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Original Article

Porous Baffle Performance in a Sloshing Tank

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Abstract *- The sloshing phenomenon is the participation of liquid in the partially filled vessels or tanks, which is a primary consideration for designing and constructing many structures in offshore, offshore, and space engineering. Employing porous baffles of varying porosities is an effective way to minimize or/and control wave elevations in the sloshing tank. In the present study, analytical investigations were carried out for the sloshing motion in the clean tank (tank without baffles) and the tank with baffles. The two porous baffles of three different porosities consider in the rectangular sloshing tank. The porous baffles place at equal intervals in the sloshing tank. The analytical simulations were carried out under a range of swaying motions. During simulation, the sway excitation frequencies cover the clean tank's first five resonant sloshing modes. The two porous baffles of lower porosity levels in the sloshing tank are beneficial in suppressing the wave elevations in the sloshing tank near the first resonant mode.*

Keywords *- Sloshing motion, Porous baffle, Analytical investigation, Rectangular tank, Resonant frequency.*

1. Introduction

Earthquakes, wind, and wave action are among the most destructive natural disasters, causing significant loss of life and livelihood. The load characteristics and the structure itself mainly govern the response of a structure during these actions. The land, ocean, and space structures are often susceptible to seismic, wave, and wind-induced vibrations due to low levels of inherent damping. The use of Dynamic Vibration Absorbers (DVAs) to reduce excessive vibrations caused by various types of dynamic actions has grown in the last few decades. A DVA improves damping by dissipating some energy generated when a structure moves under both regular and irregular excitations. As a result, the displacement of primary structures coupled with the liquid tank (DVAs) is reduced, and the structures become more stable. Various systems propose to mitigate the structural vibration against loads. Different categories of protection systems have been implemented in the last few decades based on structural conditions, configuration, and applications. The sloshing tank was found to be more effective.

Water storage tanks are liquid sloshing tanks for land structures and buildings, so-called tuned liquid dampers (TLD). The TLDs are a type of passive mechanical damper and are designed as a sloshing tank. These partially filled rigid tanks are located in the structure at or near the location of maximum modal displacement for suppressing structural vibrations. For ocean structures, William Froude proposed in 1862 that a tank partially filled with water may minimize the roll motions of cargo if the frequency and phase of the oscillating water were appropriately tuned. The idea of employing liquid-filled tanks to damp motions first emerged in the late 1800s. In the 1960s, this concept was implemented to reduce the wobbling movement of satellites in space. Sloshing dynamics in the tank provide an effective and easy technique to enhance the system's damping and rely on liquid sloshing inside the tank to dissipate energy from the viscous action and wave breaking. The sloshing in the tank functions similarly to a tuned mass damper, with the main difference being that the liquid tank relies on the sloshing fluid's inertial force to reduce the vibratory motion. The efficiency of sloshing in the tank mainly depends on the fluid height in the tank, the tank length, and the type of structure that couples with the sloshing tank.

2. Literature

In the structures-TLD and liquid storage systems, sloshing in the tank is a highly complex phenomenon to achieve the required level of damping in the tank. It may not control the vibration of land structures and the stability of ocean vehicles effectively. Thus, controlling the liquid sloshing in the tank is essential for safety and operation.

As a result, numerous researchers conducted experimental, analytical, and numerical tank studies using various flow-dampening devices. The devices mainly include; Solid baffles and porous baffles. Damping in the tank-fluid system and system coupled with the fluid tank to enhance the perforated screens is a feasible technique that can work more effectively. However, they also introduce complex nonlinear behaviour in the sloshing environment. The design of TLDs benefits from a deeper understanding of the effects and performance of perforated screens on sloshing in the tank. Hence, recent efforts have concentrated on designing and modelling the sloshing in tanks with the varying number, positions of placement, and varying percentages of perforated screens, including those by Tait et al., Love and Tait, and Molin and Remy [1–3]among other researchers. Kaneko and Ishikawa [4] and Tait et al. [1] obtained the effectiveness of the improved system with baffles screens by simulating the coupled dynamics of the major structures and TLDs.

Further, the experimental methods continued with the performance of watertight and relatively low levels of porosity baffle screens in the partially filled tank. The watertight baffles in the tank cause the resonant frequency shift due to the smaller compartments tanks [6, 7]. In investigating the tank's different obstacles to achieve the damping, the wire mesh screens in the sloshing tank were found to effectively suppress the structure's critical mode of vibration [5]. The analytical or/and theriacal, numerical and experimental models were also put forth. Faltinsen et al. [7–10] modelled the issue as a prospective flow through a multimodal description. During the investigation, the tank's sloshing liquid was analysed with a slatted screen that allowed fluid to pass between them. Considering the slots' geometry and the slats' arrangement, the flow through screen phenomenon was studied with screen blockage coefficient under the range of excitations. In the test series, the analytical conclusions qualitatively match the experimental data. Using the linear wave theory, Molin and Remy [3] conducted a sloshing investigation in the screened tank with screen loss characteristics to account for the pressure variation. The model findings are well matched with the experimental observations for small amplitude excitations, but there were differences for motions with a larger amplitude. Numerous theoretical-based designs and analyses to examine the impact of baffles with varying porosities on sloshing have been described in recent decades. Maravani et al. [11] simulated recording the sloshing phenomenon using finite-difference and Volume-of-fluid techniques for free-surface tracking. A shallow liquid height condition was recreated in a sloshing tank. The authors studied the slat screens' performance in the rectangular tank during the investigation. Model results demonstrate very excellent agreement with experimental findings under low-level excitation motions.

Carried out numerical and experimental investigations to study the effect of porous baffles in the sloshing tank, which are fixed at the bottom of the tank [12]. Numerical simulation was performed to track wave motion variations. The results exhibit that the porous screens are found to be superior in wave motion reduction under a lesser excitation range. Later, Xue et al. [13] conducted experiments with perforated baffles and watertight baffles. The authors record the pressure and wave motion variation in the presence of different bulkheads. In the test series, the tank excitation covers a large frequency set. Yu and other co-authors [14] considered sloshing dynamics with varied porosity, slot dimensions, and the number of porous baffles to study the effectiveness of slat-screen baffles in highly irregular shallow water conditions. [22-23] studied the performance of land structures with varying fill levels in the water tank under dynamic loading. Water tanks with varying fill levels were found to be effective dampers controlling structural vibrations.

From the literature, it is understood that the porous baffles are the more effective device to control or/and reduce the sloshing motion in the sloshing tank for structure-tuned liquid damper interaction problems and sloshing tank carrying vehicles in offshore environments. As far as the authors know, the performance of porous baffles in the sloshing tank, under sway excited motion, which covers up to the fifth sloshing mode of the tank without baffles condition, has not been addressed by the researchers. Therefore, in the present work, the analytical solutions were obtained considering sloshing variations in the rigid rectangular tank and tank fitted with two porous baffles following a procedure similar to Tait [15] under sway excitations. The calculated wave motion patterns of sloshing behaviour in the clean tank and tank with porous baffles were quantitatively summarized.

3. Analytical Model and Methods

3.1. Computational Domain

The analytical simulations were performed considering a 2-D rectangular sloshing tank of length 1mt and still water height of (h/L) 0.33. In the simulations, the wave motion variation in the clean tank and porous baffles in the tanks were considered. In the baffles tank, the two vertical porous baffles are fixed at 0.33L and 0.67L. Three different porous baffles of 4.4%, 6.8% and 9.2% porosities to study the effectiveness of the porosity of screens are considered.

Table 1. Resonant sloshing frequency in the clean tank

modes(n)	ω (rad/sec)	ω/ω_1 (β)
1st	4.872	1
2nd	7.719	1.584
3rd	9.595	1.969
4th	11.099	2.278
5th	12.413	2.548

The sway-excited rectangular tank with motion amplitude (A/L) of 0.003 is given as $X(t)=A\sin(\omega t)$. Where $\omega=2\pi f_n$. The n^{th} mode natural sloshing frequency (Hz) correlation was given by Ibrahim [16].

$$f_n = \frac{1}{2\pi}\sqrt{\frac{n\pi g}{L}\tanh\left(\frac{n\pi h}{L}\right)}, n = 1,2,3\ldots \quad (1)$$

Where, g is the acceleration due to gravity, and n indicates the number of sloshing modes. The natural sloshing frequencies in the screen tank for liquid-filled levels are given in Table 1.

3.2. Analytical Solution

The sloshing tank fitted with porous screens was formulated similarly to the procedure suggested by Tait (2008). Figure 1 represents the sloshing tank with screens of the velocity potential obtained as a summation of all sloshing modes present in the tank.

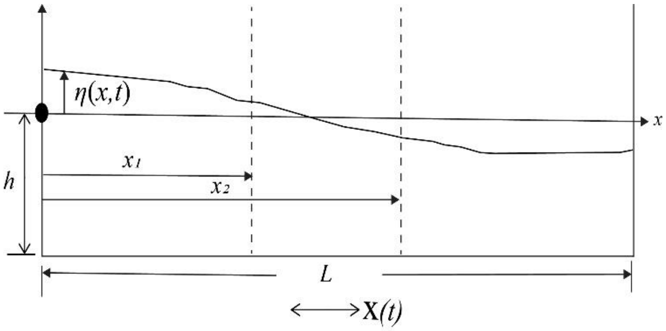

Fig. 1 Definition sketch of porous screens in a rectangle liquid sloshing tank

$$\phi(x,z,t) = \sum_{n=1}^{\infty} \dot{q}_n(t) \cos\left(\frac{n\pi x}{L}\right) \frac{\cosh\left[\frac{n\pi(z+h)}{L}\right]}{\left(\frac{n\pi}{L}\right)\sinh\left(\frac{n\pi h}{L}\right)} \qquad (2)$$

The liquid surface elevation of the n^{th} sloshing mode is

$$\eta(x,t) = \sum_{n=1}^{\infty} q_n(t) \cos\left(\frac{n\pi x}{L}\right). \qquad (3)$$

The equation of motion for liquid sloshing in a tank expressed as

$$m_n^* \ddot{q}_n(t) + c_n^* \dot{q}_n(t) + m_n^* \omega_n^2 q_n(t) = \gamma_n^* \ddot{X}(t) \qquad (4)$$

where,

$$m_n^* = \frac{1}{2} \frac{\rho b L^2}{n\pi \tanh\left(\frac{n\pi h}{L}\right)}, \quad k_n^* = m_n^* \omega_n^2 = \frac{\rho b L g}{2} \qquad (5)$$

$$\gamma_n^* = \rho b L^2 \frac{[1-\cos(n\pi)]}{(n\pi)^2} \qquad (6)$$

The damping ratio for the tank with no screen case can be estimated as follows:

$$\zeta_w = \left(\frac{1}{2h}\right) \sqrt{\frac{\nu}{2\omega_n}} \left(1 + \frac{2h}{b} + SC\right) \qquad (7)$$

Where, ν is the fluid viscosity, and SC is the surface contamination in the liquid tank and is equal to unity.

The damping for the tank with the screen can be estimated as follows:

$$c_n^* = C_l \frac{4\rho b L}{3\pi^2} \Delta_n \Xi_n q_n \omega_n \qquad (8)$$

Where, C_l represent the loss coefficient by screen, which are equal to 1.29 x10^3, 521.99 and 274.83 for the screen of porosity 4.4%, 6.8% and 9.2%, respectively [1, 17]. And the screen parameters in the equation are given as follows:

$$\Delta_n = \frac{1}{3} + \frac{1}{\sinh^2\left(\frac{n\pi h}{L}\right)}, \quad \Xi_n = \sum_{j=1}^{ns} \sin\left(\frac{n\pi x_j}{L}\right)^3 \qquad (9)$$

3.3. Validation of the Analytical Mode

The surface waveform variations with respect to time with the numerical findings of Frandsen [18] in order to validate the current analytical model (Figure 2). A tank with a *h/L* of 0.5, the excitation amplitude and frequency of 0.005*h* and *0.7*ω1, respectively, was used for the numerical study. The present analytical model test results agreed well with numerical results.

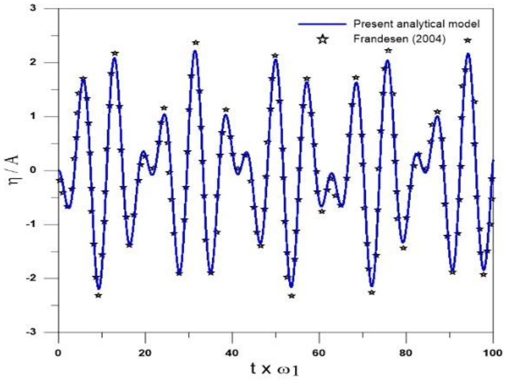

Fig. 2 Time series variation of wave oscillation

4. Results and Discussion

The variation of non-dimensional maximum surface elevation (η_{max}/A) with the non-dimensional excitation frequencies (frequency ratio) β, for the clean tank (tank without screen) and tank with a porous baffle of three different porosity 4.4%, 6.8% and 9.2% are shown in figure 3, 4, and 5 respectively. The maximum free surface wave motions were measured near the left tank wall under constant excitation amplitude and range of excitation frequencies, covering the sloshing tank's first five resonant frequencies. The tank's free surface variations were measured as the sum of all sloshing modes. The maximum free surface elevation peaks in a clean tank were observed near the odd sloshing mode, as we expected. The amplification of wave motion in a clean tank observed more peaks at the first resonant mode, reducing the next two continued odd modes.

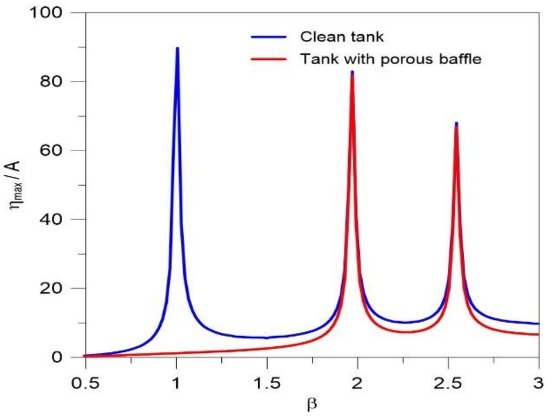

Fig. 3 Maximum surface elevation variations in the screened tank of porosity 4.4%

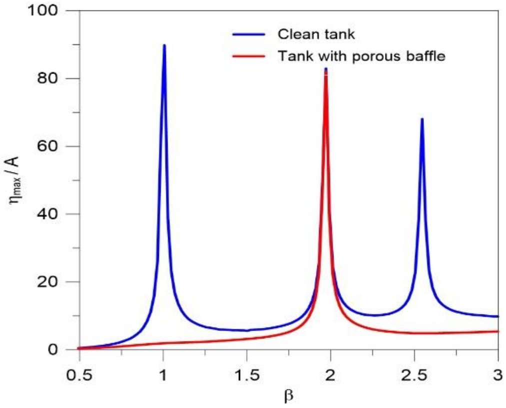

Fig. 4 Maximum surface elevation variations in the screened tank of porosity 6.8%

In the case tank with two porous baffles under sway excitation, the porosity of screens in the sloshing tank dampens the wave motion near the first resonant mode due to the resonant frequency shift phenomenon. The 4.4% porosity of screens completely suppressed the wave motion at fundamental resonant mode. This effect may be due to the screens in the tank acting as almost impermeable baffles and resonance in the tank provoked by the use of low-level porosity of screens in the tank [21]. It is also evident that the magnitude of the first resonant mode in the clean tank was observed to be similar to that of the screened tank with all three different porosities of screens at the third resonant mode for the tank.

But as porosity increases, a small peak starts appearing at first resonant mode due to a large flow through the screens. And, as excitation increases, the third resonance disappears due to the presence of 6.8 and 9.8 percentage porosity of screens in a tank. Figure 6a and Figure 6b shows the time series resonant wave elevation variation in the baffle free and with baffle screen of 4.4% porosity in the sloshing tank, respectively. Due to the presence of two porous screens, the free surface wave elevations were reduced maximum at the first resonant frequency, showing similar behaviours near the third resonant frequency (figure 6b).

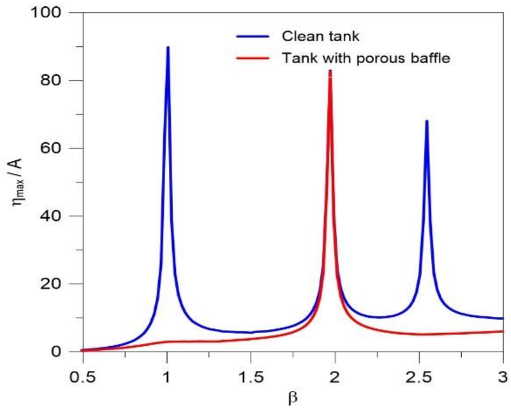

Fig. 5 Maximum surface elevation variations in the screened tank of porosity 9.2%

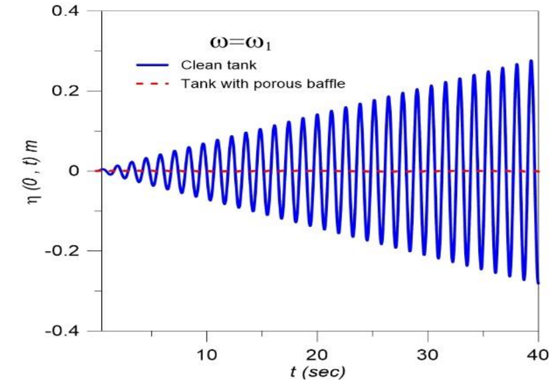

Fig. 6a Time history of surface elevation variations for the tank with baffle screen of porosity 4.4%

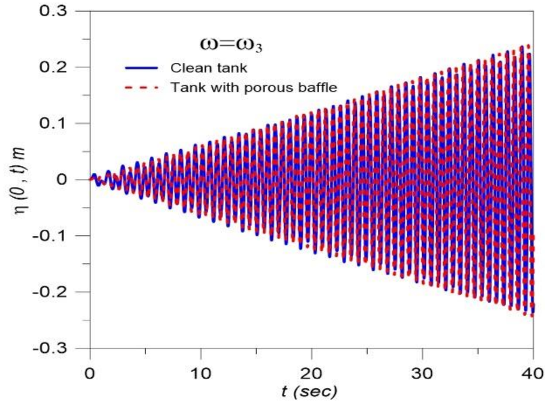

Fig. 6b Time history of surface elevation variations for the tank with baffle screen of porosity 4.4%

5. Conclusion

Analytical investigations were carried out to examine the performance of two vertical porous baffles in the rectangular sloshing tank to suppress and control the liquid sloshing variation under a range of excitation frequencies, which cover up to five sloshing mode frequencies. There are three different porosities of 4.4%, 6.8%, and 9.2% were considered in the sloshing tank to study the effectiveness of porosities under tank sway motion. The analytical model is found to be effective in predicting wave motion behaviour. The tank's sloshing motion leads to the following conclusions. The tank with relatively low porous baffles of porosities 4.4%, 6.8%, and 9.2% more effectively reduces the amplification of sloshing motion at first resonant mode. The present porosity levels in the tank resemble the same behaviours as observed in the study [24-25]. It may be helpful for liquid tank cargos under different wave actions in the offshore engineering and tank coupled with a building and other structures on onshore engineering, where structural natural frequency should match with sloshing frequency in the tank. The higher amplification was observed at the third resonant mode due to the resonant frequency of sloshing behaviour shifts. The shift in natural frequency is helpful for many engineering applications and is less than that of resonant at the clean tank.

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