## CHAPTER 180

#### MECHANICALLY COUPLED BUOYANT FLAPS: THEORY AND EXPERIMENT

by

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## Abstract

A system composed of two buoyant flaps hinged at the sea floor and coupled with weighted mooring lines is modeled analytically and experimentally. The system behavior is described theoretically utilizing an eigenseries representation of linear wave theory in the vicinity of the breakwater. The structure dynamics are modeled in terms of structure weight, inertia, buoyancy, damping, mooring line tension and the wave pressure field.

The mechanically coupled system provides shelter by reflecting incident waves and by attenuating wave energy through structural and viscous damping. The structure can be tuned to minimize wave transmission within a particular frequency range by changing the flap spacing and adjusting the mass and equilibrium position of the mooring line weights.

The theory is validated with experimental results for models fabricated from inflatable, parallel-tube membranes. Buoyancy and inertia are changed by filling tubes with air and/or water. Single and double flaps are examined with and without mooring lines. Incident, reflected, and transmitted waves are measured as well as flap motion. Theoretical results are corroborated by the experiments and the importance of including damping in the model is demonstrated.

# Introduction

Floating breakwaters have the desirable characteristics of being transportable, relatively inexpensive, and reusable and rapidly deployable. However, most floating breakwaters are relatively transparent to the incident wave field, e.g., floating parallelepipeds (Adee, 1976), tire-mazes (Harms, 1979), and tethered spheres (Seymour and Harms, 1979). In order to improve the behavior of floating breakwaters, it is necessary for the structure to occupy a major fraction of the water column or incident wave length. The effectiveness of a floating structure can also be improved by constraining some modes of structural deflection and by tuning the structure natural frequency to avoid design wave frequencies (Leach, McDougal, and Sollitt, 1985).

In this study, a flap-type floating structure is examined which occupies the entire water column and which is hinged at the sea floor. Buoyancy provides a vertical equilibrium position for the structure and additional stiffness is afforded by weighted mooring lines. Wave interference between two structures is obtained by locating the flaps at appropriate spacings. Wave reflection is increased and wave transmission decreased by coupling the flaps with a common weighted mooring line; refer to Fig. 1. The coupled flap system can be tuned to optimize performance by varying the spacing, buoyancy and inertia as well as the mass and equilibrium position of the mooring weights.

The model structure examined during the experimental phase of this study was fabricated from a parallel tube air mattress. The inertia and buoyancy of the flap was changed by filling adjacent tubes with air or water. The membrane fabric which composed the air mattress was cut and glued to change the height and width of the structure and grommets for mooring line attachments were added by gluing additional fabric to the face of the mattress. The structure was anchored with a weighted plate at the sea floor. The utility of the air mattress model has some readily apparent implications for prototype applications in terms of portability and constructibility.

The behavior of the flap system is modeled analytically utilizing an eigenseries representation of linear wave theory in the vicinity of the structure. This contrasts to the numerical solution procedure of Raichlen and Lee (1978) used for inclined plate structures. Linear flap dynamics are modeled in terms of structure weight, inertia, buoyancy, damping, mooring line tension and the wave pressure field. This contrasts to the undamped, unconstrained solution of Evans (1979) and Skrokosz and Evans (1979) for wave power absorbing bodies.

Theoretical and experimental results are compared for single flaps and double flaps, for air and air/water filled mattresses. Examples with and without moorings are included. Both damped and undamped solutions are illustrated. Experimental and theoretical results confirm that structural and viscous damping are important considerations in describing the system behavior.

## Theory

## Potential Flow Boundary Value Problem (BVP)

In this study, the fluid is considered to be inviscid and incompressible and the flow is assumed to be irrotational. Then a single-valued velocity potential  $\Phi_{\varrho}$ ,  $\ell = I$ , II, III, can be defined for each flow field separated by the flaps in Fig. 2 as

$$\vec{u}_{\ell} = -\vec{\nabla}\Phi \quad ; \qquad \ell = I, II, III \qquad (1)$$



Figure 1. Definition sketch.



Figure 2. Linearized boundary value problem.

When small amplitude waves are considered, the velocity potentials satisfy the Laplace equation and the boundary conditions shown in Fig. 2. Kinematic boundary conditions, which require continuity of normal velocity across boundaries, are imposed on the impermeable bottom, rigid flaps, and free surface. Dynamic boundary conditions, which require continuity of pressure across a boundary, are imposed on the free surface. An additional radiation condition requiring only outgoing progressive waves at infinity is imposed on the reflected and transmitted waves.

The incident wave velocity potential and water surface profile are specified as

$$\phi_{i} = R_{e} \left\{ \frac{a_{i1}g}{\sigma} \frac{\cos K_{1}(z+h)}{\cos K_{1}h} e^{-(K_{1}x+i\sigma t)} \right\}$$
(2a)

$$\eta_{i} = R_{e} \left\{ -ia_{i1}e^{-(K_{1}x+i\sigma t)} \right\} = a_{i1}\sin(kx-\sigma t)$$
(2b)

where  $K_1 = -ik$ ,  $k = \frac{2\pi}{L}$ , L is the wave length,  $\sigma = \frac{2\pi}{T}$ , T is the wave period, and  $a_{11}$  is the wave amplitude. The velocity potentials satisfying the BVP shown in Fig. 2 are found as follows:

$$\Phi_{I} = \phi_{i} + \sum_{j=1}^{\infty} \frac{ga_{rj}}{\sigma} \frac{\cos K_{j}(z+h)}{\cos K_{j}h} e^{(K_{j}x-i\sigma t)}$$
(3)

$$\Phi_{II} = \sum_{j=1}^{\infty} \frac{g}{\sigma} \frac{\cos K_j(z+h)}{\cos K_j h} \left\{ a_{pj} e^{-[K_j x+i\sigma t]} + a_{nj} e^{[K_j(x-b)-i\sigma t]} \right\}$$
(4)

$$\Phi_{\text{III}} = \sum_{j=1}^{\infty} \frac{ga_{tj}}{\sigma} \frac{\cos K_j(z+h)}{\cos K_j h} e^{-[K_j(x-b)+i\sigma t]}$$
(5)

where the eigenvalues  $\boldsymbol{K}_{j}$  can be determined from the dispersion equation:

$$K_1 = -ik \tag{6a}$$

$$(2j-3) \frac{\pi}{2} < K_{j}h < (j-1)\pi$$
 for  $j > 2$  (6b)

$$\sigma^2 = -gK_j \tan K_j h$$
 (6c)

and

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$$a_{rj} = \delta_{jl}a_{il} - i\beta_{j}S_{l}$$
<sup>(7)</sup>

$$a_{pj} = i\beta_{j} \left( \frac{S_{1}e^{K_{j}b} - S_{2}}{2 \sinh K_{j}b} \right)$$

$$K, b$$
(8)

$$a_{nj} = i\beta_{j} \left( \frac{S_{1} - S_{2}e^{-J}}{2 \sinh K_{j}b} \right)$$
(9)

$$a_{tj} = \frac{1\beta_j S_2}{2}$$
(10)

$$\beta_{j} = \frac{2 \sin K_{j}h}{K_{j}^{2}h^{2}(1 + \frac{\sin 2K_{j}h}{2K_{j}h})} [K_{j}h \sin K_{j}h + \cos K_{j}h - 1]$$
(11)

for  $j \ge 1$  and  $\delta_{j1}$  is Dirac delta.  $a_{\gamma j}$ ,  $a_{p j}$ ,  $a_{n j}$ , and  $a_{t j}$  are the complex amplitudes of the reflected waves, right-going and left-going waves between the flaps and the transmitted waves, respectively.  $S_1$  and  $S_2$  are the complex amplitudes of the two flaps, referenced to the still water, and related to the flap angle of inclination as

$$\theta_{1} \cong \frac{S_{1}}{h} e^{-i\sigma t}$$

$$\theta_{2} \cong \frac{S_{2}}{h} e^{-i\sigma t}$$
(12)
(13)

for periodic small motions.  ${\rm S}_1$  and  ${\rm S}_2$  are determined by solving the coupled equations of motion of the breakwater flaps.

Each flap is assumed to be rigid yet free to rotate about a fixed point on the seabed. The equation of motion for each flap is found by taking the moment about its hinge point at the seabed as

$$I_{\ell} \overset{"}{\theta}_{\ell} + M_{B\ell} - M_{G\ell} - M_{w\ell} + M_{m\ell} + C_{d\ell} \overset{"}{\theta}_{\ell} = 0 , \ell = 1,2$$
(14)

where  $I\bar{\theta}$  is the mass moment of inertia of the flap,  $M_B$  and  $M_G$  are the moments due to the buoyancy  $F_B$  and the weight of the flap,  $M_W$  is the moment due to wave force,  $M_m$  is the moment due to the mooring line, and the last term represents energy dissipation which may be caused by nonconservative forces. For small motions, the moments are found as follows:

$$M_{B\ell} \cong F_{B\ell}B_{\ell}B_{\ell}\theta_{\ell} \tag{15}$$

$$M_{G\ell} \cong m_{\ell}^{*} g_{G\ell} \theta_{\ell}$$
(16)

$$M_{w\ell} \cong -\frac{h}{S_{\ell}} \rho g M_{\ell} \theta_{\ell}$$
(17)

where  $\texttt{m} \star \texttt{is}$  the mass of the flap per unit width, and B and G are defined in Fig. 3, and

$$M_{1} = \sum_{j=1}^{\infty} r_{j} \{2i\delta_{j1}a_{i1} + \beta_{j}[S_{1}(1 + \operatorname{coth}K_{j}b) - S_{2}\operatorname{csch}K_{j}b]\}$$
(18)

$$M_2 = \sum_{j=1}^{\infty} r_j \beta_j [-S_1 \operatorname{csch}_j b + S_2 (1 + \operatorname{coth}_j b)]$$
(19)

$$r_{j} = \frac{K_{j}hsinK_{j}h + cosK_{j}h - 1}{K_{j}^{2}cosK_{j}h}$$
(20)

The moment due to mooring lines can be found from Fig. 4 as

$${}^{M}_{m1} \cong {}^{m}_{1}g^{d}_{1}{}^{Q}_{11} + {}^{m}_{1}g^{d}_{1}{}^{Q}_{12}\theta_{1} + {}^{m}_{2}g^{d}_{1}{}^{Q}_{13}\theta_{2} - {}^{m}_{1}d_{1}^{2}\theta_{14}\theta_{1} + {}^{m}_{2}d_{1}d_{2}{}^{Q}_{15}\theta_{2}$$
(21)

$$M_{m2} \approx m_2 g d_2 Q_{21} + m_2 g d_2 Q_{22} \theta_1 + m_2 g d_2 Q_{23} \theta_2 + m_2 d_1 d_2 Q_{24} \ddot{\theta}_1 - m_2 d_2^2 Q_{25} \ddot{\theta}_2$$
(22)

The subscripted  $Q_{ij}$  variables are determined relative to the position of the mooring line weights (Lee et al. 1986).

For a system which has vertical flaps at static equilibrium, a steady-state solution exists as described by Eqs. (12) and (13). The coupled equations of motion are obtained by substituting Eqs. (15), (16), (17), and (21) or (22) into Eq. (14), providing

$$C_{11}S_{1} - C_{12}S_{2} = -2ia_{11}\gamma_{1}$$
(23)

$$C_{21}S_1 - C_{22}S_2 = 0$$
(24)

where

$$C_{11} = C_{01} + P_{11} - \frac{i\sigma}{\rho gh^3} C_{d1}$$
(25)

$$C_{12} = C_{02} - P_{12}$$
(26)



$$C_{21} = C_{02} - P_{21}$$
(27)

$$C_{22} = C_{01} + P_{22} - \frac{i\sigma}{\rho gh^3} C_{d2}$$
(28)

$$C_{01} = \sum_{j=1}^{\infty} \beta_j \gamma_j (1 + \operatorname{coth} K_j b)$$
(29)

$$C_{02} = \sum_{j=1}^{\infty} \beta_j \gamma_j \operatorname{csch}_{j}^{K} b$$
(30)

$$P_{11} = \frac{1}{\rho g h^3} \left[ F_{B1} B_1 + m_1 g d_1 Q_{12} - m_1^* g G_1 - \sigma^2 (I_1 - m_1 d_1^2 Q_{14}) \right]$$
(31)

$$P_{12} = \frac{1}{\rho gh^3} \left[ m_2 g d_1 Q_{13} - \sigma^2 m_2 d_1 d_2 Q_{15} \right]$$
(32)

$$P_{21} = \frac{-1}{\rho g h^3} \left[ m_2 g d_2 Q_{22} + \sigma^2 m_2 d_1 d_2 Q_{24} \right]$$
(33)

$$P_{22} = \frac{1}{\rho g h^3} \left[ F_{B2} B_2 - m_2 g d_2 Q_{23} - m_2^* g G_2 - \sigma^2 (I_2 - m_2 d_2^2 Q_{25}) \right]$$
(34)

Solving Eqs. (23) and (24) simultaneously yields

$$S_{1} = i \left[ \frac{2\gamma_{1}C_{22}}{C_{12}C_{21} - C_{11}C_{22}} \right] a_{11}$$
(35)

$$S_{2} = 1 \left[ \frac{2\gamma_{1}C_{21}}{C_{12}C_{21} - C_{11}C_{22}} \right]^{a} i1$$
(36)

The flap amplitudes are specified by Eqs. (35) and (36). The flap amplitudes are substituted into Eqs. (7) and (10) for j=1 to solve for the reflected and transmitted wave amplitudes, respectively.

## Experimental Facilities and Procedures

Experiments were conducted in the Graf Hall wave channel at Oregon State University, USA. The channel is 36 feet long, 2.0 feet wide and 2.2 feet deep. The models were located midway between the wave generator and a 1:10 slope beach. Waves were generated by a flap-style wave board, powered by variable speed electric motor with a right angle gear reduction box and variable eccentric drive shaft. Monochromatic waves were generated in a period range of 0.5 to 1.1 seconds, with wave heights up to 0.27 feet. All tests were conducted in a water depth of 1.5 feet.

Individual flaps for the model breakwaters were constructed from inflatable air mattresses, 1.8 feet wide and 6.0 feet long. The mattresses were composed of seven parallel tube chambers running the length of the mattress, with separate valves in each chamber. The mattresses were fabricated from a woven synthetic textile, sealed with an internal coating.

Mattresses were modified to become breakwater models by cutting each mattress in half to reduce the length and by adhesive fastening a seventh air chamber to provide a flap width equal to the wave channel width. Additional fabric patches were adhesive fastened to each chamber at the water surface to provide a grommet attachment for braided nylon mooring lines. A three yoke bridle distributed the load from each mooring line to three tubes. Two mooring lines were attached to both sides of the moored flaps. Four pound lead weights were suspended from each mooring line to provide a positive restoring force.

The inflated dimensions of the breakwater flap were 2.75 feet high, 2.04 feet wide and 0.22 feet thick. Flaps were inflated to a common pressure head of three feet of water. Some experiments were conducted with all tubes filled with air. Other experiments were conducted with four tubes filled with water to the SWL and three tubes filled with air. Five different breakwater configurations were examined. The characteristics associated with each configuration are identified in Table 1.

Wave profiles were monitored with acoustic water surface sensors, sampling at a rate of 60 hertz. A single fixed wave sensor was placed two water depths beyond the leeward flap to measure the transmitted wave height. A single wave sensor on a sliding carriage was placed on the seaward side of the breakwater to profile the envelope resulting from the superposition of the incident and reflected waves. The incident wave height was calculated from one-half the sum of the relative maxima and minima of the envelope. The reflected wave height was calculated from one-half the diffrence of the relative maxima and minima. Breakwater flap amplitudes were measured visually by scaling flap motion at the still water level.

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Model
4
Table

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Case	Breakwater Configuration	Weight in Air (lbf/ft)	Displaced Water Weight (lbf/ft)	Center of Gravity (ft)	Center of Buoyancy (ft)	rass Moment of Inertja (slug•ft <sup>2</sup> /ft)	Distance Between Breakwaters (ft)	Mooring Weight (1bf/ft)	Damping Coefficient (lbf•ft•sec/ft)
1	Single flap, air filled, without mooring	1.1755	13.9592	1.375	0.75	0.09201	1	1	1-1
7	Single flap, air/water filled*, without mooring	8.8653	13.9592	0.8328	0.75	0.27108	1	I	1.2
۳	Double flaps, air/water filled*, without mooring	8.8653	13.9592	0.8328	0.75	0.27108	1.5	i	2.1
4	Double flaps, air/water filled*, with mooring	8.8653	13.9592	0.8328	0.75	0.27108	1.9	4.8483	2.1
ъ	Double flaps, air/water filled*, with mooring	8.8653	13.9592	0.8328	0.75	0.27108	3.0	4.8483	1.2

\*Three tubes filled with air, four tubes filled with water to SWL.

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## Experimental and Theoretical Results

Reflected and transmitted wave amplitudes are the basis for comparing measured and predicted breakwater performance in this study. The amplitudes are reduced to dimensionless reflection and transmission coefficients by division with the incident wave amplitude. Results are expressed relative to wave frequency in terms of the dimensionless ratio of water depth divided by the linear wave theory deep water wave length, h/Lo. The deep water wave length is the progressive wave solution to the dispersion equation (6), for large water depths, yielding

$$L_{o} = \frac{gT^{2}}{2\pi}$$
(37)

Results for a single flap, inflated with air without moorings are presented in Fig. 5. This corresponds to Case 1 in Table 1. In general, the reflection coefficient is shown to increase with decreasing wave length (increasing h/Lo) while the transmission coefficient decreases with decreasing wave length. Experimental results are plotted as points in the figure while theoretical results appear as continuous lines. The breakwater becomes a dynamic barrier to high frequency waves (high h/Lo) due to the structural stiffness. However, the breakwater theoretically becomes a kinematic barrier to low frequency waves because breakwater buoyancy can accommodate a head difference across the flap, effectively creating a tidal barrage. The theoretical solution displays this trend at very low frequency; no experimental results are available at this frequency. Note that theory and experiments do follow the same trend, although the theory does overestimate the transmission coefficient for the undamped solution in the upper half of Fig. 5.

A damped solution is compared to experimental results in the lower half of the figure. The damping coefficient is determined empirically by requiring the theoretical solution to dissipate the same energy as the experimental results over the full range of measured data. Resulting damping coefficients are reported in the right hand column of Table 1. Damping does decrease the transmission while increasing the reflection coefficient to a lesser degree. In general, the correlation between theory and experiment is improved for the damped case.

Results for a single flap without moorings but with water to the SWL in four of the seven buoyancy chambers are shown in Fig. 6. This condition (Case 2 in Table 1) tends to give somewhat higher reflection coefficients and slightly lower transmission coefficients at all frequencies. The damped solution in the lower half of the figure more closely follows the experimental results.

A two flap system is illustrated in Fig. 7. The flap spacing is equal to the water depth. The breakwaters are filled with air and water and no moorings are attached. This corresponds to Case 3 in Table 1. The results show that the two flap system is much more frequency selective than the one flap system. Both theory and



• •

6.0

80 0.7 0.6 50 • 0.3 0.2 5 ٥

-

02 Kr(Exper.) Kt(Exper.)

5.0 0.2 0 ۰

0.6 0.5 **\***0

-

60 0.8 0.7 **□** 4

![](_page_11_Figure_1.jpeg)

02

0 Kr(Exper.) A Kt(Exper.)

![](_page_12_Figure_1.jpeg)

![](_page_12_Figure_2.jpeg)

experiment follow this trend with relative maxima and minima occurring at two points over the data range. Damping improves correlation with the transmission coefficient in the lower figure while the undamped case appears to better reproduce the reflection coefficient behavior at intermediate frequencies.

The effects of moorings for a two flap system, filled with air and water, is shown in Fig. 8. This corresponds to Case 4 in Table 1. The mooring dynamics add additional relative maxima and minima to the breakwater behavior. Damping improves the correlation between theory and experiment at intermediate wave frequencies. The general effect of the mooring is to reduce wave transmission at intermediate frequencies. This is made evident by comparing experimental results in Figs. 7 and 8.

## Conclusions and Recommendations

Mechanically coupled buoyant flaps have been proposed and constructed from inflated membranes connected with weighted mooring lines. A closed-form, linear analytical solution to the system behavior has been presented. A model has been constructed from currently available materials, demonstrating the practicality of the application. Comparisons between theoretical and experimental wave reflection and transmission coefficients have validated the analytical model. Theoretical and experimental results suggest that structural and viscous damping are important features in the system behavior.

Damping was quantified with a semi-empirical displacement rate coefficient in the model. This coefficient requires a more deterministic approach for evaluation, utilizing drag force relationships for mooring line motion. Also, significiant bending of the hinged flap was observed during the experiments, suggesting that the rigid flap approximation may be an oversimplification. Future studies will evaluate the flap behavior as an elastic beam with structural damping quantified relative to the plastic properties of synthetic membranes.

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