

## Time-Independent Finite Difference and Ghost Cell Method to Study Sloshing Liquid in 2D and 3D Tanks with Internal Structures

C. H. Wu<sup>1</sup>, O. M. Faltinsen<sup>2</sup> and B. F. Chen<sup>1,\*</sup>

<sup>1</sup> Department of Marine Environment and Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan.

<sup>2</sup> Centre for Ships and Ocean Structures & Department of Marine Technology, NTNU, Trondheim 7491, Norway.

Received 28 October 2011; Accepted (in revised version) 2 February 2012

Available online 29 August 2012

---

**Abstract.** A finite difference scheme with ghost cell technique is used to study viscous fluid sloshing in 2D and 3D tanks with internal structures. The Navier-Stokes equations in a moving coordinate system are derived and they are mapped onto a time-independent and stretched domain. The staggered grid is used and the revised SIMPLEC iteration algorithm is performed. The developed numerical model is rigorously validated by extensive comparisons with reported analytical, numerical and experimental results. The present numerical results were also validated through an experiment setup with a tank excited by an inclined horizontal excitation or a tank mounted by a vertical baffle. The method is then applied to a number of problems including sloshing fluid in a 2D tank with a bottom-mounted baffle and in a 3D tank with a vertical plate. The phenomena of diagonal sloshing waves affected by a vertical plate are investigated in detail in this work. The effects of internal structures on the resonant frequency of a tank with liquid are discussed and the present developed numerical method can successfully analyze the sloshing phenomenon in 2D or 3D tanks with internal structures.

**AMS subject classifications:** 65M06, 76B10, 49L25, 35Q35, 74F10

**Key words:** Liquid sloshing, baffle, plate, time-independent finite difference, ghost cell.

---

## 1 Introduction

Sloshing must be considered for almost any moving vehicle or structure containing a liquid with a free surface, such as tankers on highways, liquid oscillations in large storage tanks caused by earthquakes, sloshing of liquid cargo in ocean-going vessels and the

---

\*Corresponding author. *Email address:* chenbf@faculty.nsysu.edu.tw (B. F. Chen)

motion of liquid fuel in aircraft and spacecraft. Excitation with frequencies in the vicinity of the lowest natural frequency of the liquid motion is of primary practical interest. Resonant free-surface flows in tanks in aircraft, missiles and rockets have been the focus of extensive researches. The large amplitude of the liquid motion can create high impact pressures on the tank walls, which in turn can cause structural damage and may even create moments that affect the stability of the vehicle which carries the container. For these vehicles, sloshing will have a strong influence on their dynamic stability. The hydrodynamics of sloshing is complicated and the understanding of sloshing dynamics requires a combination of theory, computational fluid dynamics (CFD) and experiments.

The numerical, analytical and experimental studies of liquid sloshing in tanks have been reported in the past several decades and these studies have explored a range of significant phenomena such as the effect of fluid viscosity, linear and nonlinear effects and the classification of sloshing waves. If the interior of the tank is smooth, the fluid viscosity plays a minor role to affect the sloshing in tanks and an inviscid/irrotational potential flow solution is, therefore, suitable for describing the sloshing in a rigid tank. Abramson [1] provides a comprehensive review and discussion of early analytic and experimental studies of liquid sloshing, with application to the aerospace industry. In the recent studies, the series of studies by Faltinsen and his co-workers constitutes a major contribution to the field of sloshing. Faltinsen, Rognebakke and Timokha [2–4] extended their asymptotic modal system to model nonlinear sloshing in a 3D rectangular tank.

Besides the potential flow approaches, many numerical studies of the sloshing problem with primitive variables have been made, particularly when the fully nonlinear effects of the waves on the free surface are included. Papers that describe the modeling of two-dimensional or three-dimensional sloshing include Chen and Chiang [5], Sames, Marcouly and Schellin [6], Frandsen [7], Chen [8], Chen and Nokes [9], Akyildiz [10, 11] and more recent papers by Liu and Lin [12], Wu and Chen [13] and Chen and Wu [14]. The comprehensive discussions are reported by Faltinsen and Timokha [15].

Tuned liquid dampers (TLDs) are used to suppress horizontal vibrations of structures. A TLD consists of a tank partially filled with water. The lowest resonant frequency of sloshing is tuned to a structural natural frequency. Warnitchai and Pinkeaw [16] studied the mathematical model compared with experimental investigations for a rectangular tank with flow-damping devices. The vertical flat plate and the wire mesh screen can cause significant damping effects on sloshing waves. Isaacson and Premasiri [17] developed the mathematic solutions and experiment investigations to solve the hydrodynamic damping due to baffles in a fluid-filled rectangular tank undergoing horizontal motions. The average rate of energy dissipation due to flow separation around baffles and the total energy of sloshing waves were used to estimate the hydrodynamic damping.

Biswal et al. [18] used FEM (Finite element method) on computing the non-linear sloshing response of liquid in a two-dimensional rectangular tank and a circular cylindrical container with rigid baffles. The effect of baffle parameters including length, numbers and position on sloshing response were discussed. A 3D FEM model for liquid sloshing in a baffled tank was adopted by Firouz-Abadi et al. [19]. The determinations of the nat-