Ocean Engineering 138 (2017) 23–34

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Sloshing reduction in a swaying rectangular tank by an horizontal porous baffle

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ARTICLE INFO

Keywords:
Sloshing
Resonance
Horizontal porous baffle
Energy dissipation
Matched eigenfunction expansion method
Model test

ABSTRACT

Sloshing occurs in a tank containing liquid with free surface. It may result in resonant liquid motions causing carrier-vessel instability or structural damage of tank walls. The horizontal porous baffle is capable of dissipating the sloshing energy and reducing the sloshing pressures acting on tank walls. In the context of linear potential theory, the MEEM (matched eigenfunction expansion method) is applied to obtain the analytic solution for the sloshing with porous horizontal baffle. A BEM (boundary element method) with the porous boundary conditions is also independently developed for double checking and the application to more general cases. Two baffle positions at the center and at both walls of a rectangular tank are considered for various porosities, lengths, and submergence depths. The theoretical prediction is then compared with a series of experiments conducted by authors using harmonically oscillated rectangular tank with various baffle porosities and submergence depths. The measured data reasonably correlate with the predicted values. It is found that horizontal porous baffles installed at both tank walls significantly suppress violent resonant sloshing responses compared to one installed at the tank center. Through parametric study using the developed numerical tools, the optimal porosity, length, and submergence depth can also be determined.

1. Introduction

Sloshing occurs in a moving tank containing liquid with a free surface and may result in large motions and excitation forces. A partially filled tank experiences violent liquid motions when the hosting-vessel motion involves energy in the vicinity of its natural sloshing frequencies. Many studies concerning the sloshing problem have been conducted for suppressing violent liquid motions and reducing sloshing loads. Rigid and porous baffles may be employed for such purposes.

Predictions of the sloshing-induced pressures on inner baffles and tank walls were made by Abramson (1966). A further analytical study on the effects of a vertical baffle on the resonant sloshing frequencies of fluid in a rectangular tank was done by Evans and McIver (1987). Recently, Akyildiz (2012) and Jung et al. (2012) observed that increasing the submergence depths of vertical baffles may enhance liquid sloshing suppression. The use of vertical baffles may not only remarkably shift the sloshing natural frequencies but also reduce the sloshing wave amplitude and impact loads on tank walls (Armenio and Rocca, 1996; Wu et al., 2013; Xue et al., 2012; Cho and Kim, 2016). The sloshing motions might also be restrained well by using a horizontal baffle near the free surface. Isaacson and Premasiri (2011) compared the horizontal and vertical baffle and observed that horizontal baffle is more effective in damping out liquid sloshing motion in deeper tank, whereas vertical baffle is better for shallower tank. Kim (2001) proved by using finite-difference method that impervious horizontal baffle reduces the impulsive sloshing pressure on a tank ceiling. Cho et al. (2005) and Biswal et al. (2004) demonstrated that decreasing the submergence depth or increasing the horizontal baffle length is helpful in reducing the maximum sloshing wave heights. Goudarzi and Sabbagh-Yazdi (2012) further observed that horizontal baffles exhibit significant damping effects in slender tanks, whereas vertical baffles are more effective in broader tank.

Panigrahy et al. (2009) conducted a series of experiments in a baffled tank to show that horizontal and vertical baffles can significantly reduce the sloshing in the tank. Jin et al. (2014) experimentally studied the effect of a horizontal porous baffle on fluid sloshing in a moving tank. In their experiment, the horizontal baffle with perforated slots was mounted in a tank with various submergence depths. The effects of the porosity and submergence depth of the horizontal baffle

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http://dx.doi.org/10.1016/j.oceaneng.2017.04.005
Received 10 October 2016; Received in revised form 7 February 2017; Accepted 2 April 2017

on the resonant sloshing frequencies were demonstrated.

In Section 2, the analytic solutions of sloshing problem in a rectangular tank with horizontal porous baffles are investigated by means of the matched eigenfunction expansion method (MEEM). The fluid domain is divided into two regions according to the presence of baffle, and then the baffle region is further separated into upper and lower regions separated by the horizontal porous baffle. The analytic velocity potentials are obtained in the respective regions after applying Darcy's law at the porous baffle. The porous parameter in Darcy's law plays an important role for sloshing energy dissipation. The porous parameter associated with horizontal porous plate like the one used in the present study can empirically be determined from experiments as described in Cho and Kim (2008). In Section 3, a multi-domain boundary element method (BEM) is independently developed to firstly confirm the analytic solutions and secondly apply to more general cases. Both MEEM and BEM results agree excellently. As far as authors know, both the MEEM solutions and BEM approaches for the present porous baffle applications are new in the open literature. In Section 4, a series of experiments are conducted with a swaying rectangular tank, equipped with horizontal porous baffles. Experiments are performed for centered/sided locations with various combinations of porosities and submergence depths to validate the analytical and BEM solutions. After cross-checking the reliable correlation between predicted and measured values, we used the analytic solutions to find the optimal design of a porous horizontal baffle through an extensive parametric study. Finally the main conclusions of this study are drawn.

2. Analytic solutions

We investigated the two-dimensional sloshing responses in a rectangular tank of the length $2a$, the water depth h with an horizontal porous baffle of the length $2c$ and porosity P. Cartesian axes are chosen with the x-axis along the mean free surface and z-axis pointing vertically upwards. The submergence depth of the horizontal baffle is denoted by d. Tank is forced to oscillate horizontally with amplitude ξ and frequency ω. It is assumed that the fluid is incompressible and inviscid, and the wave motions are small so that linear potential theory can be used. The fluid particle velocity can then be described by the gradient of a velocity potential $\Phi(x, z, t)$. Assuming harmonic motion of frequency ω, the velocity potential can be written as $\Phi(x, z, t) = \mathrm{Re}\{-i\omega\xi\phi(x, z)e^{-i\omega t}\}$.

The velocity potential satisfies the two-dimensional Laplace equation and appropriate boundary conditions:

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0, \text{ in the fluid domain } \Omega \tag{2.1}$$

with the following boundary conditions for a centered porous baffle

$$\frac{\partial\phi}{\partial z} - \frac{\omega^2}{g}\phi = 0, \quad \text{on } z = 0. \tag{2.2}$$

$$\frac{\partial\phi}{\partial z} = 0, \text{ on } z = -h. \tag{2.3}$$

$$\frac{\partial\phi}{\partial x} = 1, \text{ on } x = \pm a. \tag{2.4}$$

$$\frac{\partial\phi^+}{\partial z} = \frac{\partial\phi^-}{\partial z} = i\sigma(\phi^- - \phi^+), \quad \text{on } z = -d, |x| \le c. \tag{2.5}$$

Darcy's law (Eq.(2.5)) indicates that the vertical mass fluxes across the porous baffle are continuous and the flow velocity across the porous baffle is linearly proportional to the pressure difference between each baffle sides. The imaginary part of the proportional constant σ is related to the inertia effect and thus has nothing to do with energy dissipation. The positive real value of σ is called the porous-effect parameter and represents energy dissipation effects and can directly be obtained from experiment. The porosity parameter b is newly defined as follows:

$$b = \frac{2\pi\sigma}{k_1}, \tag{2.6}$$

where k_1 is the wavenumber. When b=0, the porous baffle reduces to a rigid baffle: while for $b \to \infty$, the baffle is infinitely transparent. After a systematic experimental investigations with a thin porous plates, Cho and Kim (2008) proposed the following empirical formula between the actual porosity P and porosity parameter b in the range of porosity P=0.05 ~ 0.4:

$$b = 57.63P - 0.9717. \tag{2.7}$$

The empirical relationship was derived through a series of hydraulic tests for various horizontal porous plates in Cho and Kim (2008). It is clear that the sloshing oscillations in a rectangular tank will be asymmetric owing to both the asymmetric sway motion of the tank and symmetry installation of the horizontal baffle, such that $\phi(x, z) = -\phi(-x, z)$, therefore we only need consider the fluid motion belong to the half tank in $x \le 0$. The boundary value problem is solved only left half-plane of $x \le 0$, the solution in the region of $x \ge 0$ can be easily obtained by asymmetric condition $\phi(x, z) = -\phi(-x, z)$.

By means of matched eigenfunction expansion method, the fluid domain is divided into two regions according to the existence of an horizontal baffle, as shown in Fig. 1(a). Region (I) is defined by $-a \le x \le -c$, and region (II) by $-c \le x \le 0$.

By the method of separation of variables, the velocity potentials in region (I) satisfying Eqs. (2.1)–(2.4) can be written as:

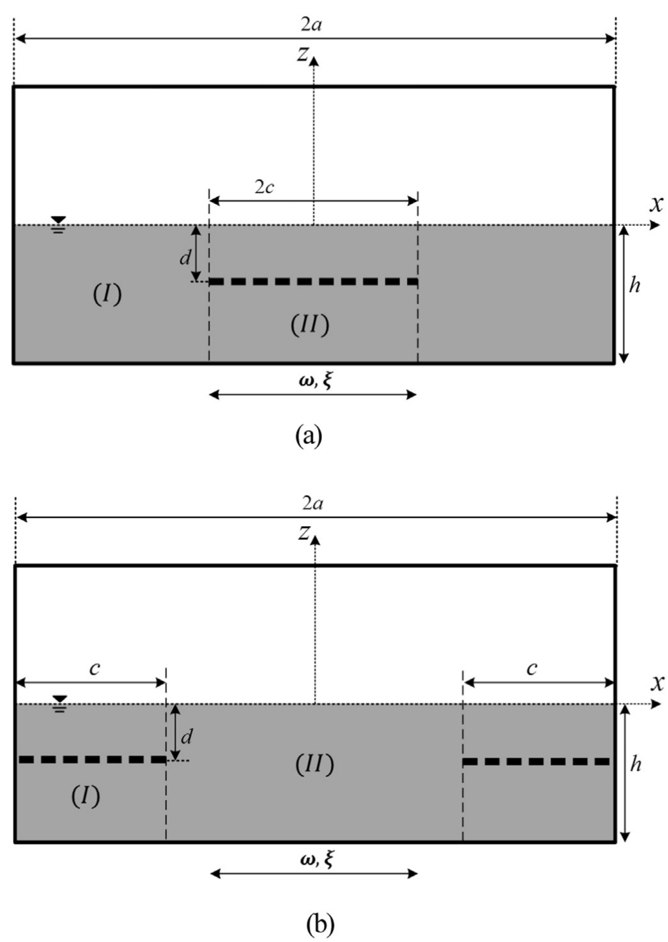

Fig. 1. Definition sketch of a rectangular tank with a centered (a) and sided (b) horizontal porous baffle.