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Efficient two-phase mass-conserving level set method for simulation of incompressible turbulent free surface flows with large density ratio

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ABSTRACT

An efficient three-dimensional two-phase flow model for simulation of free surface flows is developed. The method is based in the solution of Navier-Stokes equation for quasi-incompressible flows. The equations in generalized coordinates are solved by extension of the fully explicit MacCormack scheme, second order in time and fourth order in space. The free surface is implicitly captured by the zero Level Set of a smooth function and by the Ghost Fluid Method to capture accurately shape discontinuities for properties in the vicinity of the interface. Finally, the Volume of Fluid method is used to ensure mass conservation. Turbulence is described by large eddy simulation, where only the large-scale eddies are solved, while the small scales are modeled by using the selective structure function subgrid-scale model. Boundary shapes are represented through the immersed boundary method on the Cartesian grid. The numerical model is validated by some free surface problems. Numerical predictions by all cases are in good agreement with experimental data.

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1. Introduction

Turbulent flows problems involving free surfaces are presented in many environmental and engineering applications. However, accurate description of physical processes on free surface problems represents still a challenge, in view of the complexities of moving and deforming surfaces, nonlinear effects, large range of length scales and time scales, high turbulence, among other causes. Free surface represents a dynamic boundary, whose position and shape change in response to the interaction between the phases present; therefore, use of special techniques is needed to define the location and movement of the interface. Owing to the complexity of free surface flows, a large number of modeling methods for interface simulations have been developed. These approaches can be divided into two great classes: moving-grid methods (Lagrangian approach) and fixed-grid methods (Eulerian approach). In addition to these methods, there are special cases, such as particle methods, in which grids are not needed.

In Lagrangian description, coordinate system follows the movement of the fluid particles. The interface is a boundary between two subdomains of the grid, so the free surface is sharply defined. Although it seems the most natural way to simulate free surface flows, this method is restricted to well-defined simple surface topologies, because the grid has to be re-meshed or refined when the interface undergoes large deformations and topology changes. Meanwhile, in Eulerian, the mesh is fixed in the space. This method introduces a new variable in the model to track the presence or not of one of the two phases in the whole domain. Eulerian methods are the most used ones, since they permit to take into account large topology changes and discontinuities. Methods that fall into this category include the Volume-of-Fluid (VOF) method introduced by [1] and the Level-Set (LS) method introduced by [2]. In the former, a steep function, transported by the fluid flow, is defined in the whole computational domain. This function, which represents the fraction of the volume, is set to unity everywhere in one phase and zero in the other phase. In those regions where both phases are presented, free surface is captured through a interface reconstruction procedure. The mayor advantage of this method is the mass conserving properties. Nonetheless, the interface reconstruction is a laborious computational task. In addition, modeling errors stem from the difficulties to control the interface thickness, due to numerical diffusion. In the LS approach, the interface is simulated by the evolution of the zero level of a time-dependent smooth function transported by the fluid flow. This approach allows the simulation of complex surface evolution including topological merging and breaking; moreover, the computation of geometrical quantities like the normal and

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curvature of the interface are easily performed. The LS approach provides an exact representation of the interface, but it is by definition a not mass conserving method.

In the context of the LS method, several approaches have been developed in pursuance of maintaining the interface sharp and to improve mass conservation properties. [3–5] and [6] improve conservation properties by replacing the usual signed distance function of the original LS approach by a hyperbolic tangent function. This proposed function is transported and reinitialized using conservative equations reducing mass conservation errors while retaining the simplicity of the classic method even for complex problems. Another strategy is to implement the Adaptive Mesh Refinement (AMR) technique. This technique was introduced by [7] and later extended for the two-phase incompressible flow by [8]. In this approach, multiple component grids of different resolutions are used. In a region of the flow when more detail is required, a refined grid is placed. This approach has been used in combination with LS method by [9] and [10] not only to improve mass conservation, but also to preserve interfacial topologies. Also [11] used this technique in combination with LS method to simulate moving solid boundaries. Finally, methods that combine two different methods and takes advantages of the strengths of each of the two approaches have received considerable attention in recent years. It can be found that LS and VOF methods have the complementary advantages and disadvantages, so it is a natural trend to develop a method combining these approaches. The basic idea behind combining VOF method and LS method is to get the best from both VOF method (mass conservation properties) and LS method (easy computation of geometric properties of the interface and interface sharpness). Examples of these methods are the Coupled Level Set Volume of Fluid (CLSVOF) method of [12], the Coupled Volume of Fluid and Level Set (VOSET) method of [13], the hybrid Level Set/Volume of Fluid (LS/VOF) method of [14], and the Mass Conserving Level Set (MCLS) method of [15]. These methods have been extensively tested and validated. Results presented in [16–21] have shown interfacial geometric properties more accurately and mass conservation improvement compared to standard LS and VOF methods.

The LS function ϕ is defined as a signed distance function. However, after the advection procedure this initial condition is not preserved and a reinitialization treatment is always necessary in order to overcome some numerical instabilities and maintain a numerically well-defined interface and maintain an stable interface evolution. The two most popular approaches among them are the Fast Marching Method (FMM) [22] and the Partial Difference Equation (PDE) based method [23]. The FMM represents the most efficient reinitialization method. However, the algorithm is inherently sequential due to causal relationship between grid points and hence not straightforward to parallelize. PDE-based method represents a simple and yet efficient alternative. In this method, the values in all grid points are updated simultaneously, therefore, the algorithm is well suited to parallel computing environments. Additionally, this method offer the advantage of flexibility to use a wide range of well documented numerical techniques as well the use higher-order schemes for time and space discretization. In this work, the PDE-based method approach [24] is adopted

In this work, the approach proposed by [15] is adopted. The MCLS method is a hybrid method, based in an explicit relation between the LS function and the VOF function to find a mass conserving correction to the LS function. The locally linearized LS function and the VOF function are linked through an algebraic relation, based on a parameterized geometric construction of the interface. The method takes full advantage of all additional information provided by the Level Set function, rather than coupling LS method with VOF method. The VOF function is used as an auxiliary variable to conserve mass, without applying the difficult interface reconstruction which makes the VOF method so elaborate and computationally expensive. However, the classic implicit representation of the LS method used in [15] tracks all the LS functions throughout the entire computational domain, even though interest is really confined only to the zero LS itself corresponding to the interface. This consideration results computationally expensive. [25] introduced the idea of the narrow band approach, also called Local LS method to limits labor to a thin region around the zero LS. The savings of the use of local LS methods has been reported by [24], therefore this modified approach of the LS method is adopted in this work.

In various numerical schemes for incompressible flow, the pressure is often obtained by solving a Poisson equation. This is frequently the most costly step, which requires additional computations at each time step. A technique to overcome this difficulty is the Artificial Compressibility (AC) method proposed by [26]. The AC method considers that every theoretically incompressible fluid is actually compressible. The main idea of [26] concept is to add a time derivative of pressure into the continuity equation. This provides a direct coupling between pressure and flow velocity, thus avoiding the need to solve the elliptic Poisson equation. The AC has recently been used along with the LS method in studying moving interface problems. [27] have extended the AC method for the simulation of incompressible multiphase flows coupling the pseudo-compressibility method and the LS method. The approximation adopted in this work is, in concept, very similar to the artificial compressibility (AC) method of [26] and the pseudo-compressibility method of [27]. The fully compressible continuity and momentum equations are used, but with an isothermal equation of state. This choice allows us to bypass the Poisson equation.

On the other hand, in order to improve the accuracy and handling large gradients and material discontinuities associated with two-phase flows, the Ghost Fluid Method (GFM) of [28] is adopted. This technique based in the approach introduced by [29] provides a way of dealing problems involving large density ratio i.e. when one fluid is too stiff compared with the other, such as, air/water interface. The GFM consists in creating an artificial fluid also call ghost fluid which implicitly induces the proper conditions at the interface. In the ghost fluid regions, discontinuous variables across a fluid interface are given using a one-sided extrapolation and continuous variables are copied from the real fluid on a node-by-node basis. Finally, high-order schemes such as the Weighted Essentially non Oscillatory (WENO) scheme of [30] for space discretization and the third order TVD-RK of [31] for time discretization are used. These schemes are capable of handling large gradients and discontinuities very accurately.

In this paper, an efficient level-set two-phase flow model for the simulation of problems with a large density ratio and complicated interface interactions applied to highly turbulent water-air problems is introduced. Two sets of the flow equations are solved simultaneously, one for each fluid. Both the liquid and gas phases are assumed to be governed by Navier-Stokes equations and approximated to incompressible state through an artificial state equation. The VOF function is computed, so that mass conservation issues of the LS method can be overcome. LS function is only solved in a narrow band across the interface. This approach reduces considerably the computational time, making the method more efficient. Finally, to assure a sharp and correct evolution of the interface, higher order schemes are used for both spacial and temporal discretization. The capability, accuracy and performance of the presented numerical model is evaluated and validated by carrying out some benchmark numerical simulations. The code has been parallelized using message passing directives (OpenMP). The parallel code which was written in FORTRAN-90 has been successfully tested and validated. The CPU time quantities show that the parallel code achieves reasonably good computational efficiency for fine

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