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PIV Measurement of Violent Sloshing Flows and Comparison with CFD Computations

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In this study, a sloshing model test was conducted using particle image velocimetry (PIV) equipment, and the sloshing impact characteristics were compared to those found using computational fluid dynamics (CFD). A 2-D rectangular tank filled with water and air was used, with the specified excitations inducing impact without an air pocket at the top corner of the tank. In the model test, a high-speed camera and pressure measurement system were triggered at the same time using a synchronizer system in order to obtain the velocity of the fluid and pressure simultaneously. In numerical computations, two different codes, an in-house code and commercial software, were applied. The present in-house code was based on a finite difference discretization and constraint-interpolation-profile method using an interface-capturing method to treat the interface between the air and water. In the commercial software, a volume-of-fluid approach and Eulerian multiphase model were applied for simulating the violent flows, and an adaptive mesh model was used to reduce the computation time. The sensitivity of numerical parameters such as type of mesh model, grid spacing, and time segment to the impact pressure was observed. In addition, the calculated results of the pressure at the center of the sensor and the spatially averaged pressure over the sensor were compared. Based on the sensitivity studies of computational parameters and repeatability tests in the sloshing model test, a comparison of the impact pressure, pressure impulse, and velocity fields of the numerical computations and experiment was made. Finally, the relationship between the fluid velocity and impact pressure was investigated.

INTRODUCTION

Sloshing is an important topic in the design of ships and offshore structures used for liquefied natural gas (LNG) such as the LNG carrier, floating LNG (FLNG), and LNG-regasification vessel (LNG-RV) because sloshing flows can cause local impulsive pressures, presenting the potential danger of structural failure as reported in Gavory and de Seze (2009). In the past decade, many studies on sloshing flows have been performed, especially by the International Society of Offshore and Polar Engineers (ISOPE); sloshing symposiums were organized several times to share and learn state-of-the-art sloshing physics.

The sloshing problem has been understood to be a stochastic phenomenon. Therefore, a statistical analysis is essential to assess sloshing loads, and numerous studies have been conducted to evaluate sloshing loads based on experimental methods (e.g., Kuo et al., 2009; Kim et al., 2012). Conventional experiments, however, have technical and practical limitations. Pressure sensors are too large for a model scale, and the results only focus on the pressure caused by the free surface, without providing kinematic information about the fluids in a model tank (Ahn et al., 2012).

To identify the relationship between velocity and pressure for sloshing impact phenomena, several particle image velocimetry (PIV) experiments have been conducted. Lugni et al. (2006) investigated the sidewall impact flows of the tank with flip-through and analyzed the velocity distribution and impact pressure based on the synchronized measurement. Ahn et al. (2012) studied vibratory characteristics of the velocity, acceleration, and pressure around the top of a tank when the impact with trapped air pockets occurred.

Many numerical studies on sloshing flows have also been reported and are still being conducted. Furthermore, there are numerous papers and applications that use various numerical methods (e.g., Kim, 2001; Kishev et al., 2006; Gazzola and Diebold, 2013; Zhao and Chen, 2015). Kim (2001) pointed out that the pressure will diverge as grid spacing and the time segment become zero when the free surface hits the top of a tank. Also, a time-averaging method over several time steps was applied to obtain more continuous impact pressure signal. Apart from this, Gazzola and Diebold (2013) utilized computational fluid dynamics (CFD) as a screening tool to identify the impact spots based on the flow velocity. Conventional numerical methods provide reproducible results in terms of the global kinematics even when a coarse grid and simple modeling are applied. However, conventional numerical methods are not yet accurate enough to predict the impact pressure at the top of a tank in a high filling case because the sloshing impact pressure is highly localized in space and time.

In the present study, a sloshing model test with PIV measurement was conducted, and the sloshing impact characteristics around the top of the tank were compared to those derived using two different CFD methods for solving an incompressible two-phase flow. PIV measuring equipment (Kim et al., 2014) that is synchronized with a pressure measurement system at an experimental sloshing facility at Seoul National University (SNU) was used in this study. In numerical computations, two different codes, in-house code and STAR-CCM+ commercial software (CD-adapco, 2014), were applied. The present in-house code was based on the results of previous research (Yang et al., 2010), where the governing equation was solved by using a finite difference method and constraint-interpolation-profile (CIP) method in a Cartesian grid. To capture the interface between the air and water, the tangent of hyperbola for interface capturing (THINC)

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