, 1, 2, \ldots$$

(24)

where for the respected regions I, II and III, the wave numbers are called z_1, z_2 and z_3.

The functions $U_1(.), V_1(.), W_1(.)$ and $R_1(.)$ are given by

$$W_1\left(a_j r\right) = H_1^{(1)}\left(z_1 r\right) = H_1^{(1)}\left(ia_0 r\right), \quad j = 0$$

$$W_1\left(a_j r\right) = K_1\left(a_j r\right), \quad j = 1, 2, \ldots$$

$$V_1\left(b_j r\right) = H_1^{(1)}\left(z_2 r\right), \quad j = 0$$

$$V_1\left(b_j r\right) = K_1\left(b_j r\right), \quad j = 1, 2, \ldots$$

$$U_1\left(b_j r\right) = H_1^{(2)}\left(z_2 r\right), \quad j = 0$$

$$U_1\left(b_j r\right) = I_1\left(b_j r\right), \quad j = 1, 2, \ldots$$

$$R_1\left(c_j r\right) = J_1\left(z_3 r\right), \quad j = 0$$

$$R_1\left(c_j r\right) = I_1\left(c_j r\right), \quad j = 1, 2, \ldots$$

V. UNKNOWN COEFFICIENTS

In this section, we introduce the method to determine the unknown constants by applying the matched equations given by (10) - (14) and then multiply both sides by a suitable eigenfunction in each equation. Hence we apply the orthogonal properties of eigenfunction, we get

$$\int_{-l_3}^{0} \varphi_{r2}^{I}\Big|_{r=R''} .\cos[b_l(z+l_3)]\,dz = \int_{-l_3}^{0} \varphi_{r2}^{II}\Big|_{r=R''} .\cos[b_l(z+l_3)]\,dz \quad (25)$$

$$\int_{-l_1}^{-l_2} \varphi_{r2}^{I}\Big|_{r=R''} .\cos[\beta_l(z+l_1)]\,dz = \int_{-h_1}^{-l_2} \varphi_{r2}^{V}\Big|_{r=R''} .\cos[\beta_l(z+l_1)]\,dz \quad (26)$$

$$\int_{-l_1}^{0} \frac{\partial \varphi_{r2}^{I}}{\partial r}\Bigg|_{r=R''} .\cos[a_l(z+l_1)]\,dz = \int_{-l_3}^{0} \frac{\partial \varphi_{r2}^{II}}{\partial r}\Bigg|_{r=R''} .\cos[a_l(z+l_1)]\,dz + \int_{-l_1}^{-l_2} \frac{\partial \varphi_{r2}^{V}}{\partial r}\Bigg|_{r=R''} .\cos[a_l(z+l_1)]\,dz \quad (27)$$

$$\int_{-l_5}^{0} \varphi_{r2}^{II}\Big|_{r=R'} .\cos[c_l(z+l_5)]\,dz = \int_{-l_5}^{0} \varphi_{r2}^{III}\Big|_{r=R'} .\cos[c_l(z+l_5)]\,dz \quad (28)$$

$$\int_{-l_3}^{-l_4} \varphi_{r2}^{II}\Big|_{r=R'} .\cos[\alpha_l(z+l_3)]\,dz = \int_{-l_3}^{-l_4} \varphi_{r2}^{IV}\Big|_{r=R'} .\cos[\alpha_l(z+l_3)]\,dz \quad (29)$$

$$\int_{-l_3}^{0} \frac{\partial \varphi_{r2}^{II}}{\partial r}\Bigg|_{r=R'} .\cos[b_l(z+l_3)]\,dz = \int_{-l_5}^{0} \frac{\partial \varphi_{r2}^{III}}{\partial r}\Bigg|_{r=R'} .\cos[b_l(z+l_3)]\,dz + \int_{-l_4}^{-l_5} (z-z').\cos[b_l(z+l_3)\,dz + \int_{-l_3}^{-l_4} \frac{\partial \varphi_{r2}^{IV}}{\partial r}\Bigg|_{r=R'} .\cos[b_l(z+l_3)\,dz$$

(30)

Let us assume

$$L\left(x_n, y_n, A_1, A_2, k_1, k_2\right) = \int_{k_1}^{k_2} \cos[x_n(z+A_1)].\cos[y_n(z+A_2)]\,dz, \quad (31)$$

$$T\left(x_n, A_1, k_1, k_2\right) = \int_{k_1}^{k_2} \cos^2[x_n(z+A_1)]\,dz. \quad (32)$$

Applying equations (31) and (32) to equations (25)−(30), we get

$$\sum_{j=0}^{\infty} C_j\, L\left(a_j, b_l, l_1, l_3, -l_3, 0\right) = \left[D_l S_l' + E_l N_l'\right] \times T\left(b_l, l_3, -l_3, 0\right)$$

(33)

$$\sum_{j=0}^{\infty} C_j\, L\left(a_j, \beta_l, l_1, l_1, -l_1, 0\right) = H_l X_l T\left(\beta_l, l_1, -l_1, 0\right) \quad (34)$$

$$C_l T\left(a_l, l_1, -l_1, 0\right) = \sum_{j=0}^{\infty} \left[D_j Q_j + E_j S_j\right] \times L\left(a_l, b_j, l_1, l_3, -l_3, 0\right) \quad (35)$$

$$\sum_{j=0}^{\infty} \left(D_j + E_j\right) L\left(b_j, \alpha_l, l_3, l_5, -l_5, 0\right) = F_l T\left(\alpha_l, l_5, -l_5, 0\right) \quad (36)$$

$$\sum_{j=0}^{\infty} \left(D_j + E_j\right) L\left(b_j, \beta_l, l_3, l_3, -l_3, -l_4\right) = G_l M_l \times T\left(\beta_l, l_3, -l_3, -l_4\right)$$

(37)

$$\left[D_l O_l + E_l N_l\right] T\left(b_l, l_3, -l_3, 0\right) = \sum_{j=0}^{\infty} F_j Y_j L\left(\alpha_j, b_l, l_5, l_3, -l_5, 0\right) + \int_{-l_4}^{-l_5} (z-z').\cos[b_l(z+l_3)\,dz + \sum_{j=0}^{\infty} G_j Y_j L\left(\beta_j, b_l, l_3, l_3, -l_3, -l_4\right)$$

(38)

where

$$S_j' = \frac{V_1(b_jR'')}{V_1(b_jR')},\ N_j' = \frac{W_1(b_jR'')}{W_1(b_jR')}.$$

$$X_l = \begin{cases} R'', & l=0 \\ 1, & l=1,2,\ldots \end{cases}$$

$$P_j = \frac{a_jU_1'(a_jR'')}{U_1(a_jR')},\ Q_j = \frac{b_jV_1'(b_jR'')}{V_1(b_jR')}$$

$$S_j = \frac{b_jW_1'(b_jR'')}{W_1(b_jR')},\ M_j = \begin{cases} R', & j=0 \\ 1, & j=1,2,\ldots \end{cases}$$

$$O_j = \frac{b_jV_1'(b_jR')}{V_1(b_jR')},\quad N_j = \frac{b_jW_1'(b_jR')}{W_1(b_jR')},$$

$$Y_j = \begin{cases} 1, & j=0 \\ \dfrac{b_jI_1'(b_jR')}{I_1(b_jR')}, & j=1,2,\ldots \end{cases}$$

Since each equation of the above system contains an infinite series, hence to compute the solutions of the system of linear equation, we must truncate each series up to an equal finite number. Then the unknown constants C_j, D_j, E_j, F_j, G_j and H_j are determined by applying the matrix method in the above system of equations given by (33)-(38).

VI. HYDRODYNAMIC COEFFICIENTS

Since the cylinder merged in water will be liable to forces because of the pressure from the surrounding water and the pressure is given by following Bernoulli's equation

$$p = -\rho \frac{\partial \phi_{rad}}{\partial t}. \quad (39)$$

And the hydrodynamic forces on the cylinders due to rotational motion of the upper cylinder can be written as

$$F_r = -\iint_C p n_x ds, \quad (40)$$

where n_x is denoted for a unit normal vector which directed along the of $x-$axis and C be the cylinder surface of the merged part in water. Hence substituting the radiated potential expression given by equation (3) in equation (40), we have

$$F_r = -\rho\omega \iint_W \varphi_{r2}(R',z)\cos\theta(z-z')n_x ds \quad (41)$$

Now to determine the hydrodynamic forces, namely called damping coefficient and added mass, we follow the approach given by Rahman and Bhatta (as in [8] sec 8.7), hence we have

$$F_r = \mu_2 + i\frac{\xi_2}{\omega}, \quad (42)$$

where ξ_2 is the damping coefficient and μ_2 is the added mass due to radiation of rotational. Therefore, simplifying the equation (41), we get

$$\mu_2 + i\frac{\xi_2}{\omega} = -\rho \iint_W \varphi_{r2}^{II}(R',z)\cos\theta(z-z')n_x ds, \quad (43)$$

$$\mu_2 + i\frac{\xi_2}{\omega} = -\pi\rho R \sum_{j=0}^{\infty}(D_j + E_j) \int_{-l_4}^{-l_5} \cos[b_n(z+l_3)].(z-z')dz. \quad (44)$$

VII. RESULT AND DISCUSSION

In this section, we present the graphical representation with the explanation of analytic results of the damping coefficient and added mass. We assume the parameters throughout the calculation by taking $l_1 = 3m,\ g = 9.8m/s^2,\ l_2 = 0.75m$. In Figs. (2) and (3), respectively, we plot dimensionless damping coefficient and added mass versus wave number for different radii of the lower cylinder by taking $R'' = 1R', 2R', 3R'$. Here we fixed the values of the draft of the cylinders. Fig (2) shows that the value of the damping coefficient oscillated for the minimum value of wave number and curves of the damping coefficient shows that smooth oscillating behavior and increases with increases of R''. Therefore for the maximum value of R'', the value of the damping coefficient gives the maximum, for example, $R'' = 3R'$. In Fig. (3), it is clear that the added mass is enduring and positive for the least value of z_1, but at a particular value of wave number (since from the dispersion relation, frequency and wave number are related to each other) at $z_1R' = 2.4$ (approximately near), we saw that the added mass behave oscillate very highly which a designer can be assumed as a resonant condition.

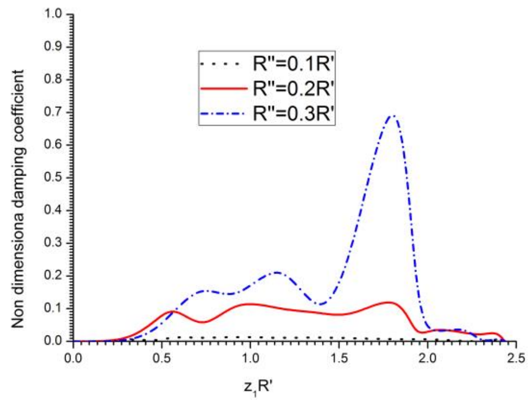

Fig. 2: Influence on dimensional damping coefficient for various radii R''.

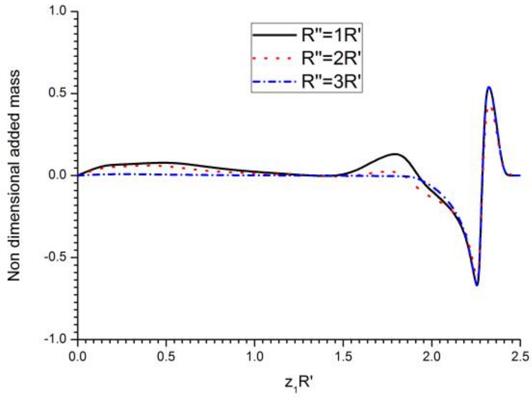

Fig. 3: Influence on dimensionless added mass for various radii R''.

Again,, in Figs. (4) and (5), respectively, we examined on non-dimensional damping coefficients and added mass for the distinct drafts of the upper cylinder i. e. $l_4 = 0.15l_3, 0.20l_3, 0.25l_3$ and here we fixed the radius of the lower cylinder by taking $R'' = 2R'$. The effect of draft on the damping coefficient shown in Fig. (4). From the figure we observed that the value of the damping coefficient oscillated for the least values of the wave number and for the maximum value of l_4, the value of the damping coefficient gives the maximum, for example, $l_4 = 0.25l_3$. From Fig. (5) observed that same kind of behavior as in Fig. (3), i.e. we have a resonant situation at particular wave number for all values of the drafts.

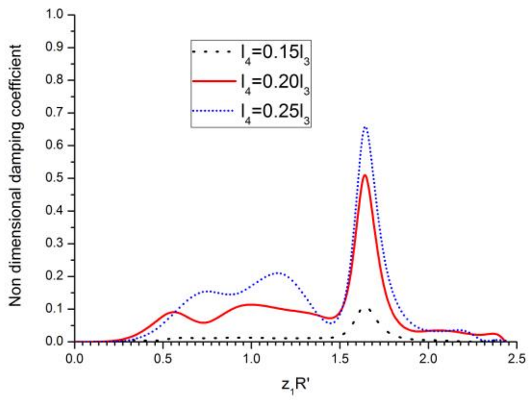

Fig. 4: Influence of dimensionless damping coefficient for different draft.

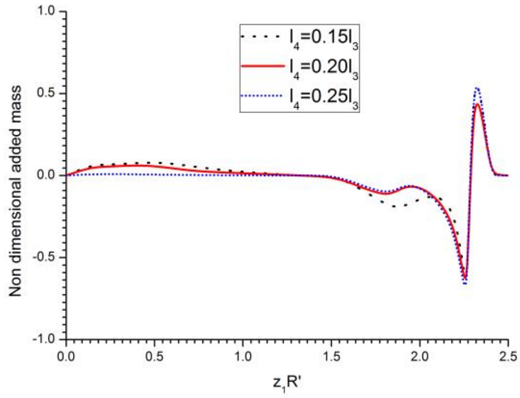

Fig. 5: Influence of dimensionless added mass for different draft.

VIII. CONCLUSION

In this work, we approach a theoretical method to solved the boundary valued problem due to the rotational motion of submerged cylinders in water under the hypothesis of linear wave theory. Also, this particular problem of radiated potentials have derived by using the variables separation and matched eigenfunctions method and hydrodynamic properties due to rotational motion of cylinder have derived based on the method given by Wu et. al. in [9]. All the numerical results are present graphically for the various parameters. From the graphs, we have seen a resonant situation for added mass and smooth oscillation for damping coefficients which can help to a designer to design a device and we conclude from the curves that a good agreement our result with the results of Borah and Konch in [4] and it shows that validation of our result.

NOTATIONS

l_1 : Water depth

(x, y, z) : Cartesian coordinate

ρ : Water density

g : Gravitational acceleration

ω : Angular frequency

p : Fluid Pressure

z_1 : Wave number

$J_1(.)$: First kind of Bessel function of first order

$H_1^{(1)}(.)$: First kind of Hankel function of first order

$I_1(.)$: First kind of modified Bessel function of first order

$H_1^{(2)}(.)$: Second kind of Hankel function of first order

$K_1(.)$: Second kind of modified Bessel function of first order

ξ_2 : Damping coefficient

μ_2 : Added mass

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