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Numerical modelling of variability in liquid impacts

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Introduction

Transport of liquefied natural gas (LNG) in LNG carriers yields a flexible delivery method for NG. The LNG is contained in large membrane tanks with a capacity of up to 40 000 m^3 as shown in Figure 1, where each LNG carrier may have up to four such tanks. There is ample opportunity for sloshing during transport, which means that the design of LNG tanks requires the prediction of pressures resulting from breaking wave impacts. Such impact pressures are often obtained using Froude scaled impact pressures from small-scale experiments (typically at scale 1 : 40), which unfortunately result in scaling biases, as we will now discuss.

When considering a breaking wave, the heavy liquid pushes the much lighter gas out of the way, resulting in a shear layer at the interface between the two fluids. Depending on the value of the nondimensional Weber number, which is a measure of the relative importance of inertia over surface tension, this may result in a Kelvin–Helmholtz (KH) instability: in this case the destabilizing influence of inertia dominates over the stabilizing capillary force. This instability leads to fragmentation of the interface, as is shown in Figure 2, and thus yields a high variability of impact pressures. The use of Froude scaling, however, implies that the Weber number is underestimated in the small-scale experiments.

This results in the aforementioned scaling bias: a smaller value of the Weber number implies that fewer KH instabilities are present, thereby resulting in less fragmentation of the interface. In the 'sloshing of liquefied natural gas' (SLING) project, the aim is to improve our understanding of the physical phenomena that are responsible for scaling biases in breaking wave impacts. Numerical simulation methods are used in this thesis to study breaking wave impacts in 3D, including the effects of KH instabilities. Due to the vast range of length and time scales, this is a challenging task which requires the development of novel numerical methods.

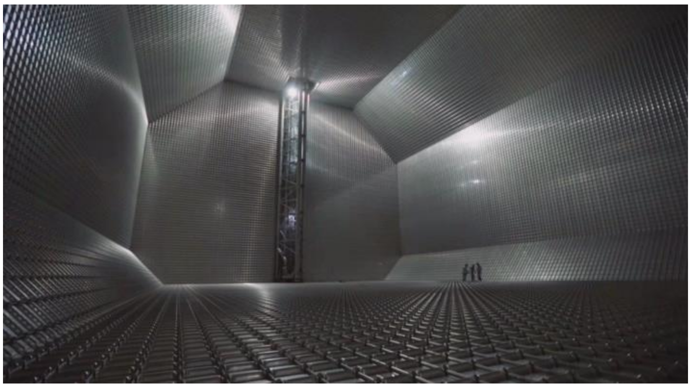


Figure 1. The interior of a Mark III LNG membrane tank.

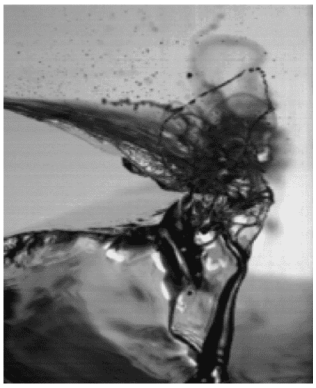
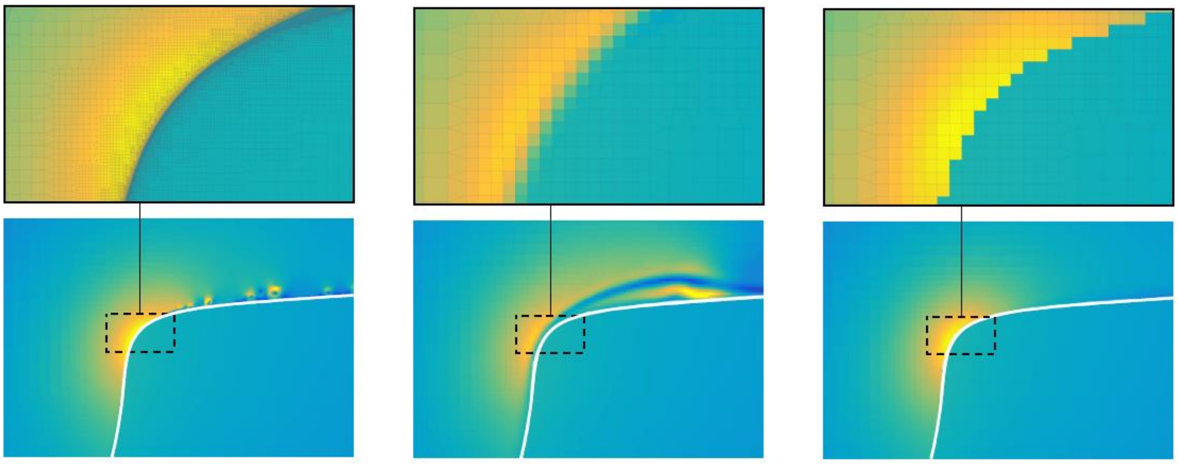


Figure 2. Experiment at scale 1 : 6.



a. Fine mesh & one-velocity. *b. Coarse mesh & one-velocity.* *c. Coarse mesh & two-velocity.*

Figure 3. The velocity magnitude at the wave crest of a 4 m long breaking wave. The 'fine' mesh yields a resolved shear layer with h ≈ 0.1 mm whereas the 'coarse' mesh corresponds to h ≈ 3.1 mm (32 times larger).

Methodology

The fluids are modelled as immiscible, incompressible and Newtonian. As we deem conservation properties of importance, we use the finite volume method on an adaptive mesh for the discretization of the resulting two-phase Navier–Stokes equations. The methods are implemented in our in-house ComFLOW code.

Transport of mass and momentum. We utilize the dimensionally unsplit geometric volume of fluid (VOF) method to advect the interface, wherein the interface is implicitly represented using the liquid volume fractions. This results in a sharp representation of the interface. Computation of the volume fluxes requires so called donating regions, for which we have derived simple conditions that guarantee boundedness of the volume fraction field, thereby no longer needing a fluid redistribution scheme. The transport of momentum is done using the same volume fluxes used for mass transport. Our approach differs from the literature in the way the staggered momentum field is transported: we introduce an efficient algebraic interpolation of the fluxes, resulting in exact mass and momentum conservation, while obtaining semi-discrete convective conservation of kinetic energy.

Modelling of surface tension. As motivated in the introduction, we want to numerically model the KH instability, which means that the balance between inertia and surface tension must be accurately captured. We use a surface tension model based on sharply imposing the Young–Laplace equation, which is achieved using a well-balanced ghost fluid method (GFM) where the interface curvature is approximated using local height-functions. Our analysis of the geometric VOF method explains why the interface curvature does not converge under mesh refinement whenever a piecewise linear approximation (PLIC) of the interface is used, resulting in spurious currents despite using a well balanced method. We propose to use a piecewise parabolic interface approximation instead, for which we show that the interface curvature does converge under mesh refinement. This results in a complete mitigation of spurious currents, also for unsteady problems.

Modelling of the shear layer. Viscous effects play a role at the interface between the fluids, resulting in a shear layer which is thin compared to our length scales of interest, and therefore expensive to resolve. We propose to model this shear layer with a tangential velocity discontinuity, resulting in a novel and truly sharp two-velocity model. In Figure 3 we show the efficacy of this approach: the simulation of a breaking wave is considered, where we use the one-velocity model on either a fine or coarse grid (the mesh size is 32 times larger), and the two-velocity model on the coarse grid. These results show that whereas the one-velocity model results in an artificial thickening of the shear layer, the two-velocity model instead accurately approximates the unresolved shear layer with a velocity discontinuity.

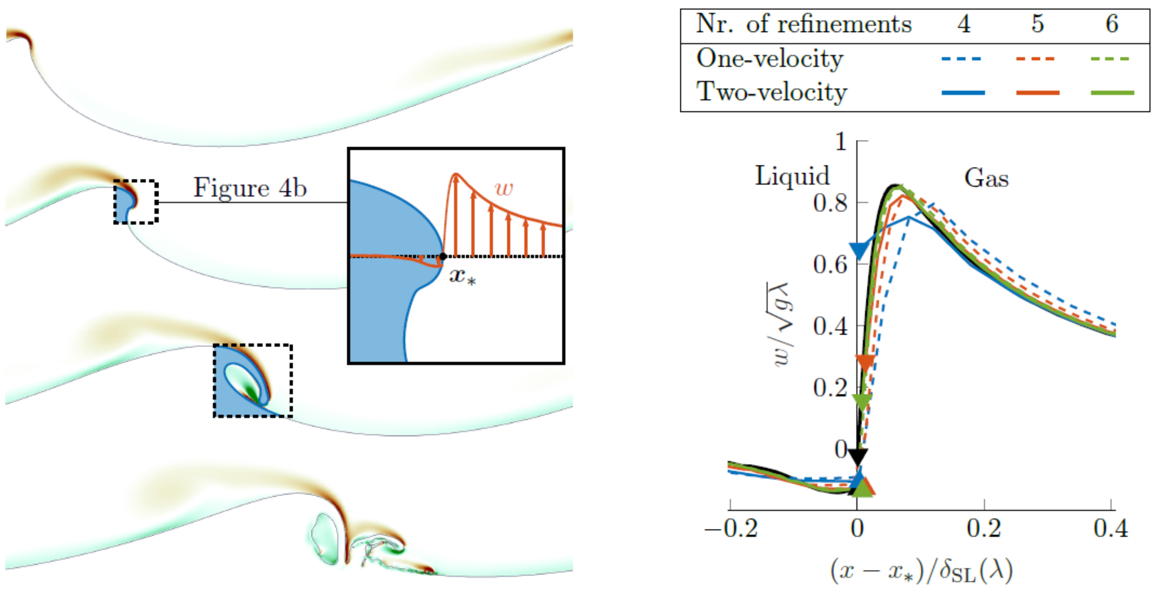


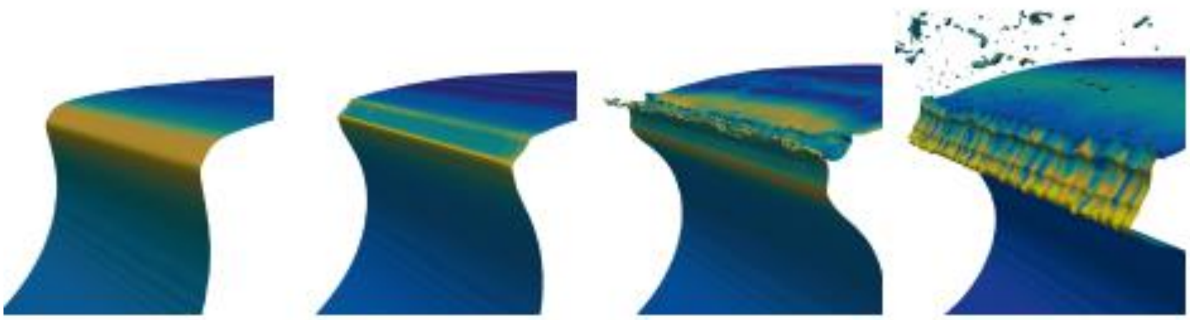
Figure 4. Two-dimensional simulations of a third-order Stokes wave.

Results

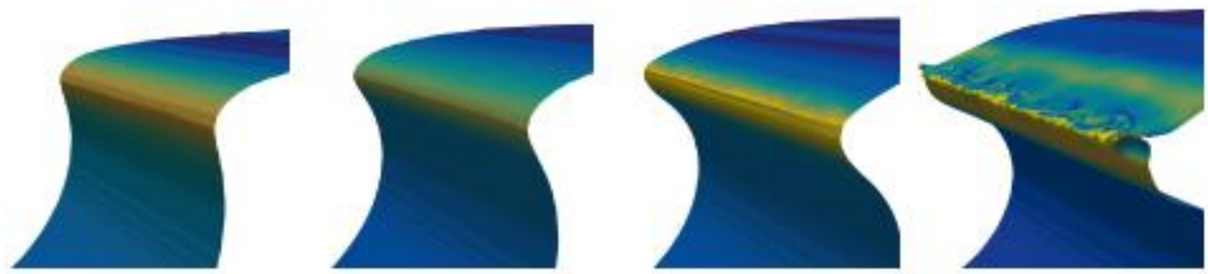
The proposed numerical methods have been thoroughly validated using many academic test problems, one of which is the simulation of a low Reynolds number third-order Stokes wave as shown in Figure 4a. In Figure 4b we show the velocity tangential to the interface as a function of the interface normal distance, at the position indicated in the boxed inset of Figure 4a (which is inside the shear layer). This result shows that both the one- and two-velocity model converge to the same solution under mesh refinement, and moreover illustrates that the velocity in the gas phase converges faster when the two-velocity model is used. Note that the tangential velocity discontinuity present in the two-velocity model, as indicated by the triangular markers, vanishes under mesh refinement.

The two-velocity model was applied to several high Reynolds number wave impact problems. In particular, the scaling bias due to surface tension was investigated by simulating a 3D large gas pocket impact at two geometrical scales. The evolution of the crest shape is shown in Figure 5, where we compare simulations done at scale 1 : 10 and 1 : 20. As discussed in the introduction, such a comparison yields an underestimated Weber number at the smaller scale. Indeed, we see that instabilities arise later in time and a larger scale (after Froude scaling) when the smaller scale simulation is considered. Furthermore, we find that the wavelength of the spanwise instability at scale 1 : 10 compares very well to theoretical predictions. These results could only have been obtained using our proposed two-velocity model, as using a standard one-velocity model would have been computationally too expensive, especially in 3D.

In conclusion, we find that the proposed numerical methods are able to capture variability of wave impacts, and therefore yield a valuable tool in the design of LNG tanks.



a. At scale 1 : 10.



b. At scale 1 : 20.

Figure 5. The interface coloured by the magnitude of the gas velocity, resulting from the 3D wave impact problem at two scales, in the frame of reference of the wave tip.

Acknowledgements

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