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Experimental study on sloshing in a tank with an inner horizontal perforated plate

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ABSTRACT

Sloshing in a liquid tank may result in ship instability or structural damage. Inner structures are often used to restrain liquid sloshing and prevent tank damage. To increase energy dissipation and reduce the forces acting on structures, a horizontal perforated plate was designed and incorporated into a rectangular liquid tank in this study. Experimental studies were conducted, and a tank with an inner submerged horizontal perforated plate was excited under different amplitudes and frequencies. The free surface elevations on the side-walls and the resonant frequencies were carefully examined. The experimental results indicate that the horizontal perforated plate can significantly restrain violent resonant sloshing in the tank under horizontal excitation.

1. Introduction

Sloshing occurs in a moving tank containing liquid with a free surface and may result in the resonant excitation of the tank liquid. A partially filled ship tank may experience violent liquid motion when the ship motion involves energy in the vicinity of the natural frequency of the liquid motion inside the tank. This liquid motion was of primary practical interest in this study.

Many studies with respect to sloshing focus on methods for suppressing resonant sloshing and reducing sloshing loads. Baffles and perforated plates are efficient inner structures for suppressing resonant sloshing. Their applicability has been confirmed over the last century for liquid sloshing in fuel rocket tanks (Abramson, 1966). Swash bulkheads (vertical baffles) in cargo ship liquid tanks are also useful for restraining sloshing. The functions of swash bulkheads are to provide sloshing damping and to promote the lowest resonant frequency to a higher frequency range over which the wave-induced ship velocity and acceleration are less severe. Rectangular tanks with perforated vertical plates are used for the anti-rolling tanks of ships and tuned liquid dampers (TLDs) of tall buildings. Properly tuned sloshing is an efficient tool for suppressing oscillations of carrying structures. For this application, the lowest resonant sloshing frequency should remain nearly by the inner structures.

Previous attempts to make accurate predictions of the sloshing-induced dynamic pressures on the inner structures and walls of fuel tanks were made by Abramson (1966). A further 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). The authors observed that a surface-piercing barrier changed the resonant frequencies significantly, whereas the effect of a bottom-mounted barrier was negligible. Recently, Akyildiz (2012) and Jung et al. (2012) observed that increasing the heights of vertical baffles may enhance liquid sloshing suppression, and Goudarzi and Sabbagh-Yazdi (2012) showed that an up-mounted vertical baffle is more effective than a low-mounted one. The use of vertical baffles may not only remarkably reduce the natural frequency of liquid storage tank systems but also reduce the sloshing amplitude and dynamic impact loads acting on tank walls (Armenio and Rocca, 1996; Wu et al., 2013; Xue et al., 2012). In addition to vertical baffles, alternative structures 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). Among these inner structures, annular baffles proved most efficient.

The forces acting on structures inside a water tank due to resonant sloshing may be relatively large. These large forces can be significantly reduced by perforating the inner structures. In addition, a perforated inner structure may dissipate more of the energy of the sloshing fluid. Perforated inner structures have garnered some attention among researchers. Tait et al. (2005a) investigated a tuned liquid damper (TLD) equipped with vertical perforated screens under 2D excitation. Their experimental results showed that perforated screens work well as an inner structure in TLDs. More recently, Tait et al. (2005b) developed two numerical models to simulate the linear and non-linear effects of sloshing. The linear

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model was capable of providing a preliminary design for the size, number and position of a TLD slat screen. However, more detailed TLD response characteristics should be analyzed using the non-linear model. Dodge (2000) experimentally demonstrated that the porosity of the inner baffle influences the slosh dynamics, but a change in the natural frequency requires a porosity of 10% or less. Recently, Faltinsen and his collaborators (Faltinsen et al., 2010, 2011; Faltinsen and Timokha, 2011) conducted detailed studies on liquid motions in a rectangular tank with a vertical slat-type screen in the middle of the tank. The authors observed that the resonant frequency of the tank with a screen was different from the natural frequency of a clean tank. They also observed that the resonant sloshing frequencies depend on the solidity ratio (unity minus the porosity), the number of submerged screen gaps, the liquid depth, and the position of the perforated openings relative to the mean free surface. The resonant frequency monotonically decreased as the solidity ratio increased. The largest amplitude response was at the resonant frequency corresponding to the third-order natural frequency of the clean tank, because the first mode disappeared and the third mode decreased. Cassolato et al. (2011) experimentally studied a TLD with inclined slat screens and observed that the energy loss coefficient of a screen decreased with an increase in the angle of inclination, and the screen had a negligible effect on the natural frequency of the water tank.

In addition to aforementioned vertical baffles and screens, horizontal plates have also been installed in water tanks to suppress sloshing. Kim (2001) proved that a horizontal plate reduces the impulsive pressure on a tank ceiling. Cho et al. (2005) and Biswal et al. (2006) demonstrated that decreasing the submerged depth or increasing the width of a horizontal plate is helpful in reducing the maximum sloshing wave heights. Isaacson and Premasiri (2001) compared horizontal and vertical inner plates and observed that horizontal plates are more effective in damping liquid motion in deeper tanks, whereas vertical plates are better for shallower water tanks. Goudarzi and Sabbagh-Yazdi (2012) further observed that horizontal plates exhibit significant damping effects in slender tanks, whereas vertical plates are more effective in broader tanks. In addition to their applications in sloshing tanks, horizontal plates have been proposed as an efficient offshore breakwater in coastal engineering (Yu, 2002). An adequately designed horizontal perforated plate breakwater may exhibit significant wave-absorbing performance and reduce wave forces (Yu and Chwang, 1994; Liu et al., 2007; Liu and Li, 2011). Evans and McIver (1987) found that a surface-piercing vertical barrier can suppress the sloshing better than a bottom one. The free surface movement might also be restrained well by a horizontal plate near the free surface. Thus, we may install a horizontal perforated plate inside a water tank to restrict fluid sloshing, which has been scarcely mentioned in the literature.

The primary objective of this study was to experimentally examine the effect of a horizontal perforated plate on fluid sloshing in a water tank. The experimental setup is introduced in the following section. In Section 3, the free surface elevations at the tank wall with different horizontal excitations and the changes after placing perforated plates in the tank are carefully examined. The effects of the porosity and the relative submerged depth of the horizontal plate on the resonant wave heights and resonant frequencies are demonstrated. Several useful results are presented for practical applications. Finally, the primary conclusions of this study are drawn.

2. Experimental setup

In this section, we provide a description of the experimental setup, including the water tank, vibrostand, vibration control system and wave probes. A Plexiglas rectangular tank (1.0 m length, 0.8 m height and 0.11 m breadth) was installed on a stable vibrostand. The tank was similar to that of Faltinsen et al. (2011). The factor determining our choice of tank breadth is that we wanted to achieve two-dimensional flow conditions, and hence, the breadth-to-length ratio had to be small. The tank was designed with an inner horizontal perforated plate, and the position of the inner plate could be changed (see Fig. 1). For testing the efficiency of the horizontal perforated plate and simplifying our experiment, the problem was restricted to liquid sloshing in a rectangular tank under sway oscillations $X(t)=A\sin(\omega t)$, where A and ω are the amplitude and angular frequency of excitation, respectively. The motion of the partially filled water tank was controlled by a servo motor and an eccentric wheel, as shown in Fig. 2. With different eccentric distances and voltages, different excitation amplitudes and frequencies could be achieved.

In our tests, the horizontal plate with perforated slots was mounted in the tank with different submerged depths. The configuration of the horizontal plate is shown in Fig. 1. The submerged depth of the plate (the space between the still water level and the plate) is a, and the distance between the horizontal plate and the tank bottom is h. The water depth is D, and $D=a+h$. For examining the effect of plate submerged depth, three different relative submerged depths of $a/D=1/3$, $1/2$ and $2/3$ were used in the tests. The consideration wanted to detect a more effective plate configuration for damping violent sloshing. A geometrical sketch

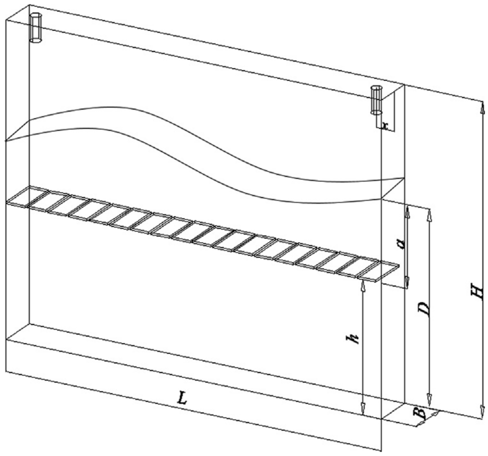

Fig. 1. Sketch of a rectangular tank with an inner horizontal perforated plate.

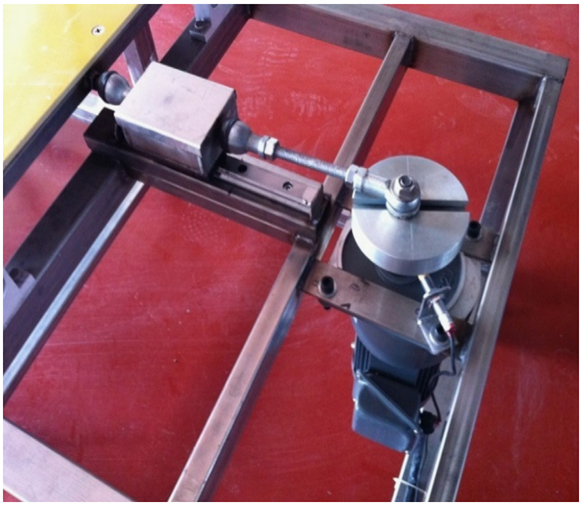

Fig. 2. Excitation device for the vibrostand.