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A new non-overlapping concept to improve the Hybrid Particle Level Set method in multi-phase fluid flows

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ABSTRACT

A novel non-overlapping concept is augmented to the Hybrid Particle Level Set (HPLS) method to improve its accuracy and suitability for the modelling of multi-phase fluid flows. The concept addresses shortcomings in the reseeding algorithm, which maintains resolution of the surface at runtime. These shortcomings result in the misplacement of newly seeded particles in the opposite signed domain and necessitate a restriction on the distance that a particle can escape without deletion, which reduces the effectiveness of the method. The non-overlapping concept judges the suitability of potential new particles based on information already contained within the particle representation of the surface. By preventing the misplacement of particles it is possible to significantly relax the distance restriction thereby increasing the accuracy of the HPLS method in multi-phase flows. To demonstrate its robustness and efficiency, the concept is examined with a number of challenging test cases, including both level-set-only simulations and two-phase fluid flows.

1. Introduction

A better knowledge of the physics of breaking waves is fundamental to improving the design of structures to cope with the demands of the ocean environment. However, this subject presents many difficulties to traditional free surface modelling techniques. The numerical technique that is able to predict the position of the interface that separates the gas and liquid phases must allow for extreme surface curvature, entrainment of air, splitting and merging to make it applicable for complicated engineering and geophysical flows such as wave breaking, sloshing and bubble flows. Two different types of methods have been used extensively to account for a free surface in numerical simulations, namely surface tracking and surface capturing. In surface tracking techniques the interface grid is updated at each time step to coincide with the position of the surface boundary, such as in Tryggvason et al. [23]. Although very accurate for simple surface configurations, their limitation is in their inability to handle complex geometry and breaking waves.

Surface capturing techniques use a stationary computational grid with the interface defined implicitly after the solutions of the domain are obtained. The most popular methods of surface capturing are Marker-And-Cell (MAC), Volume-Of-Fluid (VOF) and the level set method. The MAC scheme introduces massless particles on the surface whose motion is tracked to reveal the transient surface boundary. Complicated surface geometries and wave breaking can be captured by this method. However, drawbacks of the method include the computational effort required to track the large number of Lagrangian particles and the smoothness of the resultant surface that is reconstructed from the particle locations. Recently, the VOF

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technique has become popular due in part to its excellent conservation properties, as undertaken by Kim et al. [12], Liu and Lin [14], Khezzar et al. [10] in the study of water sloshing. Another surface capturing technique which has recently gained great popularity in the simulation of multi-phase fluid flows is the Level Set Method (LSM), in which a scalar 'Level Set' function is defined throughout the domain. The magnitude of the level set function measures the distance from a point to the surface. A distinct advantage of the LSM is the simplicity with which surface curvature is represented, aiding the modelling of surface tension, and the ease of its implementation, see Osher and Fedkiw [17] for a review.

The major drawback of using the level set method is that it becomes inaccurate when the surface geometry is under-resolved, i.e. when the surface curvature is high. Error in the position of the zero level set (i.e. surface interface) violates the conservation of mass. One way in which the conservation can be guaranteed is by solution of a separate criteria that enforces mass conservation on a cell by cell basis. For example, a mass correction factor was incorporated by Yap et al. [27] who considered two immiscible fluids in a channel thus dropping the surface tension term from the Navier–Stokes equations. Yue et al. [28] also used a volume constraint when reinitialising the level set function to conserve the volume of the fluids and Sussman and Puckett [22] coupled the level set method with the volume of fluid method. Although conservation of the global fluid mass is explicitly guaranteed it is not clear that the mass that is added to each cell is exactly the mass that was lost and is a potential source of error. Recently, Wang et al. [25] developed a new volume constraint, which treats neighbouring bubbles or droplets as a group so long as the spacing is less than three grid cells. The mass of the group is conserved rather than the individual member aiding the algorithm to handle splitting and merging of fluid.

An alternative method was proposed by Enright et al. [4], in which massless marker particles were used to better define the position of the interface. Known as the Hybrid Particle Level Set method (HPLS herein) the conservation improvement is made through correction of the grid based level set function by the Lagrangian particles. Since the particles follow the flow field characteristics they more accurately trace surface movement than the implicit calculation of the level set function. The HPLS method has been shown to perform particularly well for cases in which an arbitrary level set distribution is stretched in a prescribed velocity field to the point at which the width of level set function is of order the grid spacing. Whereas the standard level set solution loses significant fluid mass and volume conserving level sets introduce errors in the position of the interface, the HPLS method is extremely accurate to within a fraction of a percent. Later, Enright et al. [5] showed that the computational efficiency of the HPLS technique could be improved through the use of lower order schemes for both the advection of the level set function and time integration of the particles. Their test cases showed only a small decrease in the accuracy of the representation of the zero level set interface when compared to the standard HPLS.

However, the benefit of the HPLS method can be reduced when resolving unsteady multi-phase flows. If the surface is highly stretched for example in the case of oceanic breaking waves or violent sloshing in LNG tanks, the HPLS method in its standard form can degrade the solution necessitating the introduction of an additional restriction. This restriction enforces the deletion of particles that move across the surface into the opposite domain by a distance equal to 1.5 times their radius [6]. Whilst this restriction smooths and stabilises the surface through the removal of spurious particles, it also discards valuable information from valid particles thereby degrading the simulation. Wang et al. [24] attempted to address these issues by improving the particle correction procedure, although this improves mass conservation in simulations involving bubbles and droplets, a restriction is still required to simulate breaking waves and overturning fluid [1].

Here we seek to develop an improved HPLS technique in which the restriction can be relaxed or at best removed altogether. We accomplish this by first diagnosing the key flaws in existing particle level set methods and then propose routines to combat these issues. In the new approach we introduce a novel non-overlapping concept that effectively prevents the misplacement of new particles during the reseeding procedure. Our new algorithm has proved robust and enhances the mass conservation properties of our level set method which increases as the grids are refined allowing finer and finer flow features to be captured.

We first present a discussion on the particle level set method in the context of a two-dimensional constrained vortex flow. The limitation of the conventional HPLS methods is clearly shown through this example, however, the new improved HPLS method proposed here seems to provide almost perfect results. Strictly speaking, our method patches the flaw that exists in the latest HPLS technique, no matter how visible the improvement in the results is. The increase of conservation properties is further examined by a three-dimensional deformation flow and a bubble flow. Through the classical dam break case, we also investigate the influence of various parameters that are relevant to the improved HPLS method, and recommendations are made based on the comparison. With these recommended parameters, we finally study the impulsive sloshing, by which the capacity of the new HPLS method in accurately simulating complicated multi-phase fluid flows is demonstrated.

2. Mathematical model

In this study we investigate the motion of two incompressible fluids and capture the movement of the dividing interface (or free surface) by the Level Set Method (LSM). In LSM an additional scalar ϕ, known as the level set function, is specified throughout the domain representing the location of each grid cell relative to the free surface. Here, we define ϕ to be a signed distance function, which measures the shortest distance from the grid cell to the free surface (i.e. $|\nabla\phi| = 1$) and is positive in one fluid phase and negative in the other. Hence the free surface is colocated with the zero interface and is implicitly defined by the level set value at the surrounding grid nodes. The level set function is advected by the local velocity field according to