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Slosh-induced hydrodynamic force in a water tank with multiple baffles

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ABSTRACT

This study uses laboratory experiments and a Large Eddy Simulation (LES) model to investigate the sloshing phenomenon in a rectangular water tank with multiple bottom-mounted baffles. The kinematic motion of the water surface was solved by the Volume of Fluid (VOF) method. The simulation results were verified by the measured wave heights in a water tank installed on a shaking table. The numerical model was employed to systematically determine the effects of the spacing and height of the baffles on the sloshing phenomenon. The simulation results indicate that the natural frequency of the tank was altered by the multiple baffles and was related to the effective water depth above the baffles. The diminishing effect of multiple baffles on the hydrodynamic force is better than that of a single baffle. In addition, the sloshing force on the sidewalls of the tank can be characterized by the excitation amplitude, frequency, and water depth. While the sloshing height and hydrodynamic force decrease as the baffle number or baffle height increase, the effect of baffles on the sloshing lessens when the relative baffle height $h_b/h_w \geq 0.75$.

1. Introduction

The liquid sloshing in moving tanks is of great practical importance to the design of storage tanks, oil tankers and liquid fuel in spacecraft (Graham and Rodriquez, 1952; Armenio and La Rocca, 1996; Ibrahim, 2005). In addition, the water storage tanks on the roofs of high-rise buildings could be used as tuned liquid dampers (TLD) to mitigate the external excitation caused by earthquakes and hurricanes (Fujino et al., 1992). The dynamic pressure on the sidewalls of storage tanks, generated by the sloshing, could damage the tanks and/or reduce the building vibration. The amplitude of the sloshing wave and dynamic pressure are dependent upon the tank geometry, liquid depth, amplitude and frequency of the external excitation (Lamb, 1932).

The classic sloshing problem is sloshing in a rectangular water tank without baffles, the wave frequency and velocity field, under the assumption of incompressible and inviscid flow, could be predicted by the potential flow theory. For example, Fujino et al. (1992) used shaking table experiments to study the vibration of a single degree-of-freedom structure with an attached Tuned Liquid Damper (TLD). Based on the shallow water wave theory, they developed a nonlinear model to describe the liquid motion inside a rectangular water tank and semi-analytically included the damping effect of the liquid motion. Using their model, the response of a structure with TLD subjected to the harmonic external force can be predicted.

Pal et al. (2003) used a finite element numerical model to simulate the sloshing problem without baffle. Their numerical scheme was developed on the basis of a mixed Eulerian–Lagrangian approach, with the velocity potential as the unknown nodal variable in the fluid domain, and the displacements as the unknowns in the structure domain. Wu et al. (2013) proposed a three-dimensional finite difference model to study the oblique sloshing in a square water tank (without baffle) under oblique horizontal excitation. They tested different computational meshes and time steps, and validated their simulation results via experimental measurements. They also investigated the dynamic pressure on the tank walls and found that the dynamic pressure was dominated by the added mass effect when the excitation frequency was much larger than the natural frequency.

In order to mitigate the sloshing-induced forces on storage tanks, baffles have been installed in the storage tanks to damp out the sloshing (Liu and Lin, 2009). Celebi and Akyildiz (2002) experimentally investigated the nonlinear sloshing inside a partially filled rectangular tank with one vertical baffle. Their results revealed that the baffle produced a shear layer and dissipated energy by the viscous term. They concluded that, in an increased water depth, the rolling amplitude and frequency of the tank with or without baffle configurations directly affect the degree of nonlinearity of the sloshing phenomena.

Panigrahy et al. (2009) used shaking table experiments to investigate the mitigating effects of different kinds of baffles on sloshing

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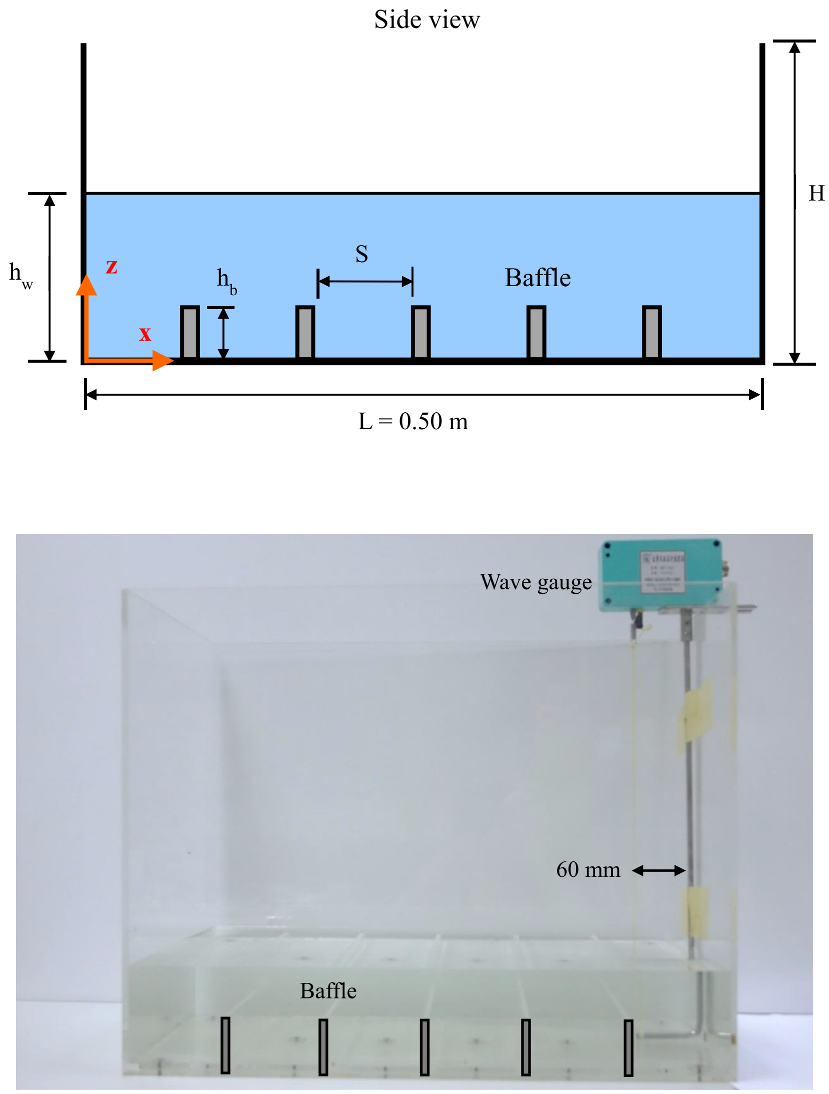

Fig. 1. Schematic diagram and photograph of the water tank with five vertical baffles.

in a square water tank. They found that the ring baffles on the tank walls were more effective than horizontal baffles due to the ring baffles absorbing and dissipating energy in all directions rather than being concentrated in particular directions. Liu and Lin (2009) summarized the previous studies on the effect of baffles on sloshing and adopted a Large Eddy Simulation (LES) model to simulate the three-dimensional sloshing in a rectangular tank with baffle. They found that the vertical baffle is more effective than the horizontal baffle in reducing the sloshing and pressure on the wall.

Akyildiz (2012) used a finite difference numerical model to study the liquid sloshing in a rectangular tank with one vertical baffle at the tank bottom. They adopted a moving coordinate system to solve the Navier–Stokes equations, but ignored the wave-breaking and turbulence in the tank. They validated their simulation results by the laboratory experiments of Akyildiz and Ünal (2005), and demonstrated that both the maximum wave height and dynamic pressure decreased as the baffle height increased.

Wu et al. (2012) used a time-independent finite difference scheme with fictitious cell technique to study sloshing in water tanks with bottom mounted baffles and surface piercing baffles. They analyzed the response frequency of the baffled tank and found that the asymptotic formula is inadequate to predict the effect of baffles on the fundamental frequency when the baffle height is large. Jung et al. (2012) applied the standard k-ε turbulence model and the volume of fluid (VOF) method to simulate the liquid sloshing in a rectangular water tank with one vertical baffle in the middle of the tank. Their results demonstrated that the vortices generated by the flow separation from the baffle tip became weaker as the baffle height increased. Nevertheless, their simulation result over-estimated the peak pressure on the side wall of the tank, as compared to the experimental result of Kang and Lee (2005).

Xue et al. (2012) and Xue et al. (2017) used numerical model and laboratory experiments to study the liquid sloshing in a square tank with different types of baffles. The compared the effects of vertical, horizontal, and perforated baffles on the sloshing. Their simulation results revealed that the baffles could change the natural frequency of the tank and reduce the amplitude of sloshing and the maximum dynamic pressure occurred near the free surface.

Zhang et al. (2014) and Chen et al. (2017) compared the simulation results of sloshing flows computed by a meshless moving particle semi-implicit (MPS) method and a grid-based level-set method. They considered two violent sloshing cases and the simulation results demonstrated that both methods can be used to simulate the sloshing flows. Nevertheless, the MPS method has better accuracy than the level-set method in capturing the second pressure peak as well as the splashing. Cao et al. (2014) used the Smoothed Particle Hydrodynamics (SPH) model to simulate the liquid sloshing in a rectangular tank with one baffle.

The above studies, whether by laboratory experiments and/or by