FLEXIBLE MEMBRANE WAVE BARRIER

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1. INTRODUCTION

Various concepts using flexible membrane such as plastic and fabric have been proposed for a variety of ocean/coastal developments. In particular, the longevity of membrane fabrics and PVCs has significantly been improved during the past decade (Broderick et al., 1993), making them a viable engineering material for future coastal/ocean applications. For example, the flexible membrane can be used as a portable temporary breakwater for strategic amphibious military operation or for the protection of sophisticated offshore and coastal operations, and as a containment boom for floating oil slicks and other surface contaminants. It has also been suggested that flexible membranes, being lightweight, inexpensive, easily and quickly handled, and reusable, be used for submerged breakwaters (Ohyama et al., 1989), transportation of freight, deepwater waste disposal, and submerged oil storage tank.

In this paper, the wave interaction with flexible membrane hinged at the seabed and the mean free surface is considered. It is assumed that the tensioned membrane is unstretchable and free to move in the transverse direction. The tension, for example, can be provided by a taut-moored small buoy which little influences the wave field. For simplicity, a two-dimensional mathematical model is used and linear theory is adopted. The membrane dynamics is modeled as that of the tensioned string, and both analytic and numerical solutions are obtained. A boundary element method based on a discrete membrane model and Rankine source distribution is developed for the numerical solutions. For the analytic solution, a continuous membrane model as well as eigenfunction expansion of the velocity potential is used. Thompson et al. (1992) studied the performance of a similar wave barrier, in which they used arbitrary constant added mass and wave damping of the flexible membrane, which should in principle depend on various modes and wave frequency.

2. ANALYTIC SOLUTIONS

For analysis, the Cartesian coordinate system with the origin on the mean free surface and the z axis positive upward is used. Assuming ideal fluid and harmonic motion of frequency ω, the velocity potential can be written as $\Phi(x,z,t) = Re[\phi(x,z)e^{-i\omega t}]$. Then, the linear complex disturbance velocity potentials, ϕ_1 and ϕ_2, for two fluid domains 1 and 2 (see Fig.1) divided by a membrane have the following forms:

$$\phi_1 - \phi_0 = \beta \cosh k(z+h)e^{-ikx} + \sum_{n=1}^{\infty} c_n \cos \kappa_n (z+h) e^{\kappa_n x} \qquad (1)$$

$$\phi_2 = \alpha \cosh k(z+h)e^{ikx} + \sum_{n=1}^{\infty} d_n \cos \kappa_n(z+h)e^{-\kappa_n x} \quad (2)$$

where $\phi_o = (-igA/\omega)(\cosh k(z+h)/\cosh kh)e^{ikx}$ is the velocity potential of an incident wave of amplitude A with g and h being the gravitational acceleration and water depth, respectively. The wavenumbers k and κ_n can be determined from

$$\omega^2 = kg \tanh kh \quad , \quad -\omega^2 = \kappa_n g \tan \kappa_n h \quad (3)$$

The above velocity potentials satisfy all the boundary conditions except on the membrane surface, where the kinematic and dynamic boundary conditions are given by

$$\frac{\partial(\phi_1 + \phi_0)}{\partial x} = \frac{\partial \phi_2}{\partial x} = -i\omega\xi \quad (4)$$

$$\frac{d^2\xi}{dz^2} + \lambda^2\xi = \frac{\rho i\omega}{T}(\phi_2 - \phi_1) \quad (5)$$

in which $\lambda = \omega\sqrt{m/T}$ with T and m being the membrane tension and mass per unit length, respectively, ρ is the fluid density, and the harmonic membrane motion $\Xi(z,t) = Re[\xi(z)e^{-i\omega t}]$. The solution of the above dynamic equation is given by a series of the eigenfunctions of the corresponding homogeneous boundary value problem as follows:

$$\xi(z) = \sum_{n=1}^{\infty} \frac{B_n}{\lambda^2 - \lambda_n^2} \sin \lambda_n(z+h) \quad (6)$$

$$B_n = \frac{2}{h}\frac{\rho i\omega}{T}\int_{-h}^{0} (\phi_2 - \phi_1) \sin \lambda_n(z+h)dz \quad (7)$$

where $\lambda_n = n\pi/h$. Using the orthogonality of the wave eigenfunctions and the kinematic and dynamic membrane boundary conditions, the unknowns α, β, c_n, and d_n of (1) and (2) can be determined. Then, the membrane motion can be determined from (6) and (7). Compared to rigid-body hydrodynamics, the body boundary condition is not known a priori in this case, thus the membrane motions and velocity potentials are solved together.

3. NUMERICAL METHODS

A boundary integral equation method based on the distribution of simple sources is developed for our numerical solutions. Using basic singularities over the entire domain, the method can be used for arbitrary bottom topography and can easily be extended to the nonlinear time-domain problem.

The integral equations for the unknown potentials ϕ_1, ϕ_2, and membrane displacements ξ are given by

$$C\phi_1 + \int_{\Gamma_{F1}} (\frac{\partial G}{\partial n} - KG)\phi_1 d\Gamma + \int_{\Gamma_{c1}} (\frac{\partial G}{\partial n} - ikG)\phi_1 d\Gamma$$

$$+\int_{\Gamma_{b1}} \phi_1 \frac{\partial G}{\partial n} d\Gamma + \int_{\Gamma_m} \phi_1 \frac{\partial G}{\partial n} d\Gamma + \int_{\Gamma_m} i\omega G \xi d\Gamma = -\int_{\Gamma_m} \frac{\partial \phi_0}{\partial n} G d\Gamma \tag{8}$$

$$C\phi_2 + \int_{\Gamma_{F2}} (\frac{\partial G}{\partial n} - KG)\phi_2 d\Gamma + \int_{\Gamma_{c2}} (\frac{\partial G}{\partial n} - ikG)\phi_2 d\Gamma$$

$$+\int_{\Gamma_{b2}} \phi_2 \frac{\partial G}{\partial n} d\Gamma + \int_{\Gamma_m} \phi_2 \frac{\partial G}{\partial n} d\Gamma - \int_{\Gamma_m} i\omega G \xi d\Gamma = 0 \tag{9}$$

where $G = \ln\sqrt{(x-x')^2 + (z-z')^2}$ with (x', z') being the source point, and $K = \omega^2/g$. All the boundary conditions of ϕ_1 and ϕ_2 including the kinematic membrane boundary codition have been used in (8) and (9). It is assumed that the truncation boundary Γ_c is located far enough from the membrane so that the local (evanescent) wave effects may be neglected. In this paper, the potential is assumed to be constant on each segment ($C = \pi$).

On the other hand, the discrete form of the membrane equation of motion for j-th element is given by

$$\rho i\omega(\phi_{2j} - \phi_{1j})l_j - T_j \frac{(\xi_j - \xi_{j-1})}{l_j^m} + T_{j+1} \frac{(\xi_{j+1} - \xi_j)}{l_{j+1}^m} = -m_j \omega^2 \xi_j \tag{10}$$

where $l_j^m = \frac{l_j + l_{j+1}}{2}$. In the above integral equations, ϕ_1 and ϕ_2 are coupled through the unknown membrane displacement ξ, hence cannot be solved independently. Two different methods can be used to solve the above integral equation. First, the two integral equations can be solved independently after assuming initial values of ξ, and then new ξ values can be obtained from (10) using the computed potentials. This procedure can be repeated until a specified convergence criterion is reached. Second, (8), (9), and (10) can be solved together to obtain ϕ_1, ϕ_2, and ξ at the same time. The size of the matrix of the first method is in general much smaller than that of the second method, thus the iteration method is expected to be more efficient than the whole matrix method if convergence can be reached quickly.

4. DISCUSSION

For illustration, linear wave interaction with a flexible membrane wave barrier of mass density=5.1 kg/m^2 is considered. The reflection coefficients of the membrane wave barrier hinged at both ends are plotted in Figure 2 as functions of nondimensional wavenumber kh with varying the membrane tension. Good agreement is observed between numerical and analytic solutions. It is seen that the membrane wave barrier can function as a very effective breakwater in broad wave frequency range when applying a tension greater than 10kN. More than 10kN of tension can easily be provided by a long cylindrical buoy of radius less than 1m. Figure 3 shows the profile of the nondimensional membrane response amplitude (per unit incident wave amplitude) for various kh values. We observe that despite appreciable membrane motions, little waves are generated in the lee side.

5. REFERENCES

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Ohyama, T., Tanaka, M., Kiyokawa, T., Uda, T., & Murai, Y. (1989) "Transmission and reflection characteristics of waves over a submerged flexible mound" *Coastal Engineering in Japan*, Vol.32

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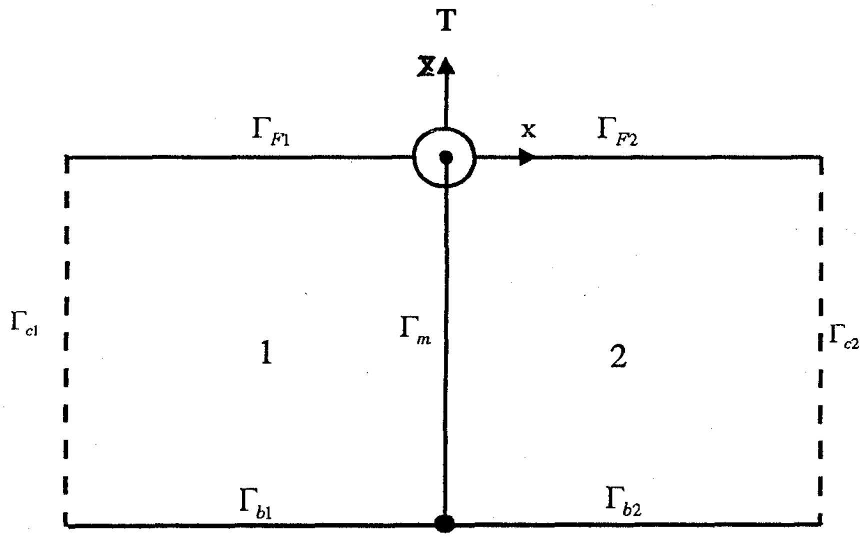

(Figure 1) Integration Domains

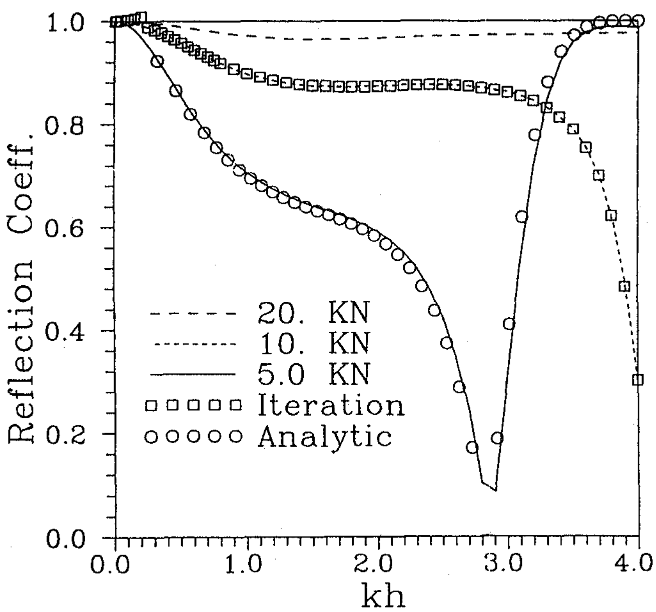

Figure 2.

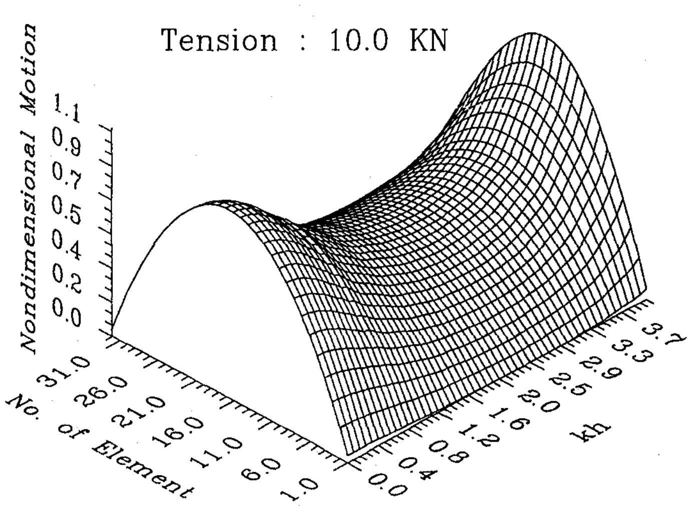

Figure 3.

DISCUSSION

Kuznetsov N.: 1) Was the uniqueness studied for your boundary value problem?
2) What is the reason for using the Rankine source instead of , e.g., the wave source, which allows to eliminate all integrals except for that over Γ_m?

Kim M.H.: 1) As far as I know, the solution is unique except at discrete irregular frequencies.
2) Although it is less efficient, the Rankine-source-based method can be used for arbitrary bottom geometry and it can also straightforwardly be extended to nonlinear time domain problem.

Sturova I.V.: Did you use your numerical scheme for the evaluation of the internal solitary wave moving with a constant speed? At the Lavrentyev Institute of Hydrodynamics (Russia, Novosibirsk) there are many theoretical and experimental results for this problem. I think it will be very interesting to make the comparison of your numerical results and the results obtained at our Institute.

Kim M.H.: Thank you for your comments. To answer to your first question, since we use a fully nonlinear numerical scheme for an initial-value problem, any nonlinear or linear phenomena will be obtained in the present method. We would also like to make comparisons with the theoretical and experimental results obtained by your Institute, in the future.

Evans D.V.: I have a comment rather than a question. If you allow a gap above the top of the flexible membrane, you permit the possibility of the wave created by the motion of the membrane cancelling the part of the incident wave passing through the gap. This theory was developed by Evans and Linton and published in Applied Ocean Research in about 1987, where the theory for a buoyant tethered circular cylinder predicted low transmission over a wide period range. Experiments confirmed the results. Further work on a higed vertical plate was presented at the OMAE conference in Houston in 1990.