Improvements of LS-DYNA ICFD's two-phase level-set solver

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1 Introduction

Numerical simulation of two-phase flows with interface capturing consists in solving a single set of Navier-Stokes equations with variable material properties. Here, we use the level set method for interface capturing [1]. That gives a simple representation of the interface – the level-set scalar field is continuous and allows easy access to geometrical properties at interfaces. That function evolves in time as it is transported by the flow velocity. As the velocity is not uniform in general, the level-set function may need be reinitialized while maintaining the position of interfaces. Numerical methods that are deployed to solve those problems must be chosen meticulously. Depending on the type of flow, advanced numerical techniques must be used to avoid unphysical motion of interfaces. Combinations of numerical methods have been tested on several benchmark tests.

2 Methods and keywords

In this work, the transport equation of the level set function is solved by using a Finite Element Method (FEM) or Semi-Lagrangian (SL) method [2]. Re-distancing of the level set function is done geometrically (Geo) or by doing a Reinitialization using Closest Points (RCP) [3]. The extra term that arises in momentum equations to account for surface tension effects is either based on a smoothed Dirac (D), smoothed Heaviside (H) [4] or Laplace-Beltrami (LB) formulation [5]. Results of benchmark tests obtained by using different combinations of advection, reinitialization and surface tension formulations are presented in the next section. The user may control new features from the following keywords.

`*ICFD_CONTROL_ADVECTION`

Set fourth field to 1 for SL advection of level set. The default is 0 for FEM advection.

`*ICFD_CONTROL_LEVELSET`

- Set seventh field on first line to 1 for linear approximation of level set gradient and curvature or 2 for least-squares computation of level set gradient. The default is 0 for use of standard gradient and divergence operators.
- Set eighth field on first line to 1 for smoothed Heaviside or 2 for Laplace-Beltrami surface tension formulation. The default is 0 for smoothed Dirac.
- Set first field on second line to 1 for RCP reinitialization. The default is 0 for Geo.

3 Some results

3.1 Rising bubble

This is a two-dimensional benchmark test reported in [6] wherein authors ran two cases of rising bubble with several solvers. Simulation parameters are gathered in Tab.1. Relevant dimensionless numbers are the Reynolds and Bond numbers.

Case	ρ_1	ρ_2	μ_1	μ_2	g	σ	Re	Bo
1	1000	100	10	1	0.98	24.5	35	10
2	1000	1	10	0.1	0.98	1.96	35	125

Table 1: Simulation parameters for rising bubbles.

3.1.1 Case 1

The element size is 1/40. The time step is 0.002. Reinitialization of the level-set function is done every 20 timestep. Qualitative results are shown in Fig.1. FEM-Geo-D yields parasitic oscillations on such a coarse mesh. Results obtained with any other method are qualitatively correct.

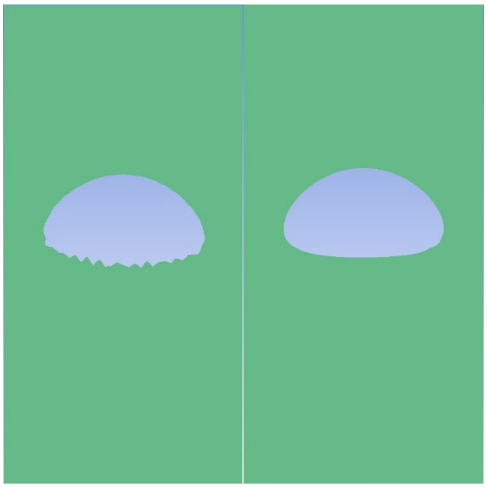

Fig.1: Interface shape at t=3. Case 1. Left is FEM-Geo-D. Right is SL-Geo-D.

The position of center of mass and volume loss at final time are shown in Tab.2. Results obtained by using SL advection are very close to those obtained in previous work [6].

	FEM-RCP-D	**SL-Geo-D**	**SL-RCPSL-D**
y	0.959	1.11	1.12
volume loss	-0.25%	-0.11%	-0.53%

Table 2: Position of center of mass and volume loss at t=3 for the rising bubble – Case 1.

3.1.2 Case 2

Element size and timestep are identical to Case 1. Qualitative results are shown in Fig.2: the Geo reinitialization seems to be more efficient in preserving thin structures than RCP, which requires a finer mesh here. The effect of the surface tension formulation has been tested and has not shown significant difference in the results. Quantitatively, the position of the center of mass obtained at t = 3 is equal to 11.5 for all methods tested here and the volume gain is below 1%.

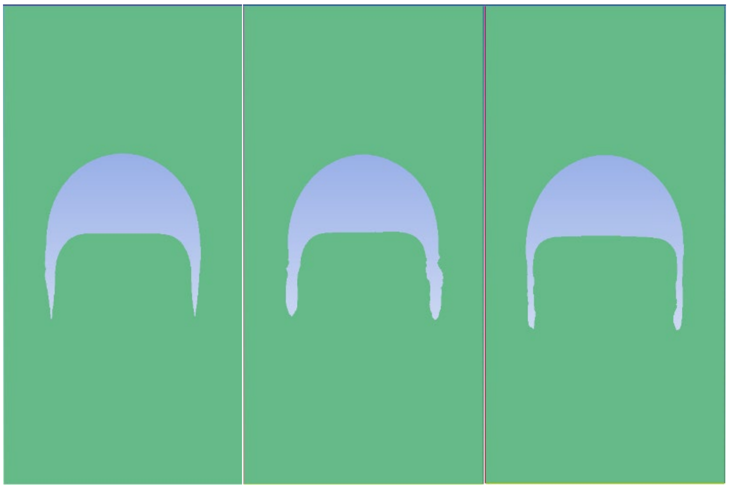

Fig.2: Interface shape at t=3. Case 2. Left is SL-Geo-H on mesh 1/40. Center is SL-RCP-H on mesh 1/40. Right is SL-RCP-H on mesh h=1/80.

3.2 Translating bubble

This test aims at quantifying parasitic velocities, also called spurious currents. These are mainly due to the numerical methods that are used to represent capillary effects and to compute the curvature. In [7], authors simulated the translation of a two-dimensional bubble in a channel with an initial velocity U. By imposing free slip at bottom and top boundaries, the motion should persist, and the velocity field should remain equal to its initial value. The Weber number is set to 0.4. The Laplace number is set to 120. The computational domain is 10D in length and 2.5D in height, with D the bubble diameter. Reinitialization of the level set function is done when max(1-|∇φ|) > 0.1. In Fig.3, qualitative results obtained with FEM advection are not satisfactory on such a coarse mesh, unlike using SL advection. Quantitative results are shown in Fig.4: the magnitude of parasitic velocities is reduced with RCP compared to Geo.

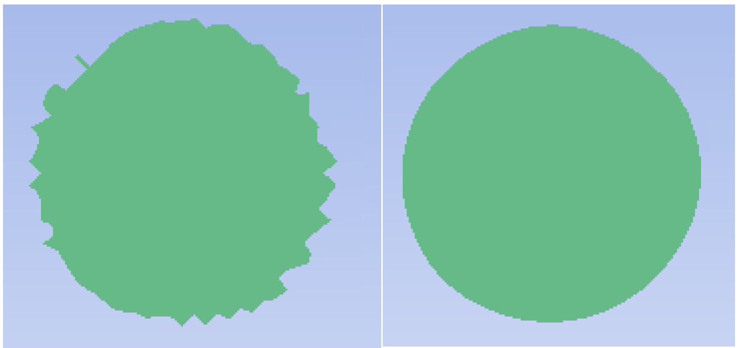

Fig.3: Bubble shapes obtained with FEM advection (left) and SL advection (right).

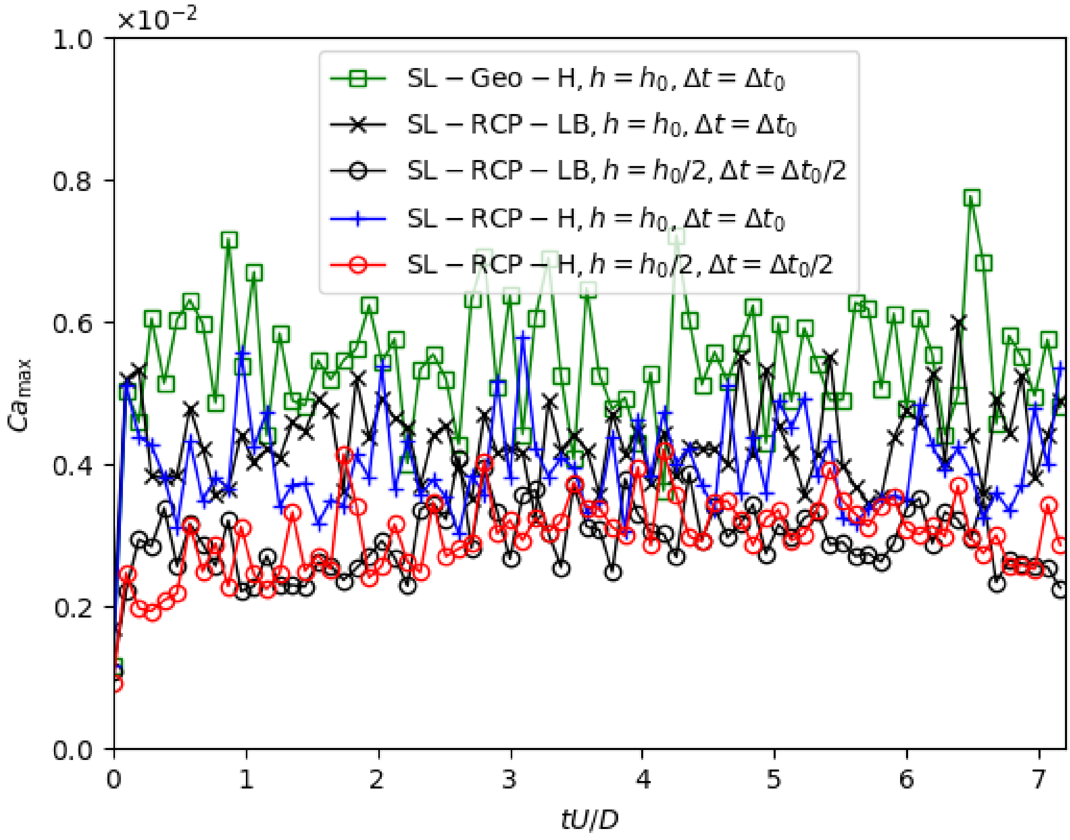

Fig.4: Time signals of errors in velocity magnitude for the translating bubble, obtained using least-squares smoothing of level-set gradient.

3.3 Spreading droplet

This is a benchmark test to validate the way of imposing the equilibrium contact angle [8]. The initial state is a two-dimensional droplet of radius R=0.01 m with an initial contact angle of 90 degrees. The computational domain is 6R in width and 2R in height. No-slip boundary condition is imposed at left, top and right boundaries. Free-slip is imposed at the bottom boundary. SL-RCPSL-H is used here. Reinitialization of level set is done at each timestep. Results of two tests are presented here. Simulation parameters are gathered in Tab.3. Drop shapes at equilibrium are shown in Fig.5: they are qualitatively correct. Results of base length and apex errors are below 2% and 1%, respectively.

Case	θ	ρ_1	ρ_2	μ_1	μ_2	Σ	**h**	Δt
1	30°	10^3	10^2	10^{-2}	10^{-3}	10^{-5}	R/40	0.1
2	140°	10^3	10^2	10^{-2}	10^{-3}	$5 \cdot 10^{-5}$	R/80	0.025

Table 3: Simulation parameters for spreading droplets.

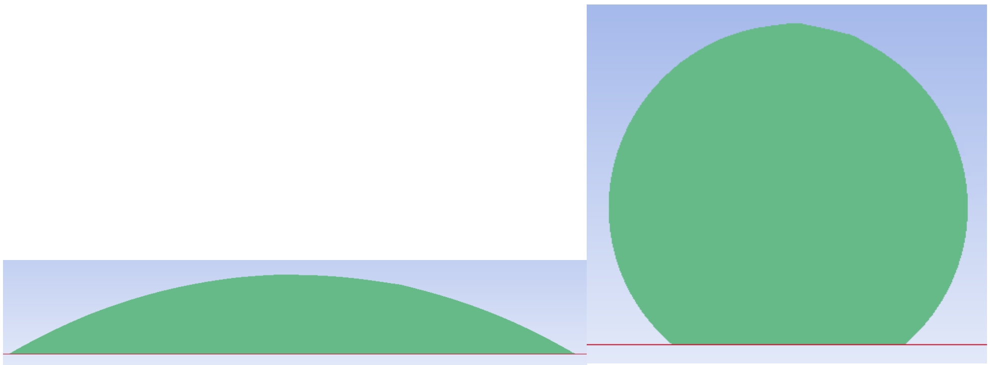

Fig.5: Droplet shapes at equilibrium for case 1 and 2.

4 Summary

New features have been implemented for enhanced numerical simulation of two-phase flows. These features will be available in the R15 release of LS-DYNA. Depending on flow types, parasitic perturbations in the level set function may be avoided by selecting numerical methods meticulously. SL advection may yield smoother solutions than FEM advection, especially for flows with significant capillary effects. Geo reinitialization may maintain sharp flow features in a better way than RCP. For flows with surface tension, the Laplace-Beltrami formulation may be a good compromise for smooth and efficient computation of extra terms. For flows with moving contact lines, SL-RCP-D or SL-RCP-H with enhanced approximation of level set gradient and curvature are recommended.

5 Literature

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