Ocean Engineering 126 (2016) 364–373

Contents lists available at ScienceDirect

Ocean Engineering

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

Effect of dual vertical porous baffles on sloshing reduction in a swaying rectangular tank

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A R T I C L E I N F O

Keywords:
Dual vertical porous baffles
Sloshing
Matched eigenfunction expansion method
Experiment
MPS (moving particle semi-implicit)
Resonant frequency

A B S T R A C T

Liquid sloshing inside tanks of a vessel may result in increased/decreased vessel motions or structural damages. The resonant sloshing motions can be suppressed by using baffles inside a tank. Especially, more energy dissipation is possible by using porous baffles. Here, the effect of dual vertical porous baffles on the sloshing reduction inside a rectangular tank is investigated both theoretically and experimentally. The matched eigenfunction expansion method is applied to obtain the analytic solutions in the context of linear potential theory with porous boundary conditions. The porosity effect is included through inertial and quadratic-drag terms. The theoretical prediction is then compared with a series of experiments conducted by authors with harmonically oscillated rectangular tank at various frequencies and baffle parameters. The measured data reasonably correlate with the predicted values. It is found that the dual vertical porous baffles can significantly suppress sloshing motions when properly designed by selecting optimal porosity, submergence depth, and installation position.

1. Introduction

A partially filled liquid tank in a ship may experience violent liquid motions called sloshing when the ship motion frequencies are close to the sloshing natural frequencies. This violent liquid motion has gained a lot of attention in coastal and offshore engineering since it is directly related to the possibility of damage on the tank wall and may affect the safety of waterway transportation and offloading. In this sense, many studies regarding sloshing have focused on suppression methods to minimize sloshing induced loads. Among the sloshing-suppression devices, various types of inner baffles have been proposed.

The inner baffles are generally used as passive sloshing-damping devices in the liquid tank to obstruct some of the lowest resonant-mode motions. The basic concept of the passive sloshing damper is to obstruct the sloshing-induced flow, dissipate the sloshing energy by viscosity, and change the lowest sloshing natural frequency to lower value. Earlier attempts to make accurate predictions of the sloshing-induced dynamic pressures on the inner baffles and tank walls were made by Abramson (1966). Later, an analytical study on the effects of a vertical baffle on the resonant frequencies of fluid in a rectangular tank was performed by Evans and McIver (1987). They observed that surface-piercing baffle changed the sloshing resonant frequencies significantly, whereas the effect of a bottom-mounted baffle was negligible. Other researchers also observed that vertical baffles not only remarkably changed the sloshing natural frequencies but also reduced the sloshing amplitudes and induced loads on tank walls (Armenio and Rocca, 1996; Wu et al., 2013; Jung et al., 2012). In addition to vertical baffles, alternative shapes of inner baffles have been incorporated into tanks, such as annular baffles and flexible baffles in cylindrical tanks (Biswal et al., 2004), horizontal baffles in cubic tanks (Akyildiz and Unal, 2005; 2006; Liu and Lin, 2009), and annular baffles in rectangular tanks (Panigrahy et al., 2009). The forces acting on baffles due to resonant sloshing are typically large and they can be significantly reduced by using porous inner baffles instead of solid ones.

Compared to solid baffles, porous baffles significantly damp out the sloshing in a moving tank, which results in reduced forces on them and tank walls and smaller vessel motions. Tait et al. (2005) investigated a tuned liquid damper (TLD) equipped with vertical perforated screens under 2D excitation. Their experimental results showed that perforated screens worked well as TLDs. Dodge (2000) experimentally demonstrated that the porosity of vertical baffles reduced the slosh dynamics and the change in its natural frequency required a porosity of 10% or less. Recently, Faltinsen et al. (2011a,b,c) and Faltinsen and Timokha (2011) conducted detailed studies on liquid motions in a rectangular tank with a vertical slat-type screen in the middle. They observed that the resonance frequencies of the tank with a porous screen were different from those of the baffle-free tank and the resonant sloshing

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http://dx.doi.org/10.1016/j.oceaneng.2016.09.004
Received 3 June 2016; Received in revised form 4 August 2016; Accepted 6 September 2016

frequencies depended on the solidity ratio(unity minus the porosity), submerged screen gaps, liquid depth, and the position of the perforated openings relative to the mean free surface. Cassolato et al. (2010) experimentally studied a TLD with inclined slat screens and observed that the energy loss coefficient of a screen decreased with the increase in the angle of inclination.

Many other theoretical and experimental researches have also been conducted with regard to the wave/sloshing energy dissipation by porous plates. Most researchers (Yu, 1995; Chwang and Wu, 1994; Wu et al., 1998; Cho and Kim, 2008; Liu et al., 2008) applied Darcy's law as the boundary condition for fluids across porous plates. Darcy's law suggested that the velocity difference across the plate with relatively fine pores can be related to the pressure drop by using a complex-valued frequency dependent parameter, which accounts for both viscous and inertial effects. Crowley and Porter (2012a) proposed a linearized model for the wave energy dissipation through thin vertical porous barrier, where both the inertial and quadratic drag effects were included. The model was then applied to the sloshing problems in a 2-D rectangular tank with a vertical screen in the middle with its bottom fully extended to tank bottom. Crowley and Porter (2012b) extended the analytic solutions of the single porous screen to the case of N vertical porous screens fully extended to tank bottom. Molin and Remy (2013) also carried out the experimental and numerical study of the sloshing motion in a rectangular tank with single perforated screen, which is again fully extended to tank bottom. The main difference between Crowley and Porter (2012a) and Molin and Remy (2013) is that Crowley and Porter (2012a) used the depth-averaged drag coefficient, whereas, in Molin and Remy's formulation, the drag coefficient was varied with baffle's depth. Hyeon and Cho (2015) experimentally demonstrated that the porosity of the vertical baffle influences both the wave elevations and dynamic pressures on tank wall.

In the present paper, we obtained the analytic solutions for the liquid sloshing with dual vertical porous baffles of arbitrary submergence depths in a sway-oscillated rectangular tank following the methodology similar to Crowley and Porter (2012a) and Molin and Remy (2013). As far as authors know, the formulations for partially submerged dual porous baffles in a sway-oscillated rectangular tank are new in the open literature. In addition, a series of experiments were conducted in the 2D rectangular tank with dual vertical porous baffles to validate the derived analytical solutions. The dual vertical baffles were each located at 1/3 and 2/3 of tank's length, which are close to the two antinodes of the 2nd anti-symmetric sloshing mode. The effects of various baffle positions were also numerically investigated. The viscous effects in limiting resonant motions were also observed by using MPS (moving particle semi-implicit) computation, grid-less Navier–Stokes solver. The effects of the porosity and the position/submergence depth of baffles on sloshing motions are systematically investigated. After checking the reliable correlation between the predicted and measured values, the analytic solutions are used to find the optimal design of baffles through an extensive parametric study. Finally, main conclusions of this study are stated.

2. Mathematical formulation and analytic solutions

We investigate the two dimensional sloshing motion in a rectangular tank of the length $2a$ with dual vertical porous baffles. Cartesian axes are chosen with the x-axis along the mean free surface and z-axis pointing vertically upwards. The water depth is denoted by h, the position of dual baffles by $x = a_j$, $(j = 1, 2)$, and the submergence depth of corresponding baffles by d_j, $(j = 1, 2)$. 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 $\Phi(x, z, t)$, which satisfy the Laplace equation

$$\nabla^2\Phi = 0 \tag{1}$$

with the following boundary conditions

$$g\frac{\partial \Phi}{\partial z} + \Phi_{tt} = 0, \quad \text{on } z = 0 \tag{2}$$

$$\frac{\partial \Phi}{\partial z} = 0, \quad \text{on } z = -h \tag{3}$$

$$\Phi_x = \omega\xi\cos\omega t, \quad \text{on } x = \pm a \tag{4}$$

where g is the gravitational acceleration.

The additional boundary conditions are required to relate the flows on both sides of porous baffle. The approximate boundary conditions at porous baffle were derived by Bennett et al. (1992) and Mei et al. (1974).

$$\left[\frac{\partial \Phi(x, z, t)}{\partial x}\right]_{x^-}^{x^+} = 0, \quad \text{on } x = a_j, -h \le z \le -d_j \tag{5}$$

$$\left[\frac{\partial \Phi(x, z, t)}{\partial t}\right]_{x^-}^{x^+} = \begin{cases} \frac{\alpha}{2}U_r(z, t)|U_r(z, t)| + 2C\frac{\partial U_r(z, t)}{\partial t}0, & \text{on } -d_j \le z \le 0 \\ 0, & \text{on } -h \le z \le -d_j \end{cases} \tag{6}$$

where the square brackets denote the jump in the enclosed quantity. $U_r(z, t) = \Phi_x - \omega\xi\cos\omega t$ is the horizontal velocity of the fluid relative to that of the swaying tank and α and C are empirically determined coefficients. α is the drag coefficient related to the energy dissipation across the porous baffle. C represents an inertial (or blockage) coefficient accounting for the added inertia felt by the fluid as it accelerates. It can be neglected when the baffle is thin and the size of holes is not large.

Mei (1989) suggested the drag coefficient α with sharp edged orifice C_c

$$\alpha = \left(\frac{1}{PC_c} - 1\right)^2 \tag{7}$$

where P is the porosity of baffle. The empirical form of C_c is given by Tait et al. (2005)

$$C_c = 0.405e^{\pi(P-1)} + 0.595 \tag{8}$$

Assuming harmonic motion of frequency ω, the velocity potential, wave elevation, and horizontal relative velocity at porous baffle can be written as

$$\begin{aligned} \Phi(x, z, t) &= \mathrm{Re}\{\omega\xi\phi(x, z)e^{-i\omega t}\}, \\ \zeta(x, t) &= \mathrm{Re}\{\eta(x)\, e^{-i\omega t}\}, \\ U_r(z, t) &= \mathrm{Re}\{u_r(z)e^{-i\omega t}\} \end{aligned} \tag{9}$$

The boundary value problem Eqs. (1)–(4) can be rewritten with the velocity potential ϕ as follows:

$$\begin{cases} \nabla^2\phi = 0, \\ \frac{\partial\phi}{\partial z} - \frac{\omega^2}{g}\phi = 0, & \text{on } z = 0 \\ \frac{\partial\phi}{\partial z} = 0, & \text{on } z = -h \\ \frac{\partial\phi}{\partial x} = 1, & \text{on } x = \pm a \end{cases} \tag{10}$$

By means of matched eigenfunction expansion method (MEEM), the fluid domain is divided into three regions (I), (II), (III), as shown in Fig. 1. The velocity potential in each fluid region satisfying the two-dimensional Laplace equation and boundary conditions, can be written as follows:

$$\phi^{(j)} = \sum_{n=0}^{\infty}\frac{1}{k_n}[A_n^{(j)}e^{-k_n(x-a_{j-1})} + B_n^{(j)}e^{k_n(x-a_{j-1})}]f_n(z), \quad (j = 1, 2, 3) \tag{11}$$

For convenience, we include the tank walls by defining $a_0 = -a$ and