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Numerical Simulation of Liquid Sloshing in LNG Tanks Using a Compressible Two-Fluid Flow Model

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ABSTRACT

In this investigation the Reynolds-Averaged Navier-Stokes (RANS) equations are modified to account for variable density and viscosity of the two-fluids flow (i.e. water-air), assuming both fluids compressible. By introducing a preconditioner, the governing equations in terms of primitive variables are solved for both fluids in a unified manner. The non-conservative implicit Split Coefficient Matrix Method (SCMM) is modified to approximate convective flux vectors in the dual time formulation. The free surface waves inside the tank, due to sloshing, are implicitly captured by using a level set approach.

The method is illustrated through applications to rectangular and chamfered tanks subject to sway or roll motions at different filling levels and excitation conditions (i.e. amplitude and frequency of oscillation). Comparisons are made between calculated and experimental pressures, where available.

KEY WORDS: Sloshing, impact pressure, compressible interface flow, level set method, LNG tank.

INTRODUCTION

The Liquefied Natural Gas (LNG) carrier is often dubbed as the pearl of the shipbuilding industry as the technology required is very demanding and complicated. Due to energy demands, increasing numbers of LNG carriers are required. The need for larger cargo capacity, coupled to the demand for more flexible operations, provide the stimulus for design changes in these vessels. There are, by and large, two types of LNG carrier tanks, namely Moss-type and membrane-type. Since LNG vessels with membrane type tanks are often the first choice for new very large vessels and as, unlike the Moss-type tanks, they experience large sloshing pressures on tank boundaries, the issue of sloshing induced pressure loads in membrane tanks has become more important than ever. The possibility of sloshing damage has already attracted much attention in the LNG industry today.

In the case of shallow filling and severe sea-induced motions a hydraulic jump forming a vertical front may be generated, resulting in very large impacts on tank walls. On the other hand, in a nearly full tank, the excited progressive wave may cause high stresses acting on its roof (Mikelis et al, 1984). The fluid impacts on the tank walls and roof are extremely localized in time and space because of the large temporal and spatial pressure gradients. Due to the very short duration of the impact pressure the accurate and stable assessment of the impulsive impact load remains a challenging task (Arai et al, 2002). Over the past few decades great efforts have been made to estimate numerically sloshing-induced pressure loads exerted on tank walls and roof, with increasing accuracy of tracing or capturing highly nonlinear free surface configurations such as wave overturning, breaking and merging. The numerical techniques most used include Marker and Cell (MAC) (Armenio and Rocca, 1996), Volume of Fluid (VOF) (Wemmenhove et al, 2007), Level Set (LS) (Price and Chen, 2006; Chen et al, 2009) and Smoothed Particle Hydrodynamics (SPH) (Delorme et al, 2009) methods.

Experiments (e.g. Rognebakke and Faltinsen, 2005; Lugni et al, 2006) have revealed that the compressibility of air has significant effects on impact pressure as trapped air, depending on the dimensions of air bubbles, may prolong the duration of the impact peak and change its magnitude. A mathematical model including gas compressibility is expected to result in better understanding and more accurate predictions of sloshing induced impacts.

It is customary to model compressible two-phase flow by employing the fully compressible Navier-Stokes equations and a different equation of state for each phase. The change in equations of state, due to the difference of their specific heat ratios, is known to cause spurious pressure oscillations in numerical solutions for compressible multi-fluids flow in conservative form near the interface (Koren et al, 2002). In addition, the standard methods adopted to solve compressible flows, based on hyperbolic conservation laws, are neither numerically robust nor efficient in the case of low Mach numbers (Turkel, 1999). In this investigation a preconditioning technique is introduced to solve low speed compressible two-fluid flows occurring in liquid sloshing in an enclosed container. The non-conservative implicit Split Coefficient Matrix Method (SCMM) is modified to approximate convective flux vectors in a dual time formulation. The level set formulation is employed to implicitly capture free surface waves generated due to sloshing. The mathematical model, including compressibility, is applied to rectangular and chamfered tanks, at different filling levels, subject to externally imposed sway or roll motions. Numerically predicted