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Two-dimensional viscous numerical simulation of liquid sloshing in rectangular tank with/without baffles and comparison with potential flow solutions

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ABSTRACT

A viscous fluid model based on non-inertial reference system is developed for the problem of liquid sloshing in rectangular tank with/without baffles. The accuracy of the numerical model is validated against available theoretical solutions, experimental data and numerical predictions by linear and non-linear potential flow models and different Navier–Stokes solvers. The numerical examinations indicate that the dissipative effects have significant influence on the sloshing responses in both non-baffled and baffled tanks. The sloshing responses that are associated with the natural frequencies can be finally damped out due to the physical dissipations, while they are entirely retained in the potential solutions, which accounts for the general over-predictions of sloshing amplitudes by the potential flow theory. The sloshing in baffled tank involves more dissipation due to the stronger vortical flow. The resonant frequency and amplitude are highly dependent on the baffle width and position. The relative sloshing amplitudes around the resonant condition are found to decrease with the excitation amplitude in a power law. The necessity of using viscous fluid model for sloshing predictions is addressed. The extremely long numerical computations have to be carried out in order to obtain convincing stable solutions, especially for the weakly damped sloshing motion.

1. Introduction

Liquid sloshing is of theoretical and practical significance, which represents one kind of complex interface flows in confined space. Sloshing is often encountered in ocean engineering, for example the violent free surface flows in an oil tanker or Liquefied Natural Gas container under the actions of water waves. From the large scale point of view, the global sloshing flow may behave extremely large amplitude of resonant response as the excitation frequency is close to one of the natural frequencies of the liquid bulk. And the strong coupling between liquid sloshing and ship motions can take place. On the other hand, the sloshing has also important small scale effects, such as the impact pressure, mixture of liquid and gas as well as the mechanical energy dissipation due to the fluid viscosity and vortical flows. Understanding the fundamental physics in sloshing flows is important to the maritime operation and structural safety.

A variety of investigations, including theoretical analysis, numerical simulations and experimental observations, have been carried out, which have significantly advanced the understandings of sloshing motions. A rather comprehensive introduction to the liquid sloshing with special interest to ocean engineering is referred to Faltinsen and Timokha (2009).

As for the small amplitude sloshing motion in a container with regular configuration, the theoretical solutions can be derived based on the linear potential flow theory. Analytical solutions were also made for the nonlinear liquid sloshing. For instance, Faltinsen et al. (2000) and Faltinsen and Timokha (2002) developed multi-dimensional and asymptotic modal approximations for the liquid sloshing in a rectangular tank with finite and small fluid depth.

Meanwhile, various numerical models in the frame of potential flow theory have been proposed for the sloshing predictions, including the linear and nonlinear models based on the boundary element method (Nakayama and Washizu, 1981), the finite difference method (Chen and Chiang, 1999) and the finite element method (Nakayama and Washizu, 1980; Wu et al., 1998; Cho and Lee, 2004; Wang and Khoo, 2005; Teng et al., 2006). Nevertheless, the potential flow models are generally found to overestimate the sloshing response, which is commonly attributed to the fundamental assumption of the potential

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flow theory, namely, the irrotational flows of ideal fluids. That means the physical dissipation in real sloshing flows is completely neglected. On the other hand, the classical dynamics theory suggests that the damping/dissipation has significant influence on the initial transient effect and the final stable solution.

The dissipation in sloshing has received increasing attention. The sloshing damping in a container undergoing steady-state forced excitation in translational motion was theoretically and experimentally investigated by Welt and Modi (1992a, 1992b). The mechanical energy dissipation due to wave breaking is particularly examined by Bouscasse et al. (2014a, 2014b). As mentioned before, the conventional potential flow theory has difficulty in predicting the resonant amplitude where the noticeable dissipation is involved. Hence attempts have been made to improve the accuracy of the potential flow models by introducing appropriate artificial damping term. The early work might be contributed to Faltinsen (1978), where a Rayleigh damping term was introduced into the linear free surface boundary condition. The similar methods were also used by Cho et al. (2005) for the sloshing problem, and the piston mode fluid resonance in a narrow gap between two closely spaced floating bodies (Chen, 2004; Lu et al., 2011b). Recently, Huang et al. (2011) raised a new approach based on the work of Malenica et al. (2003) to model the sloshing dissipation by means of modifying the boundary conditions of solid wall. The previous numerical tests have shown that the potential flow models with damping term are able to produce reasonable predictions if the damping coefficient is correctly calibrated with available experimental data or viscous numerical results. However, the generalization of the damping coefficient for varying conditions remains challenge.

With the development of Computational Fluid Dynamics (CFD), the numerical models based on the Navier–Stokes equations for violent sloshing flows were developed. Sheu and Lee (1998) investigated the large-amplitude sloshing in an oil tanker by using a two-dimensional viscous fluid model. The free surface is captured by the Volume of Fluid method based on a donor–acceptor concept (Hirt and Nichols, 1981). A two-dimensional viscous fluid model with interface capture technique was also developed by Celebi and Akyildiz (2002), and was used to simulate the liquid sloshing in the tank that is forced to move harmonically along a vertical curve with rolling motion. The sloshing of viscous fluid in a tank under coupled surge, heave and pitch motions were examined by Chen (2005) and Chen and Nokes (2005). The viscous numerical model developed by them was based on the finite difference method in conjunction with a coordinate transformation to track the free surface of liquid sloshing. The influences of Reynolds number and Froude number on the sloshing amplitude were examined. Liu and Lin (2008, 2009) studied the three-dimensional turbulent sloshing flows in various tanks. The sloshing impact is also examined in the context of viscous fluid flows. Kim (2001) developed a finite difference model to predict the impact occurrence in various two- and three-dimensional tanks, where a special buffer zone was adopted near the tank ceiling for the impact simulation, and a single-value function was used for the sloshing interface tracking. This model was further improved in Kim et al. (2004). The concept of buffer zone was extended to the sloping boundaries near the tank ceiling, and the previous sensitivity to grid resolution and time increment was mitigated.

The viscous fluid models are theoretically sound for the sloshing simulations since the physical dissipation can be correctly considered. However they generally require more computational efforts compared with the potential flow models. Moreover, when the stable solutions of liquid sloshing with weak damping are concerned, much more computational costs will be involved. This is because that, for example, a sloshing process starting from the still state, the transient effect is generally inevitable. Consequently, the sufficient computational time for the viscous numerical simulation is expected in order to obtain the stable-state solution. As a general rule, the weaker the damping requires the longer the time. The early viscous numerical simulations by Sheu and Lee (1998), over a period of time 200 s, have indicated the slow energy dissipation in the sloshing process. Although the maximum transient amplitude was speculated to be much larger than that of the steady-state response (Chen and Nokes, 2005), the numerical solutions for a period of less than 60 s seem not to be in the stable state. Hence, for the viscous numerical simulations, it is necessary to minimize the transient effect as small as possible.

Large amplitude resonant sloshing, even with strong coupling with ship motion, may lead to serious risks. It will be desirable to actively reduce the sloshing response. This can be achieved by installing blocks or baffles on the inner walls of the tank. Choun and Yun (1996) investigated the influence of a bottom-mounted block on the sloshing characteristics in a rectangular tank by using the linear potential flow model. Parametric examinations on the liquid sloshing in a rectangular tank with horizontal baffles under harmonic excitation were conducted by Cho and Lee (2004). Compared with the non-baffled case, the nonlinear potential results indicated that the liquid sloshing in baffled tank behaves more complex in terms of both sloshing flows and hydrodynamic pressures. Biswal et al. (2006) examined the influence of multiple rigid baffles on the sloshing responses in both rectangular and cylindrical tanks subjected to forced horizontal oscillations. The numerical investigations are based on a nonlinear potential flow model in time domain, and the comparisons between the numerical results of linear and nonlinear potential flow models were presented. Akyildiz (2012) further studied the nonlinear behavior of liquid sloshing in a rolling rectangular tank with vertical baffles. The frequency characteristics of the sloshing in baffled tank under coupled horizontal and vertical excitations were examined by Ning et al. (2012). The intrusion of baffles may result in significant vortical flows. Therefore, the difficulties of potential flow models in dealing with the dissipation become more severe. Isaacson and Premasiri (2001) and Maleki and Ziyaeifar (2008) estimated the hydrodynamic damping by baffles, and discussed the mechanical energy dissipation due to the flow separation around the baffles. Goudarzi et al. (2010) developed an analytical model based on the linear potential theory to estimate the hydrodynamic damping ratio for the liquid sloshing in a baffled rectangular tank. Parametric studies for the damping efficiencies show that the hydrodynamic damping can be significantly affected by the size and location of baffles.

The previous examinations on the sloshing in baffled tank are mainly focused on the influences of geometric dimension and spatial arrangement of the baffles. It was found that the intrusion of the baffles changes not only the resonant frequency but also the resonant amplitude. The decrease of the sloshing amplitude by using baffles is mainly attributed to the increase in physical dissipation. On the other hand, as for a specific arrangement of baffles, the sloshing response will also depend on the excitation amplitude in addition to the excitation frequency. The increase in the excitation amplitude may give rise to more significant vortical flows, and consequently more energy dissipation. The influence of the excitation amplitude on the sloshing responses and dissipation requires further examination, which has to be investigated by using the viscous fluid model.

In general, comprehensive investigations have been conducted so far for the sloshing problem in tanks with/without baffles based on various numerical models. However, several aspects associated with the dissipation in sloshing flow require to be further clarified, including the transient effect involved in the numerical simulation, the role of sloshing frequency in dissipation, influence of the excitation amplitude on the sloshing response as well as the estimation of the damping effects. These issues will be examined in this work based on the numerical simulations of viscous sloshing flows in both baffled and non-baffled tanks. In particular, the cases of baffled tank can provide scenery with manifested damping effect. The structure of this article is organized as follows. In the following Section 2 the viscous numerical model used in this work will be described. After necessary numerical verifications and validations against available data, the numerical results of this work and their comparisons with