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Simulation of Liquid Sloshing in Model LNG Tank Using Smoothed Particle Hydrodynamics

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The Smoothed Particle Hydrodynamics (SPH) method is applied to the problem of modeling sloshing in a 2-D water model that is a representation of a scaled LNG tank. Two different tank configurations are considered with 2 fill levels (20%, 70%) and 2 different oscillation amplitudes (10% and 20% of the tank dimension). Predicted pressure signals are compared to experimental measurements. The peak pressure values predicted in the simulations are generally lower than the experimental values, although they are the correct order of magnitude. While the stochastic nature of the oscillations in practice means that an exact match between simulation and experiment is not feasible, the statistics of the pressure signals allow a more meaningful comparison. Also presented are ensemble-averaged pressure traces and standard deviations of the pressure from the simulation results and a sub-set of the experimental results, and these show generally higher variability in the pressure signals for low fill ratios compared to high fill ratios. There is generally good agreement between the simulation and experimental ensemble mean and standard deviation results. The magnitude of fluctuations is also sensitive to the sensor location. SPH is seen to distinguish between the different flow cases; it provides results for the peak pressures that are the correct order of magnitude on average, although the highest peaks are underpredicted. It is a natural numerical technique for coupled fluid-structure problems with large free-surface deformations.

INTRODUCTION

Sloshing in partially filled LNG tanks can arise under different wave conditions when loading and/or unloading LNG from a tanker ship, when tankers must disengage part way through offshore loading due to approaching adverse weather conditions, or in FPSO under normal operating conditions. Sloshing may resonate with the frequencies of wave-induced ship motions and may resonate with structural frequencies. This in turn can affect ship stability and, of particular importance here, can produce large loads on the internal walls of the tank, potentially leading to structural damage to tank membranes and insulation, leakage and, in the worst case scenario, tank rupture.

Small-scale physical experiments can be undertaken with water or other fluids and then scaled up to full size to predict tank loadings under different wave conditions and fill levels. However it is highly desirable to have robust computational tools that provide accurate estimates of loadings under different conditions. Not only do computational methods allow a quick turnaround for investigating different tank geometries, wave conditions and fill levels, but it is also possible to apply the correct equations of state for liquid LNG. The use of LNG in experiments is problematic due to the difficulty in making measurements at very low temperatures as well as the significant safety issues when using liquid LNG.

The nonlinearity of fluid motions when the forcing amplitude becomes large combined with the possibility of free-surface overturning, fragmentation and entrainment of a gaseous phase all indicate that simplified computational approaches (e.g. potential flow methods) are inadequate in the general sloshing case. Thus an appropriate numerical method must be able to handle arbitrary, complex free-surface behaviour. Two main classes of methods are able to handle such complexity:

1. Interface capturing techniques: Examples are Volume-of-Fluid (VOF) originally developed by Hirt and Nichols (1981) and Level Set methods, Sussman et al. (1994)); and,
2. Smoothed Particle Hydrodynamics (SPH), originally developed by Gingold and Monaghan (1977) and then extended to free-surface incompressible flows by Monaghan (1994).

A number of numerical investigations of sloshing has recently appeared, including Wemmenhove et al. (2007), Jung et al. (2008), Schreier and Paschen (2008), Singh et al. (2008) and von Bergheim and Thiagarajan (2008). Most of these studies use either commercial software (CFD/Fluent/MSc.Dytran) coupled to a VOF technique or purpose-built VOF codes such as the ComFlow code (Gerrits and Veldman, 2003).

Here we apply the Smoothed Particle Hydrodynamics (SPH) technique to model the 2-D sloshing systems specified in Kim et al. (2009). These systems were thin-slice scaled water models that were instrumented to allow measurement of pressure signals in the tank.

NUMERICAL METHOD

SPH is a computational technique that has been widely applied to industrial and environmental flows (e.g. Cleary, 1998; Cleary and Prakash, 2004). It has more recently been applied to oceanic and offshore hydrodynamics (e.g. Gomez-Gesteira, 2005; Shao, 2006; Cleary and Rudman, 2009).

Unlike most numerical techniques for Computational Fluid Dynamics, SPH does not utilize a fixed nodal grid. Instead, the grid is replaced by a set of moving particles on which the discretised equations are solved. Each particle carries mass, momentum and energy and moves with the local fluid velocity. There is no explicit connectivity of the particles, which means, for example, that particles that are close neighbours at one instant in time can be quite distant from each other at a later time. Also, because the particles are transported with the local fluid velocity, the nonlinear

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KEY WORDS: Sloshing, LNG, tank, pressure, Smoothed Particle Hydrodynamics (SPH).