Applied Ocean Research 68 (2017) 307–324

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Experimental and numerical investigation of sloshing using different free surface capturing methods

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ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form 31 July 2017
Accepted 20 September 2017
Available online 6 October 2017

Keywords:
Liquid sloshing
Compressible and incompressible fluid
Free surface capturing method
PIV sloshing

ABSTRACT

We investigated the use of numerical methods to predict liquid sloshing phenomena in a moving tank and compared our results to model test measurements. The numerical techniques for the free surface, based on the so-called finite Volume-of-Fluid (VoF) approach, comprised an incompressible VoF method, an incompressible coupled Level-Set and Volume-of-Fluid (clsVoF) method, and a compressible VoF method. We assessed the capability of these three numerical methods to achieve suitable numerical predictions of sloshing phenomena, specifically, air pockets and bubbles on the free surface inside a test tank. To observe the described sloshing phenomena, we simulated tank motions leading to well defined single impact wave motions. We performed repeated physical tests for validation purposes. Computed velocity and pressure time histories were compared to experimental data we obtained from Particle Image Velocimetry (PIV) and pressure sensor measurement. Grid sensitivity and turbulence model studies were performed. We demonstrated that the compressible VoF method was the most suitable method to obtain accurate predictions of sloshing phenomena.

1. Introduction

Fluid dynamic sloshing is a complex free surface phenomenon caused by the movement of liquid inside partially filled tanks which, typically, are also undergoing motion. The liquid's free surface constitutes a slosh dynamics problem when the moving liquid interacts with the tank walls to significantly affect system dynamics [1]. Serious sloshing related problems occur in many applications, such as with propellant tanks in aerospace containments and with Liquefied Natural Gas (LNG) cargoes onboard ships [2,3]. Violent ship motions caused by adverse weather conditions may excite strong fluid motions. Sloshing may produce highly peaked local impact loads, which may lead to severe structural damages on tank walls and ceiling. In addition, the large sloshing-induced forces and moments may cause significant changes in ship motions, which are crucial to the safety and stability of LNG carriers during delivery and offloading operations.

Many researchers have devoted their efforts studying liquid sloshing problems analytically [4,5,6,7,8] and experimentally [9,10,11,12,13,14]. Extensive numerical studies on the liquid sloshing problem have been conducted using grid methods as well as gridless methods, such as the Boundary Element Method (BEM) [15,16], the Finite Element Method (FEM) [17,18], the Finite Difference Method (FDM) [19,20], the Finite Volume Method (FVM) [21,22,23,24], the Smoothed Particle Hydrodynamics (SPH) method [25,26], the Moving Particle Semi-implicit (MPS) method [27], and the Consistent Particle Method (CPM) [28].

When solving the Navier–Stokes equations with grid methods, due to the presence of the free surface, additional schemes have to be applied to simulate sloshing waves. The Marker and Cell (MAC) method, the Volume-of-Fluid (VoF) method, and the Level-Set (LS) method have been successfully applied to capture the profile of the interface in liquid sloshing simulations. Arai et al. [29] used the MAC method to compute sloshing impact pressure in simulations. Nam and Kim [30] used the SPH method, which was developed from the MAC scheme, to solve two-dimensional sloshing flows. Using the VoF method and solving the Navier-Stokes equations and considering liquid free surface deformation, liquid viscosity, and surface tension, Elahi et al. [2] developed a two-dimensional numerical model to study liquid sloshing in containers. Bai et al. [31] used the Level-Set (LS) method to obtain a finite difference approximation for the simulation of a two-dimensional tank under three-degrees-of freedom excitations.

The VOF method has the capability to preserve mass conservation, but it may lack accuracy for the calculation of the surface normal and the interface curvature because the VoF functions behave as step functions. The Level-Set method is better able to capture the sharp and smooth interface, but it is not able to preserve mass conservation. A coupled Level-Set and Volume-of-Fluid (clsVoF) method to simulate liquid sloshing flows was proposed

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http://dx.doi.org/10.1016/j.apor.2017.09.008
0141-1187/

Table 1
Tank inner dimensions.

Variable	Symbol	Value
Length	L	946 mm
Width	B	118 mm
Height	H	670 mm
Volume	V	0.075m^3

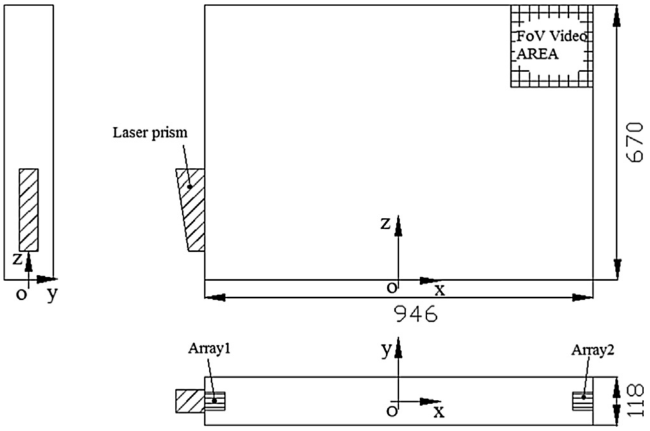

Fig. 1. Inner volume of the test tank showing the two sensor arrays, the video area, and the laser prism (numbers are given in mm).

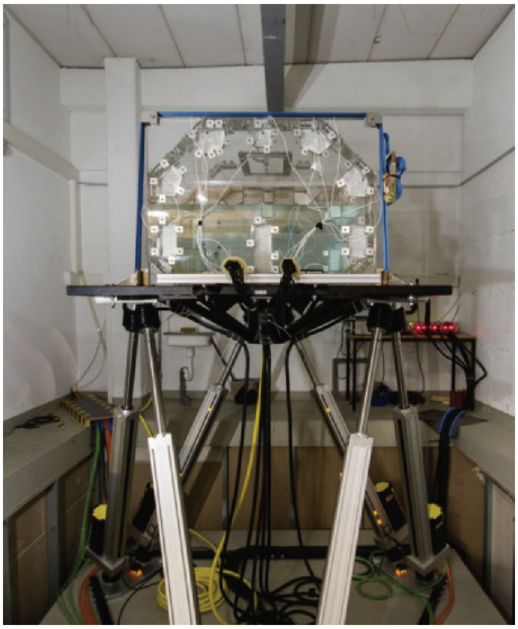

Fig. 2. A test tank situated on top of the hexapod [39].

by [32]. [33] used this method to study three-dimensional sloshing flows in partially filled LNG tanks. This method reconstructs the interface from the VoF method to preserve mass conservation, and the LS method evaluates the geometric properties.

Under certain conditions, it is necessary to account for compressibility to ensure an accurate representation of flow dynamics. Researchers showed that the presence of the compressible air reduces peak pressure levels, but increases the duration of impact [34,35,36,37]. To model such problems, three main approaches are available. The first approach considers both phases as incompressible, and the fully incompressible Navier-Stokes equations are used to solve the problem. The second approach assumes gas and liquid phases behave as compressible and incompressible flows, respectively. In the third approach, both phases behave as compressible flows. In the second and third approaches, the compressible Navier-Stokes equations with different equations of state for each phase are usually used [38].

In our paper, we investigated the use of three different numerical methods, all based on the Finite-Volume method, suitable to predict sloshing flow problems in a tank, namely, an incompressible VoF technique, an incompressible clsVOF method, and a compressible VoF approach. Using these three methods, we were able not only to represent typical sloshing phenomena, such as air pockets and bubbles, but also to depict the free surface, local velocity vectors, and pressures. We performed repeated physical tests for validation purposes. We first performed grid and turbulence model studies. Further on, we compared results obtained from two- and three-dimensional computations.

2. Experimental setup

The experimental setup consisted of the partially filled test tank, the test motion rig, the sensors, and the data acquisition system. For additional details, see Neugebauer et al. [39], Loysel et al. [40], and Loysel et al. [41].

2.1. Test tank

Sloshing experiments were carried out in a quasi two-dimensional test tank made of Plexiglas. A parallelepiped with internal dimensions listed in Table 1 represented its inner volume, which is schematically pictured in Fig. 1. The tank accommodated pressure sensors located at two corners of the tank's ceiling and a high-speed video camera to monitor the free surface elevation over a certain area. Fig. 1 shows the location of the two sensor arrays (Array1 and Array 2), the area (Field of View: FoV Video Area) over which PIV measured velocities, and the prism (Laser prism) which beamed a laser light sheet into the tank. A reference system (o, x, y, z) was defined with its origin (o) located at the center of the inner bottom.

2.2. Test motion rig

The test motion rig comprised several components. The main component, a hexapod, executed six Degrees-of-Freedom (DoF) motions. Motions are described by motion path files which contain the position and orientation of the hexapod at a rate of 100 Hz. Further, trigger wires were activated by means of control commands from the motion path files. Typically, one trigger started the motion acquisition, while a second trigger initiated pressure data acquisition and high-speed video acquisition. Fig. 2 shows a photograph of a test tank situated on top of the motion rig.

Table 2 summarizes the test conditions (including driving motions) investigated. We considered two different kinds of excitation motions, both Single Impact Wave (SIW) motions with different excitation period.

We introduced single impact wave motions to study different impact types in our tank. The SIW driving signals were generated via a hyperbolic tangent superimposed on a sine signal between $t = 0$ and $t = 2T$ as follows:

$$x(t) = \begin{cases} A\sin\left(\frac{2\pi t}{T}\right)\tanh\left(\frac{\pi t^2}{T}\right), & \text{if} \quad 0 \le t \le T \\ A\sin\left(\frac{2\pi t}{T}\right)\tanh\left(\frac{\pi(2T-t)^2}{T}\right), & \text{if} \quad T < t \le 2T \end{cases} \tag{1}$$

where period T and motion amplitude A are listed in Table 2. Obviously, every SIW condition lasted only a relatively short time. A