Theoretical and Experimental Studies of Upright Perforated Wave Filters

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Abstract

Liu et al. (1987) proposed a theoretical solution for scattering of waves through a permeable dissipation region. On the basis of bulk dissipation of the incident wave energy, this method is extended to evaluate the reflection and transmission coefficients of waves through a wave filter composed of rows of perforated sheets aligned normally to the direction of wave propagation. The results of the theoretical model are verified by laboratory tests with regular waves.

Keywords: Wave Filter, Perforated Plates, Wave Dissipation, wave Reflection, wave Transmission

Introduction

Wave filters are used in wave tanks to reduce the wave reflection from wave generators. Also, the secondary modes of the generated wave can be eliminated by using a wave filter. The various kinds of wave filters that have been investigated experimentally are tabulated in Table (1).

Berkhoff (1972) derived an equation to describe the phenomenon of combined refraction - diffraction for simple harmonic waves. His equation is:

$$\nabla.(cc_g \nabla \tilde{\phi}) + \frac{\sigma^2 c_g}{c} \tilde{\phi} = 0 \qquad (1)$$

where:

$\nabla = \frac{\partial}{\partial x}, \frac{\partial}{\partial y}$, horizontal vector differential operator

$\tilde{\phi} = \tilde{\phi}(x, y)$, velocity potential on the mean free surface, z = 0

$c_g = n c$, wave group velocity

c = phase velocity

σ = wave angular frequency ($=2\pi / T$)

n = ratio of group velocity to phase velocity

T = wave period

Equation (1) is known as the mild-slope wave equation.

Booij (1981) suggested the modified mild-slope wave equation for the regions of energy dissipation as follows:

$$\nabla(n c^2 \nabla \tilde{\phi}) + (n\sigma^2 + i\sigma W)\tilde{\phi} = 0 \qquad (2)$$

Table 1 - List of Investigated Wave Filters

Material	Direction of erection	Experienced at	Reported by
wire mesh screens	normal to the direction of wave propagation	St. Anthony Falls (FAS) Hydrodynamic Lab., Univ. of Minnesota Hydrodynamics Lab., M.I.T. National Hydraulic Lab., National Bureau of Standard & Vicksburg Waterways Experiment Station (WES)	Herbich (1956), Bowers and Herbich (1957) Goda and Ippen (1963) Keulegan (1968, 1973)
solid plates	parallel to channel walls	Louisiana State College SAF Hydraulics Lab., Univ. of Minnesota	Meyer (1950) Herbich (1956), Bowers and Herbich (1957)
perforated plates	parallel to channel walls	Neyrpic Lab. SAF Hydraulics Lab., Univ. of Minnesota	Biesel (1950) Bowers and Herbich (1957)
perforated plates	normal to the direction of wave propagation	Water Research Lab., Univ. of New South Wales	Chegini (1994)
porous walls	normal to the direction of wave propagation (submerged)	Berlin University of Technology	Clauss & Habel (1999)

where:

$W = \frac{\bar{\varepsilon}_d}{E}$ (3), rate of energy dissipation per unit wave energy

$\bar{\varepsilon}_d = -\nabla(E\, c_g)$ (4), rate of wave energy dissipation per unit area

$E = \frac{1}{2}\rho g a^2$ (5), wave energy

ρ = water density

g = acceleration of gravity

a = wave amplitude

Assuming a two-dimensional flow and a constant water depth, equation (2) may be written in the following form:

$$\frac{d^2\tilde{\phi}}{dx^2} + \bar{k}^2\tilde{\phi} = 0 \qquad (6)$$

where:

$$\bar{k}^2 = k^2 (1 + \frac{iW}{n\sigma}) \tag{6a}$$

$$\bar{k} = \bar{k}_r + i\,\bar{k}_i \tag{6b}$$

$$\bar{k}_r = k \left\{ \frac{[1 + (\frac{W}{n\sigma})^2]^{1/2} + 1}{2} \right\}^{1/2} \tag{6c}$$

$$\bar{k}_i = k \left\{ \frac{[1 + (\frac{W}{n\sigma})^2]^{1/2} - 1}{2} \right\}^{1/2} \tag{6d}$$

$$i = \sqrt{-1}$$

On the basis of equation (6) Liu, Yoon and Dalrymple (1987), proposed a theoretical solution for the calculation of the reflection coefficient from dissipative regions, with or without an end solid wall. In the latter case (fig. 1) the solutions for regions I, II and III were written as:

$$\phi_I = -\frac{iga}{\sigma}(e^{ikx} + K_r e^{-ikx}) \quad x < 0 \tag{7}$$

$$\phi_{II} = -\frac{iga}{\sigma}(Be^{i\bar{k}x} + F e^{-i\bar{k}x}) \quad 0 < x < l \tag{8}$$

$$\phi_{III} = -\frac{iga}{\sigma} K_t e^{ikx} \quad x > l \tag{9}$$

where B and F are unknown constants to be determined. The matching conditions are:

$$\phi_I = \phi_{II}\,, \quad \text{at} \quad x = 0 \tag{10}$$

$$\frac{d\phi_I}{dx} = \frac{d\phi_{II}}{dx}\,, \quad \text{at} \quad x = 0 \tag{11}$$

$$\phi_{II} = \phi_{III}\,, \quad \text{at} \quad x = l \tag{12}$$

$$\frac{d\phi_{II}}{dx} = \frac{d\phi_{III}}{dx}\,, \quad \text{at} \quad x = l \tag{13}$$

After substituting equations (7) to (9) into equations (10) to (13), Liu et al. concluded that:

$$F = \frac{2(\frac{\bar{k}}{k} - 1)}{(\frac{\bar{k}}{k} + 1)^2 e^{-2i\bar{k}l} - (\frac{\bar{k}}{k} - 1)^2} \tag{14a}$$

$$B = \frac{2 - F(1 - \frac{\bar{k}}{k})}{1 + \frac{\bar{k}}{k}} \tag{14b}$$

$$K_r = \frac{2(1 + \frac{F\bar{k}}{k}) - (1 + \frac{\bar{k}}{k})}{1 + \frac{\bar{k}}{k}} \tag{15}$$

$$K_t = B e^{i(\bar{k}-k)l} + F e^{-i(\bar{k}+k)l} \tag{16}$$

Theoretical Development

A rows of perforated sheets aligned normally to the direction of wave propagation is considered (fig. 2). It is assumed that the dissipation of energy of an incident wave passing through a series of perforated sheets, employed as a wave filter is due to the resistance of the screens' assembly, i.e.:

$$R = n_s \mathrm{K} \frac{\rho}{2} v^2 A \tag{17}$$

where:

- R resistive force of the screen assembly
- n_s number of perforated sheets in the assembly
- K resistance coefficient of the perforated sheet
- v approach velocity to the screen
- A wetted cross sectional area of a screen

Generally, K is a function of the porosity, the geometry of the perforated sheet and the Reynolds number. However, K becomes independent of the Reynolds number for high values of this parameter.

Based on equation (17) the resistance force from the strip *b.dz* of a single perforated sheet is:

$$\Delta R = \frac{\rho}{2} \mathrm{K} b v^2 dz \tag{18}$$

where b is the width of the perforated sheet. This strip absorbs a part of the incident wave energy which its amount per unit time is:

$$\Delta E_d = \frac{\rho}{2} \mathrm{K} b v^3 dz \tag{19}$$

Thus the energy absorbed during a period T per unit width of the screen is:

$$E_d = \int_0^T \int_{-h}^0 \frac{\rho}{2} \mathrm{K} v^3 dz\, dt \tag{20}$$

The energy dissipated per unit surface area during period T may be expressed as follows:

$$E_D = \frac{1}{S} \int_0^T \int_{-h}^0 \frac{\rho}{2} \mathrm{K} v^3 dz\, dt \tag{21}$$

For surface waves the approach velocity to the screen is:

$$v = (u^2 + w^2)^{1/2} \tag{22}$$

where:

- u horizontal particle velocity of the wave
- w vertical particle velocity of the wave

According to the Airy's theory the horizontal and vertical components of particle velocities are:

$$u = a\sigma \frac{\cosh k(h+z)}{\sinh kh} \cos(\sigma t) \tag{23}$$

$$w = -a\sigma \frac{\sinh k(h+z)}{\sinh kh} \sin(\sigma t) \tag{24}$$

where:

- a wave amplitude
- h water depth
- k wave number
- σ wave angular frequency

Using equations (21) and (22) the average rate of energy dissipation of an incident wave passing through the wave filter per unit width of the channel is:

$$\bar{\varepsilon}_D = \frac{2}{ST} \int_{-h}^{0} \int_{0}^{T/2} \frac{\rho}{2} \mathrm{K} (u^2 + w^2)^{3/2} dz\, dt \tag{25}$$

Substituting u and w from (23) and (24) in equation (25) yields:

$$\bar{\varepsilon}_D = \frac{2}{T} \int_{-h}^{0} \int_{0}^{T/2} \frac{\rho}{2} \mathrm{K} \frac{a^3\sigma^3[\cosh^2 k(h+z)\cos^2(\sigma t) + \sinh^2 k(h+z)\sin^2(\sigma t)]^{3/2}}{\sinh^3 kh} dzdt \tag{26}$$

After changing the following variables:

$k(h+z) = \chi$, and

$\sigma t = \theta$,

equation (26) becomes:

$$\bar{\varepsilon}_D = \frac{\rho K}{ST} a^3 \sigma^3 \frac{1}{k\sigma} \int_0^{kh}\int_0^{\pi} \frac{(\cosh^2\chi \quad \cos^2\theta + \sinh^2\chi \sin^2\theta)^{3/2}}{\sinh^3 kh} d\chi d\theta$$

or :

$$\bar{\varepsilon}_D = \frac{\rho K a^3 \sigma^3}{2\pi k S} f(kh) \tag{27}$$

where:

$$f(kh) = \int_0^{kh}\int_0^{\pi} \frac{(\cosh^2\chi \cos^2\theta + \sinh^2\chi \sin^2\theta)^{3/2}}{\sinh^3 kh} d\chi d\theta \tag{27a}$$

The values of $f(kh)$ as a function of kh are tabulated in Table A.1, Appendix (I).

Combination of equations (3), (5) and (27) gives:

$$W = \frac{K a_i \sigma^3 f(kh)}{\pi g k S} \tag{28}$$

Substituting equations (28) into equation (6d) yields:

$$\bar{k}_i = k \left\{ \frac{[1 + (\frac{K F(kh) a_i}{\pi S})^2]^{1/2} - 1}{2} \right\}^{1/2} \tag{29}$$

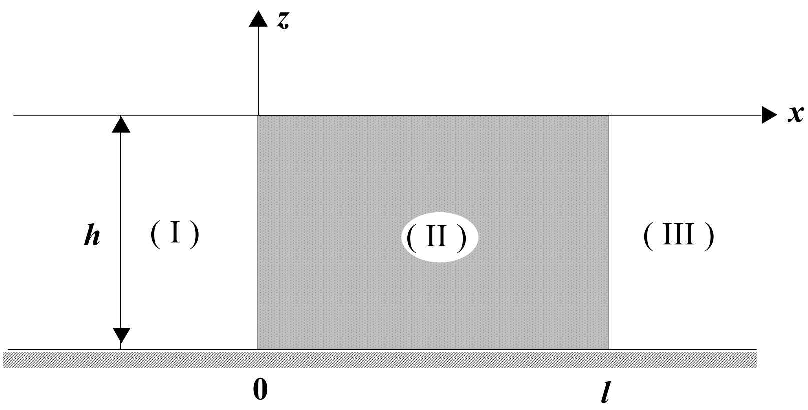

Fig. 1 - Definition sketch for a dissipation area analysed by Liu et. al. (1987)

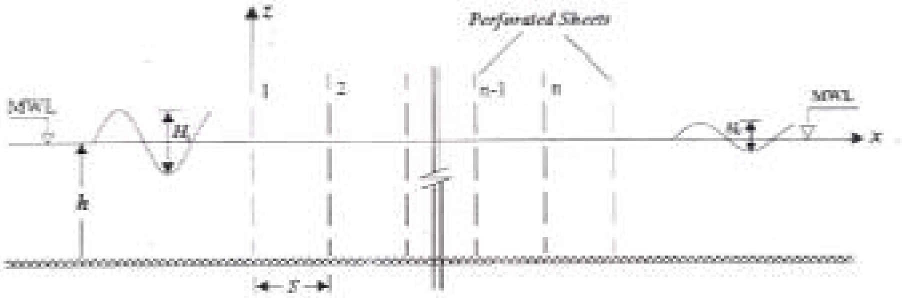

Figure 2- Definition sketch for an upright perforated wave filter

Experimental Tests

Experimental studies of upright perforated wave filters were performed in the 0.9 m wide wave flume of the Water Research Laboratory of the University of New South Wales (WRL). All the tests were undertaken with a water depth of 0.8 m. Reflection and transmission coefficients were measured for wave filters composed of four perforated plates of the same porosity. The screens were aligned normally to the direction of wave propagation. The porosity of the sheets was 40 and 62 percent. The diameters of screen perforations for sheets of 40 and 62 percent porosity were 6.35 and 7.94 mm, respectively. The wave periods were 1.25, 1.35, 1.50, 1.75 and 2.50 seconds (L_0 / h= 3.05 to 12.20, where L_0 is the deepwater wave length). The reflection and transmission coefficients were measured for waves of steepness ratios ranging from 0.003 to 0.1.

The support structure for the perforated sheets was made of $40 \times 40 \times 1.9$ mm steel angles. A permeable slopping wave absorber made of artificial horse hair was installed at the end of the flume to attenuate the energy of waves transmitted through wave filters (Chegini, 1994). Wave profiles were measured by four fixed capacitive-wire wave probes located in either side of the wave filter. The distance between the probes at each side of the filter was 40 centimetres. Lotus-Measure Software was employed to transfer the collected data to a Portable Microcomputer. Four channels of data were recorded simultaneously at a sampling rate of 50 samples per second on each channel. Fourier analysis was used to evaluate the wave amplitude of the fundamental frequency. The reflection coefficients were calculated from the "two probes technique" reported by Thornton and Calhoun (1972).

Theoretical and Experimental Results

Figure (3) shows the results of method of Liu et al. (1987) compared with the measured values of coefficients of wave reflection and wave transmission through upright perforated wave filters. As can be seen from this figure there is a good agreement between the results of this model and the experimental data.

To apply the theoretical models, the resistance coefficient of perforated plates (K) was obtained from the results of tests on single perforated plates (Chegini, 1994). These coefficients are 5.3 and 2.3 for perforated plates of 40 and 62 percent porosity, respectively.

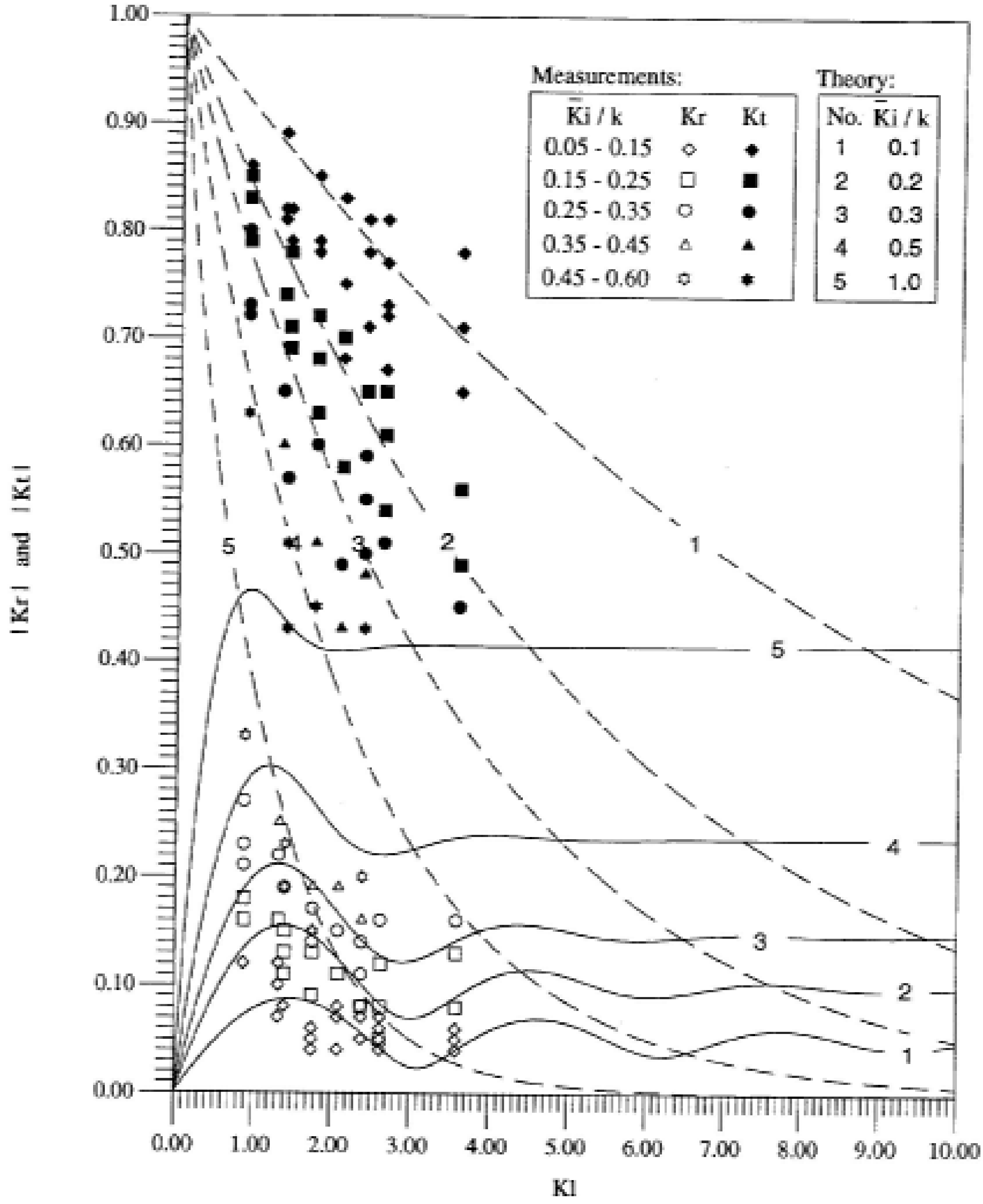

Fig. 3 - Reflection and transmission coefficients of upright perforated wave filters analysed by the method of Liu et al. (1987)

The results of the experimental tests and the theoretical expansion have been compared in figure (3). Correlation coefficients between the experimental and the theoretical results have been calculated. The squares of these coefficients (i.e. the coefficients of determination) for transmission and reflection coefficients are R^2=0.87 & 0.76, respectively.

Conclusions

Based on bulk dissipation of the incident wave energy, the method of Liu et al. (1987) is extended to predict the coefficients of wave reflection and wave transmission through upright perforated wave filters. The results of a set of experimental studies was presented for the measurements of the reflection and transmission coefficients of waves through upright perforated wave filters composed of four screens.

The experiments illustrated that:

i) Transmission coefficient increases with increasing wave period and screen porosity and it decreases as either the filter length or the wave steepness increases.

ii) Reflection coefficient generally increases with increasing wave period and wave steepness and it decreases as the screen porosity increases.

iii) The spacing between perforated plates has not an important effect on the transmission coefficients. However this variable has an effect on the reflection coefficients.

The comparison between the theoretical and experimental studies showed that the reflection and transmission coefficients of waves through upright perforated wave filters can fairly be predicted from the theoretical model.

APPENDIX I

Table A.1 - Values of $f(kh)$

(After Goda et al., 1963)

h/L	0.030	0.035	0.040	0.045	0.050	0.055	0.060	0.065	0.070	0.075
f(kh)	37.7685	27.8506	21.4153	17.0052	13.8524	11.5214	9.7503	8.3736	7.2829	6.4046
h/L	0.080	0.085	0.090	0.095	0.100	0.110	0.120	0.130	0.140	0.150
f(kh)	5.6873	5.0943	4.5987	4.1807	3.8252	3.2576	2.8303	2.5017	2.2447	2.0408
h/L	0.160	0.170	0.180	0.190	0.200	0.220	0.240	0.260	0.280	0.300
f(kh)	1.8769	1.7440	1.6351	1.5453	1.4707	1.3561	1.2748	1.2161	1.1734	1.1420
h/L	0.320	0.340	0.360	0.380	0.400	0.450	0.500	0.550	0.600	0.650
f(kh)	1.1187	1.1013	1.0883	1.0785	1.0711	1.0595	1.0536	1.0505	1.0489	1.0481

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