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Numerical Study of the Influence of Weber and Reynolds Numbers on the Development of Kelvin–Helmholtz Instability

Simon Fortin, Stéphane Etienne*, Cédric Béguin and Dominique Pelletier
Ecole Polytechnique de Montréal
Montréal, Québec, Canada

Laurent Brosset
GTT (Gaztransport & Technigaz)
Saint-Rémy-lès-Chevreuse, France

Sloshing model tests or wave impact tests in flumes show large variability of local impact pressure measurements. One of the reasons for such variability is the generation of free surface instabilities by the shearing gas flow at the free surface just before the impacts. To better understand the first steps of the development of free surface instabilities around the crest of breaking waves, a bi-fluid, high-fidelity front-tracking software based on the Navier–Stokes equations has been developed. Named CADYF, this software simulates separated two-phase incompressible viscous flows with surface tension. The numerical method uses adaptivity in space (adaptive remeshing) and time (hp-adaptivity) to yield accurate predictions while keeping computational cost low. As a first application, a simple experiment carried out by Thorpe, which enabled the generation of Kelvin–Helmholtz instability in a rectangular tube completely filled with two liquids of different densities, is simulated. Numerical results are compared with experimental results and other simulations. A parametric study is performed varying surface tension and fluid viscosities at a constant viscosity ratio. The evolutions of the main parameters describing the Kelvin–Helmholtz instability are provided in dimensionless form, giving some clues about the scaling process.

INTRODUCTION

The context of the present study is the sloshing assessment of liquefied natural gas (LNG) tanks on floating structures based on sloshing model tests. The model tank, most of the time at scale 1:40, is put on the platform of a six-degree-of-freedom motion generator. The liquid inside the model tank is water; the ullage gas is a mixture of sulfur hexafluoride (SF_6) and nitrogen tuned in order to keep the gas-to-liquid density ratio equal to that of natural gas (NG) and LNG. The excitations are downscaled from ship motions calculated at scale 1 with a boundary element method (BEM) according to Froude scaling. Numerous pressure sensors, arranged in rectangular arrays, are placed in the locations submitted to liquid impacts. All conditions (i.e., sea states, loading cases and speeds of the floater, incidences of the wave with regard to the floater, and filling levels) the floating structure is expected to encounter during its life are studied. Long-term distributions of pressure peaks are built for different sizes of the loaded area, mixing all conditions with an estimated probability of occurrence.

Because of the high variability of the local pressure measurements, the conditions, especially those that are contributing the most, are needed to be tested many times in order to build a converged long-term pressure peak distribution. This leads to sloshing model tests running night and day for many weeks (at least seven for Gaztransport & Technigaz (GTT)) to perform a reliable sloshing assessment.

Although the sources of variability of the local pressure during sloshing model tests are crucial to master the resulting statistics, they have not been studied much. According to Frihat et al. (2016), the variability of the local pressure measurements is due to the variability of the flow, and three main sources of variability may appear during a sloshing model test:

- The development of free surface instabilities triggered by the shearing gas flow, especially before impact, when the gas between the wave and the wall is pushed away by the liquid
- The fall of liquid droplets onto the interface after splashing, leading to a highly perturbed interface just after an impact
- The production and evolution of random distributions of bubbles within the liquid

All these sources of variability are generated by gas-liquid interactions during wave breakings and liquid impacts. They are strongly related to the surface tension (Frihat et al., 2017) and the viscosity in both fluids. As surface tension and viscosities in both fluids are much larger at model scale than the ideal values for a complete similarity with scale 1, the statistics from model scale are directly biased with regard to what would be obtained at scale 1, even disregarding the other biases as a result of other unscaled properties (for instance, liquid and gas compressibility).

For irregular excitations, the variability of the flow is not only local. The global wave shapes start to vary after a few impacts but with limited variations: regularization processes such as viscous dissipation and a lock-in phenomenon resulting from the forced motions prevent a complete deterioration of the global flow and preserve the synchronism of the impacts (Karimi et al., 2015).

For a single impact wave (SIW), as generated in a flume tank by a wave maker with a focusing process or during two-dimensional (2D) sloshing model tests by a short back-and-forth sway motion of the sloshing rig, the liquid is initially at rest, and the only

*ISOPE Member

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KEY WORDS: Sloshing, wave impact, LNG containment system, breaking wave, free surface instability, Kelvin–Helmholtz, surface tension, viscosity.