Interface Reconstruction in Multi-fluid, Multi-phase Flow Simulations

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Summary. An advanced Volume-of-Fluid or VOF procedure for locally conservative reconstruction of multi-material interfaces based on volume fraction information in cells of an unstructured mesh is presented in this paper. The procedure employs improved neighbor definitions and topological consistency checks of the interface for computing a more accurate interface approximation. Comparison with previously published results for test problems involving severe deformation of the materials (such as vortex-in-a-box problem) show that this procedure produces more accurate results and reduces the “numerical surface tension” typically seen in VOF methods.

1 Introduction

Hydrodynamic simulations of flows involving multiple fluids and/or multiple phases are an important research area with many applications such as droplet deposition, sandwich molding processes, underwater explosions, mold-filling in casting, simulations of micro-jetting devices, etc.

A very important feature of multi-fluid, multi-phase flow simulations is the interface between materials and phases, and it is often crucial to follow such interfaces at each step of the simulation. Lagrangian simulations (where the mesh deforms with the material) automatically maintain interfaces, but fail if the mesh is excessively deformed and the interface topology changes. On the other hand, Eulerian simulations (where the material moves through a stationary mesh) but often require special procedures to keep track of the interfaces in the flow.

In general, there are three broad categories of methods to track interfaces in hydrodynamic simulations – front tracking[GLIM98a], level set methods[OSHE01a, SUSS98a] and interface reconstruction [YOUN82a, RIDE98a]. Front tracking methods advect marker points on an initial interface with the flow so that a continuous, piecewise smooth interface approximation is known at each time step. In general, in this method, the global topology of the interface is fixed at the initial and not changed during the simulation. This is obviously disadvantageous for flows in which materials coalesce or fragment. Level set methods model the interface as the zero
contour line of a distance function from mesh points to the interface. Level set methods model complex interface topology relatively easily but, in general, do not conserve material volumes very well. Volume tracking or Volume-of-fluid (VOF) methods compute an interface approximation at each time step using volume fraction information in mesh cell. Volume tracking methods can be accurate but the local topology of the interface in a cell is quite limited (such as a single line segment) making it difficult to capture subcell details such as thin filaments.

In this paper, an improved volume tracking technique is described for reconstructing complex material interfaces in unstructured meshes. The method currently allows one arbitrarily aligned linear interface segment per cell and thereby belongs to a venerable class of interface approximations that goes back at least to Debar [DEBA74a] and Youngs [YOUN82a, YOUN84a]. More recently, this class of interface approximations have been referred to as PLIC or Piecewise Linear Interface Calculation by Rider and Kothe [RIDE98a]. The method described here incorporates several new techniques designed to make the reconstruction method more accurate (generally second-order), rapid, and robust. These include the careful selection and use of interface neighbor cells, and a topological consistency checking and repair algorithm for the interface that is designed to minimize fragmentation of the material regions being reconstructed.

2 Interface Reconstruction Procedure

2.1 Overview

The primary problem being addressed in this research is the reconstruction of a piecewise linear interface given the volume fractions of different materials in the cells of an unstructured mesh. Cells filled with only one material are referred to as pure cells, and cells with some amount of two or more materials are referred to as mixed cells. Each mesh cell may contain at most one linear segment representing the interface. The reconstruction procedure must conserve the different cellular material volumes, make the interface as continuous as possible, and avoid non-physical holes and fragments in the material regions.

The main steps of the interface reconstruction procedure are:

1. Interface Estimation: A rough estimate of the interface is constructed using the volume fraction data specified on cells.

2. Interface Smoothing: Interface segments are adjusted taking into account other interface segments in the neighborhood so that the resulting interface is as smooth as possible. For example, straight line interfaces are typically recovered by this interface smoothing step.

3. Interface Topology Repair: The interface segments are adjusted so that they satisfy topological consistency checks (described below). This operation tries to ensure that the reconstructed material regions are continuous and do not have holes or fragments where the physics does not dictate it.

4. Constrained Interface Smoothing: The alterations made to the interface in the repair step are smoothed, with the constraint that topological consistency of any vertex cannot be destroyed.