Accurate Prediction of Violent Slosh Loads via a Weakly Compressible VoF Formulation

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ABSTRACT
The standard CFD scheme used today for the purpose of slosh loads predictions is based on an incompressible type volume of fluid (VoF) scheme. This however results in over-predicted pressure spikes and slow simulations due matrix conditioning in the case of violent slosh. In a recent review article Ibrahim (2020) further postulates the importance of accounting for gas compression in quantifying pressures due wave impact. We have therefore furthered the development of a novel weakly compressible ELEMENTAL® formulation for the accurate modelling of violent slosh loads. New developments include the introduction of a momentum conservative HiRAC VOF scheme as well as accounting for surface tension effects via higher order accurate height functions Ilangakoon et al. (2020). The developed modelling capability was proven via application to simulating two violent slosh experiments viz. lateral and verticle slosh in the presence of gravity. Particularly high accuracy was demonstrated, where the L2 error norm in the latter case was less than 2%. It was further shown that accounting for gas compressibility in a weak sense reduces predicted pressure peaks by up to 50% while the solver was 7 times faster to run. This is seen as a key development for more effective slosh impact design.

KEY WORDS: VoF; Weakly Compressible; Surface Tension; CSF; Height Functions.

INTRODUCTION
Violent slosh is of key concern to a range of applications due the high pressure loads involved. These range from ship tanker designs and aircraft fuel tanks to breakwater mitigation structures. The peak pressures due impacting waves remain a challenging phenomenon due it involving a range of interrelated physics. A recent seminal article devoted to this topic by Ibrahim (2020) postulates the importance of not only the liquid motion but also the compressibility of the gas. To date however incompressible VoF is the standard method for violent slosh simulations. This can result in the prediction of unrealistic pressure spikes and matrix ill conditioning (long solution times).

As such, we employed a weakly compressible formulation Heyns et al. (2013b) in this article in combination with the HiRAC Heyns et al. (2013a) compressive VoF interface capturing scheme. The citations however were limited in applicability to violent slosh due a non-conservative momentum implementation while accurate surface tension modelling was not employed. This is key particularly when Rayleigh-Taylor instability drives the mode of the first liquid impact as is the case with verticle slosh cases.

To address the cited shortcomings, this article describes a formulation for the accurate prediction of violent slosh related impact loads. The key components include a weakly compressible gas formulation (in conjunction with incompressible liquid), momentum conservative HiRAC and accurately accounting for surface tension via a recently developed higher-order surface tension formulation Ilangakoon et al. (2020). The resulting simulation framework is implemented into the ELEMENTAL® software and applied to modelling two violent slosh experimental benchmark test-cases. The first involves lateral excitation and the second verticle. High accuracy and computational efficiency were demonstrated.

GOVERNING EQUATIONS
The governing equations describe, for a weakly-compressible gas coupled with an incompressible liquid, the conservation of momentum, volume fraction and mass:

\[
\frac{\partial \rho u}{\partial t} + \nabla \cdot \rho u \otimes u = -\nabla p + \nabla \cdot \mu \left(\nabla u + \nabla u^T\right) + \rho a
\]  
\[\frac{\partial \alpha}{\partial t} + \nabla \cdot \alpha u = 0\]  
\[\frac{1 - \alpha}{\rho^e} \frac{1}{c_s^e} \frac{\partial p}{\partial t} + \nabla \cdot u = 0\]

where \(u\), \(p\) and \(a\) are the fluid velocity, pressure and domain/tank acceleration. Further, \(c_s\) is the acoustic velocity for the gas phase . The fluid density and viscosity are represented by \(\rho\) and \(\mu\). For two phase modelling the VOF fraction is denoted \(\alpha\) such that fluid propertie \(\phi\) is defined by