LS-DYNA® R7 : Free Surface and Multi-phase Analysis for Incompressible Flows

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Abstract

LS-DYNA R7 introduced an incompressible flow solver which can track flow interfaces such as free surfaces or the interface between two fluids. Several industrial applications may be simulated with these features. In the area of free surface flows the effects of the lighter phase are neglected, i.e. in the case of water-air interfaces the air could be ignored if its effect does not change significantly the dynamics of the water phase. Some typical problems are wave propagation, dam break, sloshing problems and green water on decks. On the other hand problems where both phases should be taken into account are mixing problems, bubble dynamics and lubrication problems among others. In this work examples of both problems will be presented and explained. The set up process as well as the post processing will be detailed. Validation examples will be shown and compared to analytical or experimental solutions. Finally the current development status for some of the multiphase features will be discussed.

Introduction

A common problem that arises in industrial design is that involving immiscible fluids that can collide, exchange heat, impact into structures and generally speaking change their interface geometry and topology as the flow develops. These kinds of problems have been widely studied in numerous scientific applications and there exists well known methodologies that provide robust and accurate tracking of the interfaces. A common approach which was implemented in the incompressible CFD (ICFD) solver in LS-DYNA is the one that involves the tracking of level sets [1]. In what follows a brief introduction of the method will be presented as well as some detail regarding the set-up of such a problem in an LS-DYNA input deck. Finally two validation problems are presented, one for free surface and the other one for a two phase problem.

The Level Set Method

The level set method uses a scalar field which provides an implicit representation of the interface where the value of the level set $\phi = 0$. The level set function is advected using the following Eikonal equation:

$$\frac{\partial \phi}{\partial t} + u\frac{\partial \phi}{\partial x} = 0$$

where u is the fluid velocity. In the ICFD solver the level set ϕ is the distance function to the interface. Clearly a maximum of two fluids can be represented with this approach, one taking the positive side of the level set and the other the negative.

The material properties of the fluids such as density and viscosity are recovered using:

$$\rho = \rho_1 \, H(\phi) + \rho_2[1 - H(\phi)]$$

$$\mu = \mu_1 \, H(\phi) + \mu_2[1 - H(\phi)]$$

where $H(\phi)$ is a regularized Heaviside function defined as:

$$H_\epsilon = \begin{cases} 0 & \text{if } \phi \leq -\epsilon \\ 0.5(1 + \phi/\epsilon + 1/\pi \sin(\phi \, \pi/\epsilon) & \text{if } |\phi| < \epsilon \\ 1 & \text{if } \phi > \epsilon \end{cases}$$

Important aspects of a free surface / multi-phase input deck and post-processing

The input decks used to define a free surface or a two-phase problem have two main difference to those defining a regular CFD problem. The first deference resides in the mesh. Although a single volume mesh is used for the two phase problem an interface mesh needs to be provided defined by the keyword *MESH_INTERF. The interface mesh defines the initial level set at time t=0 with $\phi = 0$. The element size of this mesh is important since the volume mesh will respect this size when the volume elements are created.

The other important aspect of a level set approach is the material definition. Two material keywords will be defined in an input deck with free surface or with two phase fluids using the standard *ICFD_MAT keyword. In the case of free surface one of the materials, the one normally identified as air will be defined as void simply by setting the second field or the density to zero. In the case of two phases both materials will have the physical properties of each phase.

After running the simulation LS-PrePost® may be used for post-processing the results. Apart from the regular fields like velocity, pressure, etc. the user may need to study the position of the interface like the free surface or the boundary between two fluids. In LS-PrePost this is done by using the *Assembly and Select Part* tool located in the *Model* menu, SelPart button (see figure 1). Once in this menu click on the check-box named *LevelSet* and a new part will be created, in this case named *3 Levelset.* Activating this part will show the interface surface in the model.

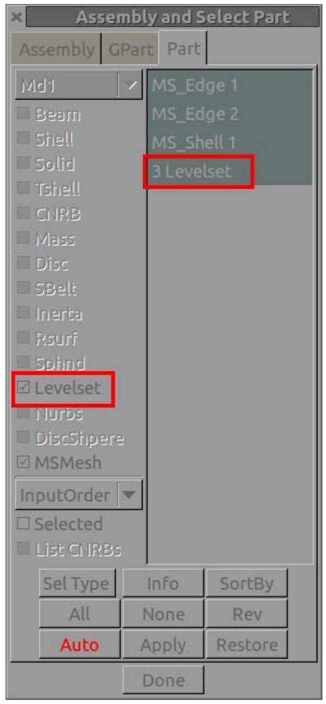

Figure 1: Assembly and Select Part windows used to create the level set part.

Validation Problems

Free surface: Sloshing Problem

In this validation test case, the periodic angular motion of a partially filled sloshing tank is considered [2,3,4,5]. The sketch of the tank is in figure 2.

Two filling levels will be considered corresponding to 18% and 70% filling tank level. The liquid studied is oil with material properties: $\rho = 990$ Kg/m^3, μ =0.045 kg (m s)$^{-1}$.

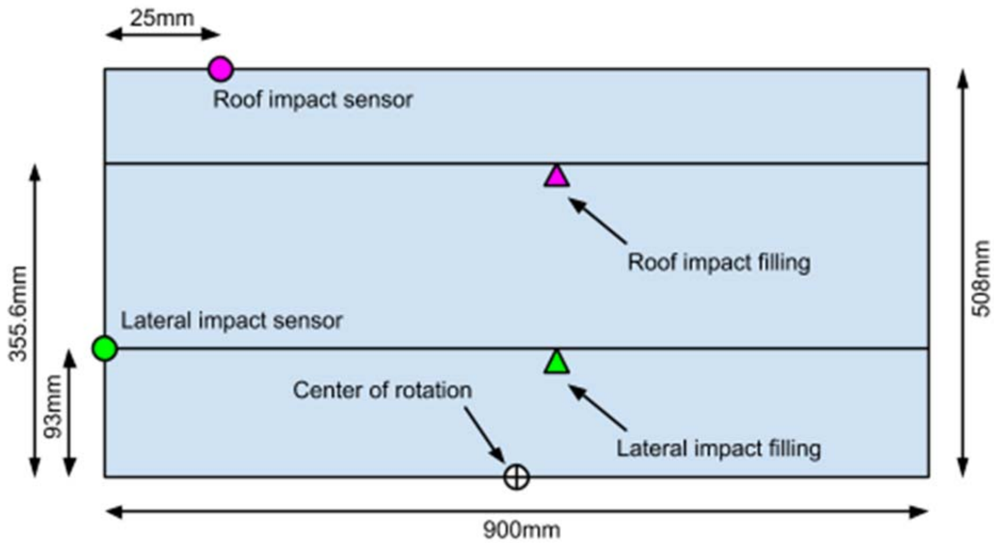

Figure 2: Sketch of the experimental set up.

Figure 3 shows the experimental set up of the sensors.

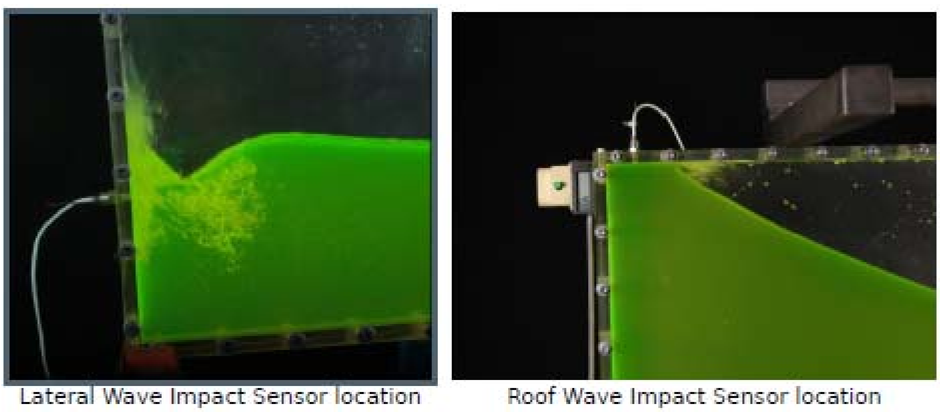

Figure 3: location of the sensors for the experimental set up.

The free surface location is shown in figure 4 where it is compared to the experiment. Close agreement is obtained.

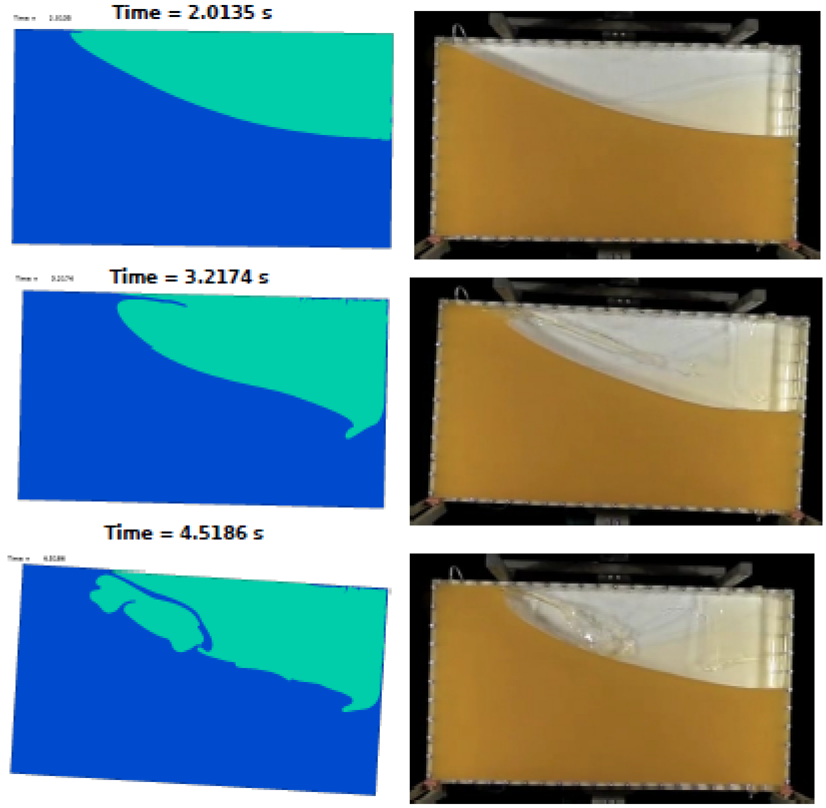

Figure 4: Free surface comparison with experiment.

The pressure values for the two sensors are observed in figure 5 and 6.

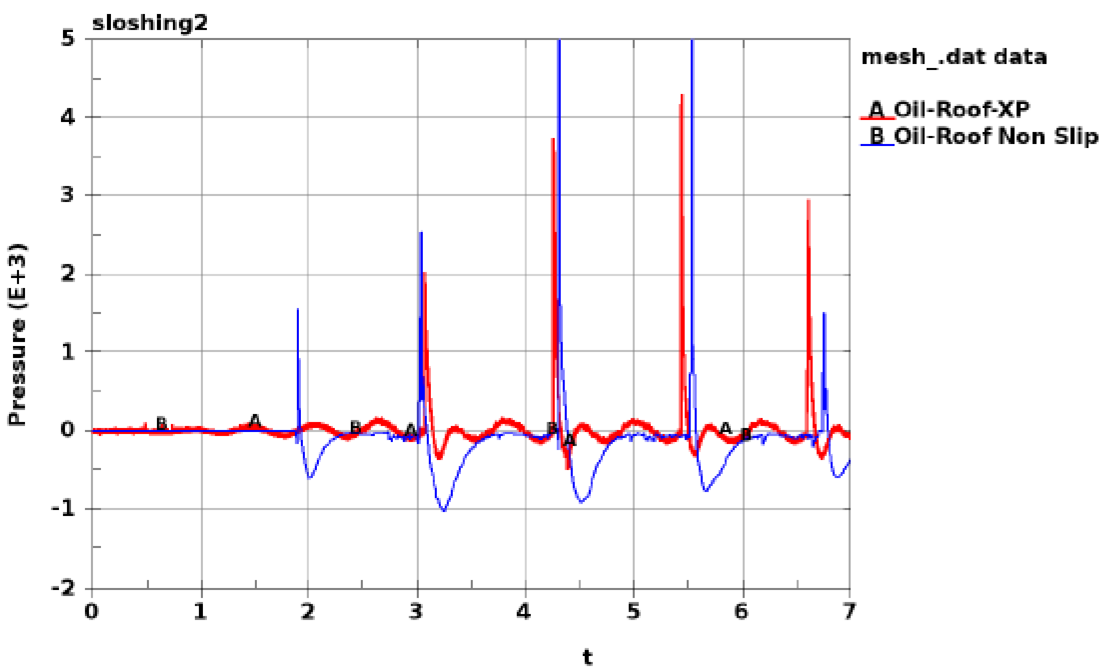

Figure 5: Pressure sensor at the Roof.

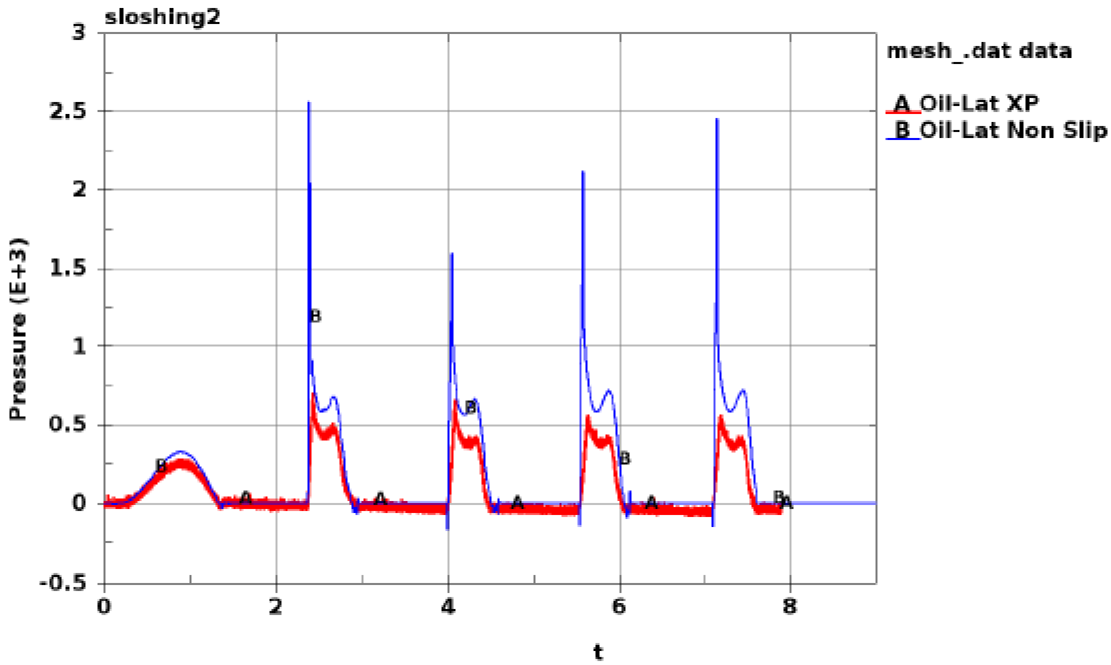

Figure 6: Pressure sensor at the Lateral wall.

Two phase: Rayleigh-Taylor Instabilities

This is a classical test first introduced by Puckett et al.[6] to validate two phase flows. A 1 m wide, 4 m high rectangular domain is discretized. The fluid densities are 1.225 and 0.1694 Kg/m^3. The fluid viscosity is 0.00313 kg/m/s. The interface between the fluids is an initially sinusoidal perturbation of amplitude 0.05 m and the heavier fluid is located on top (see first frame of Figure 7).

Figure 7 shows the evolution of the interface at times 0, 0.7, 0.8 and 0.9 s. which compares well with the results from Puckett et al[6].

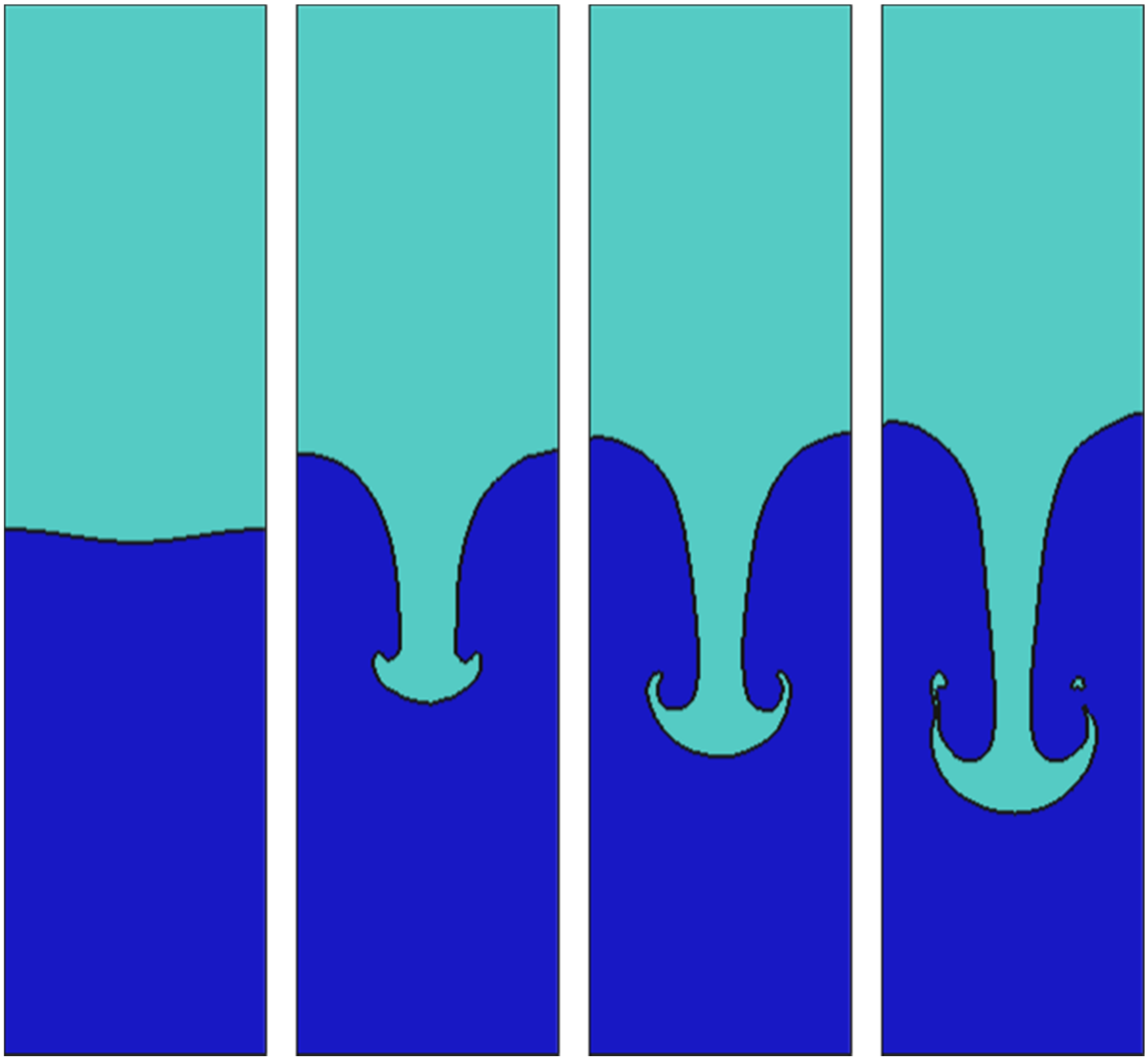

Figure 7: Rayleigh–Taylor instability for different time steps: t=0, 0.7, 0.8, 0.9.

Development Status

Currently the free surface feature is in production mode and it is available from the latest release. The two phase solver is currently in testing and validation stage. There will be two different approaches to this problem. The first one will be the one presented in this paper where Heaviside functions are used to regularize the interface. The other approach under development is the use of discontinues interpolation spaces to better capture the physics of multi-phase problems like surface tension effects and different fluid viscosity.

References

[1] S. Osher, J.A. Sethian, Fronts propagating with curvature-dependent speed: algorithms based on Hamilton–Jacobi formulations, Journal of Computational Physics 79 (1988) 12–49.

[2] S.-I. A, B.-V. E, M. A, and P.-A. F, A set of canonical problems in sloshing. part 0: Experimental setup and data processing. Ocean Engineering (submitted for publication).

[3] S.-I. A, A.-V. E, and A. G, Repeatability and two-dimensionality of model scale sloshing impacts., International Offshore and Polar Engineering Conference (ISOPE), (2011).

[4] B.-V. E, A.-I. A, A. G, and A. L, Three sph novel benchmark test cases for freesurface flows., 5th ERCOFTAC SPHERIC workshop on SPH applications, (2010).

[5] A. C. L, Delorme, S.-I. A, Z.-R. R, and B.-V. E, A set of canonical problems in sloshing. part i: Pressure field in forced roll. comparison between experimental results and sph, Ocean Engineering, 36 (2009), pp. 168-178.

[6] E.G. Puckett, A.S. Almgren, J.B. Bell, D.L. Marcus and W.J. Rider, ‘A high-order projection method for tracking fluid interfaces in variable density incompressible flows’, J. Comp. Phys., 100, 269–282 (1997).