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Experimental study on vertical baffles of different configurations in suppressing sloshing pressure

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ABSTRACT

The effectiveness of four types of the baffles in suppressing pressure is experimentally investigated under a wide range of forcing frequencies. The dynamic impact pressure variations alongside the central line of the tank wall and the baffle response to different excitation frequencies were measured for tanks without baffles and with immersed bottom-mounted vertical baffles, vertical baffles flushing with free surface, surface-piercing bottom-mounted vertical baffles and perforated vertical baffles, respectively. The maximum impact pressure on the tank wall generally increases with decreasing the distance of the pressure sensor away from the free surface. In the frequency range from $0.4\omega_1$ to $1.4\omega_1$, the vertical baffle flushing with free surface is an more effective tool on reducing impact pressure comparing with the immersed bottom-mounted vertical baffle, especially near the first-mode natural frequency, and effects of the perforated vertical baffle in suppressing sloshing pressure is more significant than that of the surface-piercing bottom-mounted vertical baffle, especially in high forcing frequency region. It is found that the first-mode natural frequency of liquid-tank is altered by the vertical baffles. The experimental results show that changing flow fields and altering natural frequency may effectively suppress the impact pressure on the tank walls.

1. Introduction

Liquid sloshing is a motion of the free surface of a liquid in a partially filled tank or container, usually excited by the motion of the tank/container. Unstinted sloshing can produce sloshing forces that cause additional tank accelerations, which may lead to an instability of the cargo ship carrying liquid-tank and a tank structural failure. Dynamic impact pressure on the tank wall particular its local temporal peaks may reach as more orders of magnitude than corresponding static pressure and plays an important role in the safety assessment of the tank structure. Anti-slosh baffles are usually required to diminish the sloshing motions particular the giant pressure peak and to prevent such instability by increasing the damping. Effective design of baffles requires a detailed understanding of the hydrodynamic forces as well as the effectiveness of the baffles in suppressing sloshing pressure associated with the baffle configurations. The baffle configuration, including location, shape, size, number, stiffness and perforations, shall be taken into account for the effects on the damping of the additional factors, such as amplitude, frequency and type of tank motion, liquid filling level, size and geometry of tank, physical properties of liquid (Abramson, 1969). A typical baffle configuration for current Liquefied Natural Gas tanks consists of a stack of vertical or horizontal baffles fitted around the inner periphery of the tank. The effectiveness of the baffles in suppressing sloshing pressure have been widely investigated numerically, experimentally, and analytically (Faltinsen and Timokha, 2009).

Numerical simulation techniques based on solving potential equation have been widely applied for modelling of liquid sloshing in baffled tanks, and the results of pertinent studies will be discussed briefly. Gedikli and Erguven (1999) presented the effects of a rigid baffle on the seismic response of liquid in a rigid cylindrical tank. Maleki and Ziyaeifar (2007) investigated the effect of baffles in reducing earthquake responses of seismically isolated cylindrical liquid storage tanks. The results show that the average damping ratio of sloshing mode due to ring baffle increases with a decrease in liquid height and highest damping may be achieved for height to radius ratios of between 1.0 and 1.5. Cho and Lee (2004) numerically investigated the large amplitude liquid sloshing in two-dimensional (2-D) baffled tank subject to

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horizontal forced excitation. They concluded that the quantities of interest in the liquid sloshing display the strong dependence on the baffle design parameters, so that the baffle design for suppressing the liquid sloshing effect should be made through the comprehensive parametric investigation. Cho et al. (2005) presented a numerical analysis of the resonance characteristics of liquid sloshing in a 2-D baffled tank subjected to the forced lateral excitation based on the linearized potential flow theory by considering an artificial damping term in the kinematic free surface condition. In their study, the parametric effects of the liquid fill height, the baffle number, the opening width and the baffle location have been parametrically examined.

Biswal and Bhattacharyya (2010) considered the dynamic interaction that exists between the liquid and elastic tank-baffle system to evaluate the coupled response of liquid and tank-baffle system. It is observed that both the liquid and structural responses may be controlled by using the baffle. However, the maximum reduction in both the responses may be achieved by placing the baffle closer to the free surface. Sygulski (2011) studied numerically the natural frequencies and mode shapes of liquid sloshing in three-dimensional (3-D) baffled tanks with arbitrary geometries. Hasheminejad and Mohammadi (2011) numerically studied the effect of anti-slosh baffles on free liquid oscillations in partially filled horizontal circular tanks based on the linear potential theory. The results show that the baffle installation position has distinct effects on the sloshing frequencies and the associated hydrodynamic pressure fields. Hasheminejad and Aghabeigi (2012) investigated the effects of surface-piercing or bottom-mounted vertical baffles on 2-D liquid sloshing characteristics in a half-full non-deformable horizontal cylindrical container of elliptical cross section. Ebrahimian et al. (2013) investigated the sloshing natural frequencies of symmetric and antisymmetric modes of an axisymmetric multi baffled tanks with non-axisymmetric boundary conditions. They obtained results confirm that the effect of the baffle position on the sloshing natural frequencies is more important than the size of it. Hasheminejad et al. (2014) concluded that the surface-touching side baffles are found to be most effective in terms of suppressing the total induced force amplitudes, while the worst performance is associated with the bottom-mounted vertical baffle, and the surface-piercing vertical baffle is of intermediate value. Ebrahimian et al. (2014) thought that the presence of baffle on the equivalent masses is significant when it is only near the free surface.

However, the sloshing amplitude is, in general, much over-predicted by the potential flow theory for the baffled tank comparing with the predictions of viscous fluid model (Lu et al., 2015). Therefore, numerical model based on solving Navier-Stokes equation is widely used in investigating of the sloshing problems in the baffled tanks. For example, Liu and Lin (2009) concluded that the vertical baffle is a more effective tool in reducing the sloshing amplitude comparing with a horizontal baffle. Delorme et al. (2009) investigated experimentally and numerically impact pressure in the case of shallow water sloshing under forced rolling motion. They conclude that the maximum of pressure occurs at a frequency higher than the first sloshing frequency for the excitation period T=0.9T_O. Belakroum et al. (2010) numerically predicted the damping effect of baffles on sloshing in tanks partially filled with liquid. In their studies, horizontal baffle, vertical baffle at the bottom of tank and vertical baffle at the free surface are introduced and concluded that the effectiveness and the effect of mounting a baffle vertically just at the free surface on the attenuation of sloshing waves and reduction of the overturning moment were underlined. Xue and Lin (2011) and Xue et al., (2012, 2013) investigated numerically and experimentally viscous liquid sloshing in a tank with different internal baffles such as ring baffle, perforated baffle, horizontal baffle.

Jung et al. (2012) investigated the effect of the vertical baffle height on the liquid sloshing in a laterally moving 3-D rectangular tank and concluded that the vortex generated by the flow separation from the baffle tip becomes weaker and smaller with increasing baffle height, leading to a diminished damping effect of the tip vortex on the liquid sloshing. Akyildiz (2012) investigated numerically the effects of the vertical baffle height on liquid sloshing in a rolling rectangular tank. The results show that the vertical baffle suppresses slightly the liquid sloshing as the baffle height increases, even small baffle height, due to the hydrodynamic damping of the baffle including the blockage effects and the viscosity of baffle walls. Wu et al. (2012) thought that the largest wave damping might occurs when the distance between baffle is 0.2 L for the two vertical baffles being installed in the tank with length L. Koh et al. (2013) simulated water sloshing in prismatic tank with a constrained floating baffle (CFB). The comparison of pressure histories between free sloshing and sloshing with CFB shows that the CFB is effective in suppressing sloshing. Cao et al. (2014) analyzed the influences of vertical baffle for the liquid sloshing in a tank under forced surging. Their results show that the baffle can change the direction of sloshing wave and at the same time the magnitude of the liquid sloshing is reduced by about 50% for the 3-D sloshing tank under a coupled excitation.

Experimental tests play an important role in accurate prediction of the sloshing phenomena. Akyildiz and Ünal (2005) investigated experimentally pressure distribution due to sloshing in a rectangular tank at a model scale with various filling levels and baffles. They concluded that the baffle located vertically on the center of the bottom of the tank reduces the maximum pressures on the sides of the tank compared to the un-baffled tank. The vertical baffle can produce a shear layer when flow over it and energy is therefore dissipated by the viscous action. Panigrahy et al. (2009) carried out a series of experiments to estimate the pressure distribution on the tank walls and the free surface displacement of water from the mean static level in a rectangular tank without and with baffles by varying fill level and frequency. The results show that the ring baffles are more effective as compared to the conventional horizontal baffles due to its absorbable the energy at all the walls. Pistani and Thiagarajan (2012) developed a sloshing experiment setup to measure with accuracy the high pressure generated during the impacts of the fluid in the case of rectilinear sinusoidal motion in the direction of sway. Akyildiz et al. (2013) designed an experimental setup to study the non-linear behavior and damping characteristics of liquid sloshing in a partially filled cylindrical tank with ring baffles. It is found that ring baffle arrangements are very effective in reducing the sloshing forces.

Molin and Remy (2013) performed experimental and numerical study of the sloshing motion in a rectangular tank with a perforated screen. Hosseinzadeh et al. (2014) carried out shake table tests on a reduced scale model steel storage tank in two cases of with and without annular baffles. Their studies indicated the significant effects of the annular baffles in reducing the fluid wave sloshing height as sloshing dependent variable dampers. Jin et al. (2014) conducted an experimental study on sloshing in a tank with an inner horizontal perforated plate. The experimental results indicate that the horizontal perforated plate can significantly restrain violent resonant sloshing in the tank under horizontal excitation. Sauret et al. (2015) studied experimentally the effect on sloshing of liquid foam placed on top of a liquid bath. They conclude that only a few layers of bubbles are sufficient to significantly damp the oscillations and only the bubbles close to the walls have a significant impact on the dissipation of energy. Nayak and Biswal (2015) conducted a series of experiments in a rigid rectangular tank on a shake table under lateral harmonic excitation. In their studies, bottom-mounted vertical baffles, surface-piercing wall-mounted vertical baffles, and bottom-mounted submerged-blocks are tried out as potential passive slosh damping devices. The parametric studies shown that the surface-piercing wall mounted baffles are the most effective one in sloshing damping among the three configurations.

An analytical model for determination of baffle damping is available methods for design of the baffle configurations and arrangements. Maleki and Ziyaeifar (2008) developed a theoretical damping model of liquid sloshing in baffled tanks undergoing horizontal excitation