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High-fidelity interface tracking in compressible flows: Unlimited anchored adaptive level set

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Abstract

The interface-capturing-fidelity issue of the level set method is addressed wholly within the Eulerian framework. Our aim is for a practical and efficient way to realize the expected benefits of grid resolution and high order schemes. Based on a combination of structured adaptive mesh refinement (SAMR), rather than quad/octrees, and on high-order spatial discretization, rather than the use of Lagrangian particles, our method is tailored to compressible flows, while it provides a potentially useful alternative to the particle level set (PLS) for incompressible flows. Interesting salient features of our method include (a) avoidance of limiting (in treating the Hamiltonian of the level set equation), (b) anchoring the level set in a manner that ensures no drift and no spurious oscillations of the zero level during PDE-reinitialization, and (c) a non-linear tagging procedure for defining the neighborhood of the interface subject to mesh refinement. Numerous computational results on a set of benchmark problems (strongly deforming, stretching and tearing interfaces) demonstrate that with this approach, implemented up to 11th order accuracy, the level set method becomes essentially free of mass conservation errors and also free of parasitic interfacial oscillations, while it is still highly efficient, and convenient for 3D parallel implementation. In addition, demonstration of performance in fully-coupled simulations is presented for multimode Rayleigh–Taylor instability (low-Mach number regime) and shock-induced, bubble-collapse (highly compressible regime).

Keywords: Level set; Multi-fluid flow; Capturing interfaces; Interfacial instability; Contact discontinuities; Compressible flow; Adaptive mesh refinement; High order discretization

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1. Introduction

We are working on the direct numerical simulation of interfacial instabilities in compressible multi-fluid flows and at the foundation of our approach we have adopted the level set method [28,29,35]. In a previous paper we addressed issues of coupling the flows on either side of the interface coherently with capturing the interface motion in an adaptive mesh refinement environment (as needed for the simulation of real flows of practical interest) [26]. In that development we paid special attention to the dynamics of sharp capturing at high acoustic impedance mismatch interfaces. In the present paper we focus on the kinematics of the interface

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itself, and we address issues of fidelity via higher grid resolution along with higher-order-accurate schemes, as made evident by Sethian [35], Osher and Fedkiw [29], Peng et al. [30], and others. More specifically, we will examine fidelity at the limits of grid resolutions, not only as expressed by mass conservation, but also by preservation of interfacial topologies, and by spurious, even if bounded, numerically-induced oscillations, as they could be damaging to the predictive capability we wish to attain.

These fidelity issues have been well known for some time (e.g., [32]), but were addressed effectively only very recently ([8,9,15] – see Table 1 for related work leading up to these). The approach [9] involves increasing the resolution through adaptive mesh refinement, implemented by means of the quad/octree-based algorithms, and incorporating particle-tracking features, implemented through Lagrangian markers "seeded" around the interface (PLS). As indicated in Table 1, with one exception all this work was done in the context of incompressible flow. For compressible flows, the structured adaptive mesh refinement (SAMR) is the preferred algorithm (to quad/octrees) [19], as spurious wave-reflections on interfaces of grids with different resolutions [7] are minimized. Furthermore, rather than marker particles, we thought it pertinent to examine the potential role of high order treatment for the advection operator. These two premises converge in suggesting the SAMR

Table 1
Works addressing the fidelity of the level set method[a]

Ref.	Year	Method	AMR	C/I	Order/scheme	Test problems	Coupled two-phase flow simulations
Mulder et al. [21]	1992	LS	–	C	2nd, ENO_2	–	Rayleigh–Taylor and Kelvin–Helmholtz instabilities
Sussman et al. [39]	1994	LS	–	I	2nd, ENO_2	–	Bubble rising; falling/colliding drops
Rider and Kothe [32]	1995	VOF, LS, MP	–	I	up to 4th, limited	ST and SBR, SVS, MVT2	–
Peng et al. [30]	1999	LS	–	I	up to 5th, $WENO_5$	ST and SBR	Volume-preserving mean curvature flow; motion with curvature dependent acceleration; 3D double bubble minimizer; incompressible vortex sheet
Strain [37]	1999	LS	Quad/ Octrees	I	2nd, unlimited	ST and SBR, SVS	–
Sussman et al. [41]	1999	LS	SAMR	I	2nd, ENO_2	–	Bubble(s) rising/merging; drop oscillation/ impact on water surface; collision of drops
Sussman and Puckett [42]	2000	Hybrid LS + VOF	SAMR	I	2nd, ENO_2	ST and SBR	Drop oscillation/impact on solid wall; capillary instability; bubble(s) rising
Enright et al. [8]	2002	Hybrid[b] LS + MP	–	I	up to 5th, $WENO_5$	ST and SBR, SVS MVT2, MVT3	Water poured into a cylindrical glass
Enright et al. [9]	2005	Hybrid LS + MP	Quad/ Octrees	I	up to 5th, $WENO_5$	ST and SBR, SVS MVT2, MVT3	–
Present		LS	SAMR	C/I	up to 11th, unlimited HOUC	ST and SBR, SVS MVT2, MVT3	Rayleigh–Taylor instability; shock-induced bubble collapse

The following notation is used: I: incompressible; C: compressible; VOF: volume of fluid; LS: level set; MP: marker particles; ST: simple translation; SBR: solid body rotation; SVS: single-vortex stretching; MVT2/3: 2/3D multiple-vortex tearing.

[a] Mass conservation of the level set method coupled with compressible fluid dynamics solvers is also discussed in [10,22].

[b] An application to solid mechanics is also available [43].