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Resonance and response of the submerged porous-membrane breakwaters in oblique seas

수중 잠재 이중 부유체 유공 유연막 소파시스템의 공진과 거동

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1. INTRODUCTION

The advantages of floating flexible membrane wave barriers over conventional fixed breakwaters include their reduced environmental impacts, ability of relocation, simple sacrificial design, free from bottom foundation consideration, and comparably low cots in deep water constructions. The vertical floating flexible membrane breakwater was investigated by Thompson et al.(1992), Aoki et al.(1994), Kim and Kee(1996), Williams(1996). Kim and Kee(1996) showed that the a good performance can be obtained in spite of appreciable sinusoidal motions of membrane because the vertical sinusoidal motions tends to generate only exponentially decaying local (evanescent) wave in the lee side.

Chwang (1983) developed a porous wave maker theory to study the problem of the generation of water waves by the harmonic oscillation of thin permeable plate immersed in water of finite depth, and found that the porous effects reduce not only the wave amplitude but also the hydrodynamic force acting on the wavemaker. Yu and Chawang (1994) investigated numerically the problem of reflection and transmission of water waves by a horizontally submerged plate in water of finite depth, and found that a plate with proper porosity can suppress significantly the wave reflection. Cho and Kim (2000) studied the interaction of monochromatic incident waves with a horizontal porous flexible membrane in the context of two-dimensional linear hydro-elastic theory, and found that the overall performance of the horizontal flexible membrane can be further enhanced by using a proper porous material.

Ideally, the breakwater should have minimum transmission at lee side. It is also often desirable that the reflection should be small. In addition the breakwater has to be submerged (Kee and Kim. 1997, Choi et al. 1998) in order to reduce the hydrodynamic pressure on the body of structures, and insure the water circulation to prevent stagnation and pollution in the sheltered region. In this point of view, the performance of the fully submerged floating buoy/porous-membrane breakwaters is investigated for arbitrary incident wave angles and for various permeability on membranes. This breakwater system is able to reduce reflection and transmission simultaneously, and is a very eco-friendly system. The fully submerged system allows gaps to exist over and beneath the structures hinged at some distance over sea bottom, which enables wave transmission through the gaps. The obliquely incident surface waves traveling over long horizontal submerged

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cylindrical buoy can be trapped inside of the dual system, which act as wave scatterer reducing the wave amplitude, and excites the energy dissipation through fine-pores on membranes.

To assess the efficiency of this dual submerged porous-flexible system, two-dimensional multi-domain hydro-elastic formulation was carried out in the context of linear wave-body interaction theory and Darcy's law. The hydrodynamic interaction of oblique incident waves with the combination of the rigid and porous-flexible bodies was solved by the distribution of the simple sources (modified Bessel function of the second kind) that satisfy the Helmholz governing equation. The velocity potentials of wave motion are fully coupled with membrane deformation and porous damping based on Darcy's law.

2. THEORY AND NUMERICAL METHOD

An inertial, Cartesian coordinate system (x, y) with its origin located at the still water level is used as reference system. As shown in Fig. 1, the submerged dual system is composed of fully submerged buoy/ vertical-flexible-porous-membrane placed in parallel with spacing, and allows flow passing over and beneath structures.

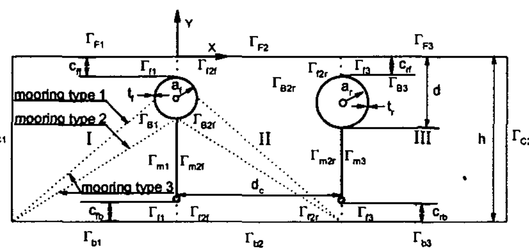

Fig. 1. Coordinate system and integration domains for dual fully submerged buoy/porous-membrane breakwater

The integration fluid domain is subdivided into three domains. An incident wave train with small amplitude A and harmonic motion of frequency ω propagates towards the breakwater with an angle θ (wave heading) with respect to x axis in water of constant depth h. For ideal fluids, the wave field may be represented by a velocity potential of an oblique wave as

$$\Phi(x,y,z,t)=\mathrm{Re}[\{\phi_o(x,y)+\phi(x,y)\}e^{ik_z z-i\omega t}] \qquad (1)$$

where Re denotes the real part of a complex expression, $i=\sqrt{-1}$, t denotes time, and $k_z=k_0\sin\theta$ is the wave number component in the z direction, and k_0 is the wave number of the incident wave, which is the positive real solution of the dispersion equation $\omega^2=k_0 g\tanh k_0 h$ with g being the gravitational coefficient. Then, the velocity potential of small amplitude of wave train height A, wavenumber k_0, and wave heading θ is given by

$$\phi_o=\frac{igA}{\omega}\frac{\cosh k_0(y+h)}{\cosh k_0 h}e^{ik_0\cos\theta x} \qquad (2)$$

ϕ_o is the known incident potential and ϕ is the time-independent unknown scattered potential, which includes both diffraction and radiation effects. The complex velocity potentials, ϕ_l in three fluid domains $l=1,2,3$ (see Fig. 1.), satisfy the Helmholtz equation as governing equation and the following linearized free-surface (Γ_F), bottom (Γ_b), and Sommerfeld radiation conditions (Γ_C):

$$\nabla^2\phi_l-k_z^2\phi_l=0 \qquad in\ \Omega\ (l=1,2,3) \qquad (3)$$

$$-\omega^2\phi_l+g\frac{\partial\phi_l}{\partial y}=0 \qquad (\text{on } \Gamma_F) \qquad (4)$$

$$\frac{\partial\phi_l}{\partial n}=0 \qquad (\text{on } \Gamma_b) \qquad (5)$$

$$\lim_{|x|\to\infty}(\frac{\partial}{\partial x}\pm ik_x)(\phi_l)=0 \qquad (\text{on } \Gamma_C,\ l=1,3\ ) \qquad (6)$$

where Γ_C is the vertical truncation boundaries at far fields and n= (n_x,n_y) is the unit outward normal vector. Along the vertical fictitious boundaries (matching boundaries) in fluids $x=0$ and $x=d_c$, the pressure and normal velocity are required to be continuous as follows;

$$\phi_l=\phi_{l+1}\ ,\quad \frac{\partial\phi_l}{\partial x}=-\frac{\partial\phi_{l+1}}{\partial x} \quad \text{at } \Gamma_f \qquad (7)$$

Based on Darcy's law the normal velocity inside of membrane with fine pores is linearly proportional to the pressure difference between the two sides of the membrane (Chwang 1983).

$$W(y,t) = \frac{B}{\mu}(p_1 - p_2) = \frac{B}{\mu}\rho i w[\phi_l - \phi_{l+1}]e^{-i\omega t}$$
$$= w(y)e^{-i\omega t} \qquad \text{at } x = 0, d_c \qquad (8)$$

The scattered potentials must satisfy the following linearized kinematic boundary conditions on the membrane surface:

$$\frac{\partial \phi_l}{\partial x} = -\frac{\partial \phi_{l+1}}{\partial x} = -i\omega\xi + w(y)$$
$$= -i\omega\xi + \frac{B}{\mu}\rho i w[\phi_l - \phi_{l+1}] \qquad (9)$$

where μ is constant coefficient of dynamic viscosity, ρ is constant fluid density, and B is a material constant called permeability having the dimension of a length, and the harmonic membrane motions $\Xi(y,t) = \mathrm{Re}[\xi(y)e^{k_z z - i\omega t}]$ in Eqs. (8)~(9). For simplicity, the heave motion of the buoy is assumed to be negligible under large initial tension of membrane. Then the boundary condition on the floating buoy is

$$\frac{\partial \phi_l}{\partial n} + i\omega\{\eta_1 n_x + \eta_3 n_\theta\} + \frac{\partial \phi_0}{\partial n} = 0$$
$$l = 1,2,3 \ (\text{on } \Gamma_B) \qquad (10)$$

where $n_\theta = x n_y - y n_x$. To solve the present boundary value problem, a three-domain boundary integral equation method using simple sources along the entire boundary is developed. Two truncation boundaries (Γ_C) are located sufficiently far from the membrane such that the Sommerfeld condition (6) is valid.

The fundamental solution (Green function) of the Helmholtz Eq. (3) is $G = -(1/2\pi)K_0(k_z r)$. Here $K_0(k_z r) \approx -\gamma - \ln(k_z r/2)$ is the modified zeroth-order Bessel function of the second kind, and r is the distance from the source point (x', y') to the field point (x, y). As $r \to 0$, one obtains the asymptotic behavior, where θ is known as Euler's constant.

Applying Green's second identity in each of the domains to the unknown potentials ϕ_l and imposing the relevant boundary conditions Eqs. (4)~(10), the integral equations in each fluid domain can be written as

$$C\phi_l + \int_{\Gamma_F}[k_z K_1(k_z r)\frac{\partial r}{\partial n} - \nu K_0(k_z r)]\phi_l d\Gamma$$
$$+ \int_{\Gamma_C}[k_z K_1(k_z r)\frac{\partial r}{\partial n} - i k_x K_0(k_z r)]\phi_l d\Gamma$$
$$+ \int_{\Gamma_B}\phi_l k_z K_1(k_z r)\frac{\partial r}{\partial n} + i\omega K_0(k_z r)(\eta_1 n_x + \eta_3 n_\theta)d\Gamma$$
$$+ \int_{\Gamma_B} K_0(k_z r)\frac{\partial \phi_0}{\partial n}d\Gamma$$
$$+ \int_{\Gamma_m}\phi_l\{k_z K_1(k_z r)\frac{\partial r}{\partial n} - s_l\frac{B}{\mu}i\rho w K_0(k_z r)\}d\Gamma$$
$$+ \int_{\Gamma_m} s_l\frac{B}{\mu}i\rho w K_0(k_z r)\phi_{l+1} + s_l(i\omega\xi)K_0(k_z r)d\Gamma$$
$$+ \int_{\Gamma_b}\phi_l k_z K_1(k_z r)\frac{\partial r}{\partial n}d\Gamma = 0 \qquad (l = 1,2,3) \qquad (11)$$

where $\nu = \omega^2/g$ is the infinite-depth wave number, C=solid-angle constant, $s_1 = 1$, $s_3 = -1$, and in domain II $s_2 = -1$, and $s_2 = 1$ are for backward side of front membrane and forward side of rear membrane respectively.

The integral Eq. (11) should be coupled with the equations of motion of the membranes ξ_f, ξ_r and buoys η_1 , η_3 . In addition, the disturbance potentials must satisfy the following linearized dynamic boundary conditions on the membrane surface:

$$\frac{d^2\xi}{dy^2} + \lambda^2\xi = \frac{\rho i\omega}{T}(\phi_l - \phi_{l+1}) \ (\text{on } \Gamma_m) \qquad (12)$$

where $\lambda = \omega\sqrt{m/T}$ with T and m being the membrane tension and mass per unit length respectively. For a numerical approach the discrete form of equation of membrane motion for $j-th$ element is given by

$$\rho i\omega(\phi_{l(j)} - \phi_{l+1(j)})l_j - T_{(j)}(\frac{\partial\xi}{\partial\zeta})_j + T_{(j+1)}(\frac{\partial\xi}{\partial\zeta})_{j+1}$$
$$= -m l_j \omega^2 \xi_{(j)} \qquad (13)$$

where $(\partial\xi/\partial\varsigma)_j = (\xi_{f(j)} - \xi_{f(j-1)})/\Delta\zeta_j$, l_j is the length of the $j-th$ segment, and $\Delta\zeta_j = (l_j + l_{j+1})/2$.

The geometric boundary conditions at the seabed and the top connection points of membrane $(0,-r_c)$ are $\xi=0$ at $y=-h$, $\xi=\eta_1+R\eta_3$ at $y=-r_c$. R is distance from the connection point $(0,-r_c)$ to rotation center of buoy.

As mentioned before, it is assumed that the heave response is negligible due to large initial tension. The coupled equations of motion for sway and roll are given by

$$M(-\omega^2)X=F_p-(K_{HS}+K_m)X-F_T+F_D \qquad (14)$$

where X is displacement of sway and roll, M is a mass matrix of buoy, F_p is hydrodynamic forces and moments on buoy, K_{HS} is the restoring forces and moments due to the hydrostatic pressure, K_m is sway and roll mooring stiffness coefficients including the effects of pretension, F_D is the nonlinear viscous drag force, and these are detailed in Kee & Kim (1997). The symbol F_T is forces and moments on the buoys caused by the initial tension of membrane at the connection points between membranes and buoys.

$$F_T=T_{(N_m+1)}\begin{Bmatrix}-\sin\alpha\\ R\sin\eta_3\cos\alpha-R\cos\eta_3\sin\alpha\end{Bmatrix} \qquad (15)$$

where α is the angle of membrane at the connections with respect to the y axis and the symbol R is the radial distances from the center of rotation of buoy to the connection point on buoy. Assuming the angle α is small, then $\cos\alpha\cong 1$, $\sin\alpha\cong-(\partial\xi/\nabla\varsigma)_{N_m+1}$, and Eq. (15) can be rewritten as

$$F_T=T_{(N_m+1)}\begin{bmatrix}\frac{2}{l_{N_m}} & \frac{2R}{l_{N_m}}\\ \frac{2R}{l_{N_m}} & R+\frac{2R^2}{l_{N_m}}\end{bmatrix}\begin{Bmatrix}\eta_1\\ \eta_3\end{Bmatrix}-T_{(N_m+1)}\begin{bmatrix}\frac{2}{l_{N_m}}\\ \frac{2R}{l_{N_m}}\end{bmatrix}\xi_{N_m} \qquad (16)$$

This equation is composed of two terms: positive restoring forces and moments to the each buoy, and excitation force proportional to the motion amplitude of the neighboring membrane element. Therefore, the membrane tensions can be either restoring forces or excitations.

So far, we have obtained integral Eq. (11) for ϕ_l, $l=1,2,3$, and equation of membrane motion (13) and equations of buoy motions (14). They are mutually coupled, so they need to be solved simultaneously. If we discretize fluid domain 1 and 3 by $NE_{1,3}$ segments, and discretize middle domain 2 by NE_2, we have $2NE_{1,3}+NE_2$ unknowns for ϕ_1, ϕ_2, and ϕ_3, $N_{mf}+N_{mr}$ unknowns for ξ_f and ξ_r, and four more unknowns η_{f1}, η_{f3} and η_{r1}, η_{r3}, where the sub notations f, r mean front and rear respectively. Therefore, we have to solve NT number of linear simultaneous equations.

$$NT=2NE_{1,3}+NE_2+N_{mf}+N_{mr}+4 \qquad (17)$$

3. NUMERICAL RESULTS AND DISCUSSIONS

The three-domain boundary element program has been developed based on linear potential theory and Darcy's law as described in the preceding section, and was used to demonstrate the performance of fully submerged dual buoy/porous-membrane floating breakwaters in oblique seas. The computational domain is defined as in Fig. 1. The two submerged system is situated in parallel with spacing d_c. The submerged buoy/porous-membrane system allows gap c_{ff}, c_{fb}, c_{rf}, c_{rb}, which present front free surface gap, front bottom gap, and rear free surface gap, rear bottom gap respectively.

When the buoy is absent or negligibly small, the results with increasing the number of segments is converged well (not presented here). As coordinate system and computational domain are defined in Fig. 2, the two submerged membrane system in parallel with spacing and gaps. The convergence test of the developed BEM program has been done for the system design parameter $\widetilde{T}=0.255$, $c_{ik}/h=0.125$, $d_c/h=1$.

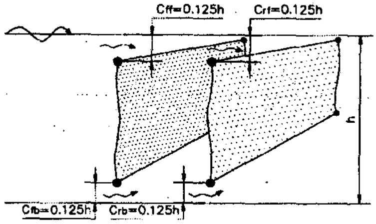

Fig. 2. Definite sketch of dual submerged permeable membrane breakwater

Figs. 3a~3b shows the results with increasing the permeability coefficient B =0, 1E-09, 5E-09, 1E-08, 5E-08, 1E-07, 5E-07, 1E-06. $\widetilde{T}$ is non-dimensional tension of membrane by $(T/\rho g h^2)$. Fig. 3a. shows wave reflection coefficients converged continuously according to the various B values.

Fig. 3b shows the energy relation error (%) with respect to varying B values. It is interesting that the limit value of B for maximum energy dissipation exist over all frequencies $kh = 0.2 \sim 6$ for beam seas. When B is greater than 1E-07, the energy dissipation effects starts to be diminished at $kh = 4.2$, and gradually reduced over all frequency band as B further increased.

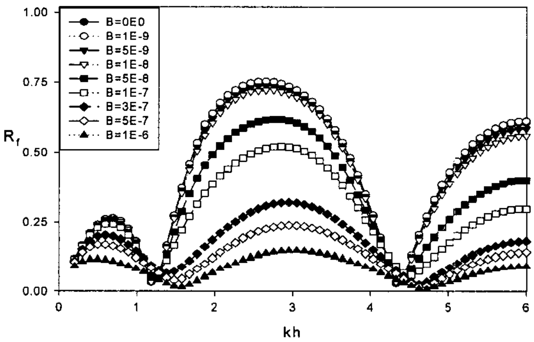

Fig. 3a. Convergence Test; Reflection coefficients of varying permeability of membrane

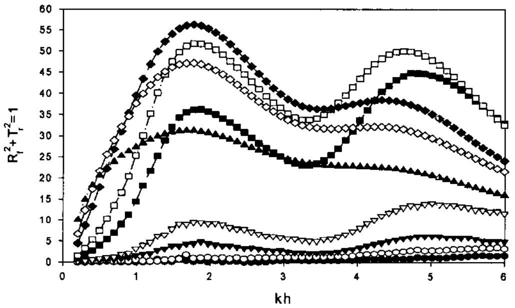

Fig. 3b. Convergence Test; Energy relation coefficients of varying permeability of membrane

The comparison of performances for an ideal dual submerged membranes wave barrier of $\widetilde{T} = 0.255, c_{ik}/h = 0.125, d_c/h = 1$ with and without permeability is presented in Figs. 4a~4b. as function of kh and θ.

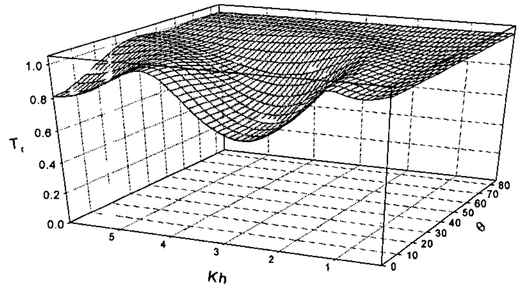

Fig. 4a. The transmission coefficients as function of kh, θ, and $B = 0$

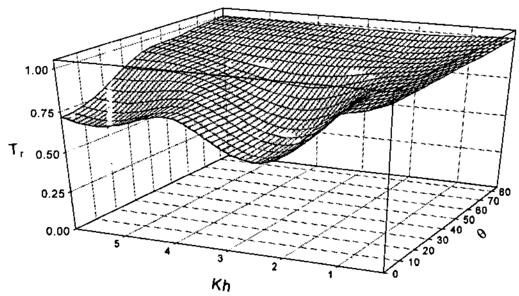

Fig. 4b. The transmission coefficients as function of kh, θ, and $B = 1E-8$

In the oblique seas, the effective wavelength in the x-direction becomes shorter and submerged systems with or without permeability (B=1E-07) turns out to be little effective. When the initial tension is relatively large, gap is not small compared to wave length, the positive effects of membrane hydrodynamics is diminished for the shorter wavelength in oblique sea.

In reality, the buoyancy force of buoys can easily provide the external tensions in membrane. However, the presence of large buoys can significantly change the scattered wave field. In addition the permeability on membrane dissipates the fluctuations by re-reflected and radiated waves between two submerged vertical systems, and behaves as dampers with relevant to its velocity.

The convergence test for the submerged dual buoy/porous-membrane BEM code shows, in Fig. 5, that permeability of membrane can enhance the efficiency only at the limited range of frequencies. The tested model is $T_f/K_{f1} = 0.1$, $T_r/K_{r1} = 0$, $t_i/a_i = 0.02$, $a_i/h = 0.2$, $c_{ik}/h = 0.125$, $d_c/h = 1$. As B increased, the transmitted wave is decreased at some region of frequencies $kh = 0.2 \sim 1.5$ and $kh = 5. \sim 6.$, and the transmitted wave is increased at $kh = 3.5 \sim 5.0$ as shown in Fig. 5. As B increase, the reflection coefficient is gradually reduced up to B=1E-07, and starts to increase. It means that the hydrodynamic effects by membrane motions in vertical sinusoidal manner are less than that of buoys for dual system with highly permeable membranes.

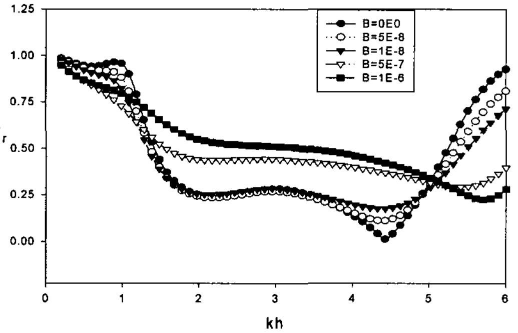

Fig. 5. The transmission coefficients with varying permeability of membrane for $\theta = 0$.

The performance of dual submerged buoy/solid-membrane floating wave barriers for $T_i/K_{i1} = 0$, $T_i/K_{i2} = 0.1$, $t_i/a_i = 0.02$, $a_i/h = 0.2$, $c_{ik}/h = 0.05$, $d_c/h = 1$ is shown in Fig. 6. These two systems have same design parameters, and allow semi-pivotal motions of buoys with only joint moorings. Thus we can observer several resonance in the performances, in which will be subsequent to system failure or give severe damages on the integrity of structures. After putting a permeability B=3E-08 on the membranes, the resonance is quite diminished in transmission and reflection as shown in Fig. 7. Therefore permeability coefficient B=3E-08 seems to be proper to maximize the performance based on the energy dissipation within dual buoy/porous-membrane systems.

The amplitudes of buoy/porous-membrane motion or forces on membranes are also of practical interest for the given system. Figs. 8a~8b. show the profiles of the non-dimensional membrane response amplitudes (per unit incident wave amplitude as function of kh and vertical position y/h for beam seas. As expected, the

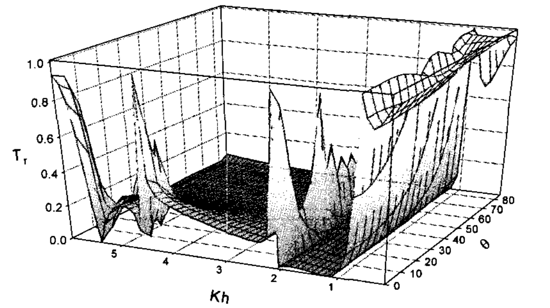

Fig. 6. The transmission coefficients as function of kh, θ, and $B = 0$

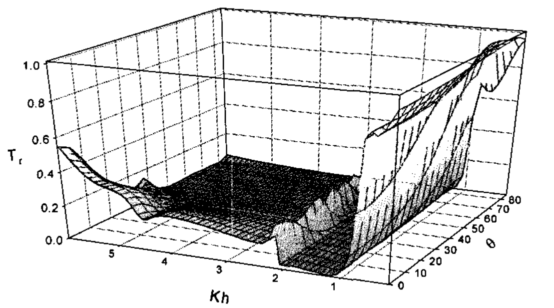

Fig. 7. The transmission coefficients as function of kh, θ, and $B = 1E-8$

response amplitude sharply increased at resonance frequencies, which generate large propagating waves in lee side. It is interesting that motion amplitude of rear membrane for $B = 3E-8$ is quite small compare to that of $B = 0$ one. It just implies that peak amplitudes except the very low one are at the near frequencies of system resonance.

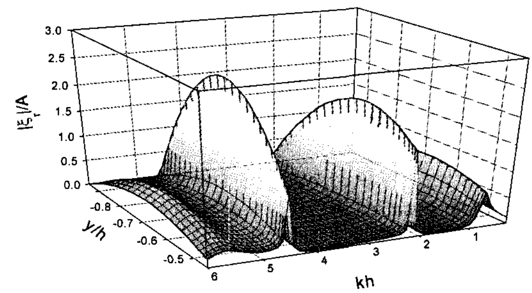

Fig. 8a. Responses of a rear membrane as function of kh and y/h for $\theta = 0°$ and $B = 0$

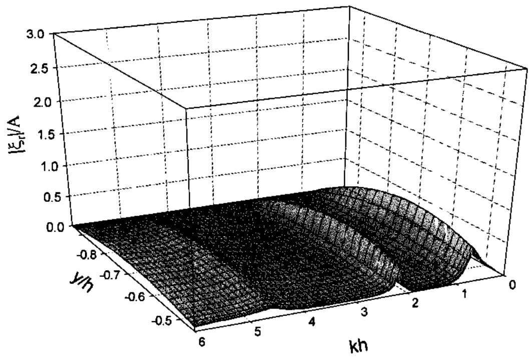

Fig. 8b. Responses of a rear membrane as function of kh and y/h for $\theta = 0°$ and $B = 3E-8$

The motion amplitudes of rear buoy are shown in Figs. 9a~9b, and sway motion amplitude of rear buoy for $\theta = 0°$ is small enough for us to see near zero motion at $kh = 1.5$.

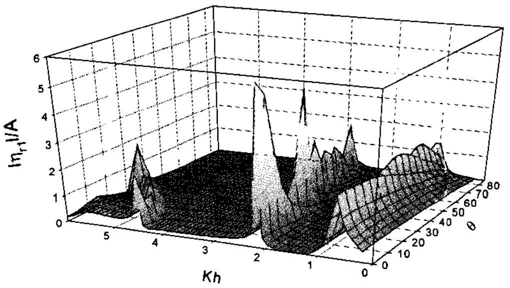

Fig. 9a. Sway motion of rear cylinder as function kh and θ for $B = 0$

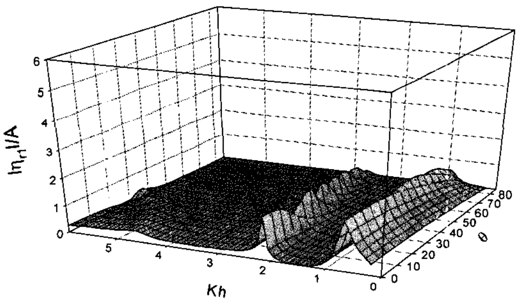

Fig. 9b. Sway motion of rear cylinder as function kh and θ for $B = 3E-8$

The sharp spikes in motion amplitudes of buoy/membrane are completed eliminated after applying permeability on membranes. The comparison of rear motions for B=0 and for B=3E-8 shows that high peak amplitudes are significantly reduced.

Therefore the proper permeability on membranes seems to magnify the performances of breakwater system by energy dissipation within dual buoy/porous-membranes.

4. SUMMARY AND CONCLUSIONS

The interaction of oblique incident waves with submerged dual buoy/porous-membrane was solved in the context of two-dimensional linear hydro-elastic interaction theory and Darcy's law. Both the ideal system composed of only submerged dual porous-membrane with spacing and more practical dual submerged buoy/porous-membrane systems were considered.

Using the developed program code, the performance of fully submerged dual systems in oblique waves was tested with various breakwater design parameters, wave conditions, and permeability on membranes. From these examples, it is shown that the use of the submerged dual buoy/flexible porous-membranes can significantly increase the overall wave blocking efficiency in normal and oblique incident waves except long wave frequencies. Allowing proper motions of buoys and membranes, the mutual cancellation effect of incident waves and scattered waves significantly enhance the performance as breakwaters. In addition, applying proper permeability on membrane eliminates resonance of system to secure the safety of structural dynamics, and reduces transmission and reflection. Using a properly devised asymmetric system, which can complement each other, we can further enhance the efficiency. In most cases, mooring type, gaps, proper permeability, and size of buoy for sufficiently large membrane tension needs to be provided to guarantee high performance over a wide range of wave frequencies.

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