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Development of a Volume Of Fluid Method for Computing Interfacial Incompressible Fluid Flows

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Abstract. This study is aimed to develop a volume of fluid (VOF) method to capture the free surface flow. The incompressible two-phase flow is computed by second-order Adams-Bashforth algorithm with a uniform staggered Cartesian grid arrangement. The tangent of hyperbola for interface capturing (THINC) scheme and weighted linear interface calculation (WLIC) based geometrical reconstruction procedure have been implemented in the operator-splitting method for the VOF method. The proposed VOF method preserves mass well, and the interface normal vector can be easily estimated from the level set (LS) function. The LS function, which is a continuous signed distance function around the interface, is represented by solving the re-initialization equation. Numerical results using the present scheme are compared with experimental data and other numerical results in the Rayleigh-Taylor instability, dam-break flow, travelling solitary wave, Kelvin-Helmholtz instability, rising bubble and merging bubble problems. We also present numerical results in detail between computations made with the proposed VOF method and computations made with the conventional LS method.

AMS subject classifications: 35Q30, 76D05, 76D27, 76M20
Key words: Volume of fluid, free surface flow, THINC, WLIC, level set function.

1 Introduction

Study of evolution of free surface flows has been an important subject in ocean, civil engineering and environmental problems [1–5]. Commonly-used methods for simulating free surface flows include: (a) interface fitting method, (b) interface tracking method

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and (c) interface capturing method [6]. The interface fitting (Lagrangian) method treats the interface as a sharp boundary and uses a moving mesh to follow the phase interface. However, this method fails when handling bubble breakup and coalescence problems [7]. Also, the requirement of grid modification to follow the transient moving interface makes this method computationally expensive. The interface tracking method uses a fixed grid to obtain the velocity field and a moving surface mesh to track the interface. This method requires surface remeshing as the interface deforms [8], which makes this method computationally expensive and difficult to implement. In the interface capturing method, free surface flows involve complicated topological change processes such as wave breaking and spray formation, which can be simulated efficiently [9]. The interface capturing methods which advect the corresponding phase function in a fixed (Eulerian) grid have been developed including volume of fluid (VOF) methods [10–13] and level set methods [14–17].

In VOF methods, the volume fraction scalar field F ranging from 0 to 1 is transported by advection equation. $F=1$ means that the cell is totally filled with liquid phase while $F=0$ means that the cell is totally filled with gas phase. It is noted that a volume fraction value between 0 and 1 implies a cell in the interface zone, where the cells are partially filled by both air and water phases. The advection of VOF is based on the computation of volume flux at each cell, which requires the interface information to complete the calculation. The used interface reconstruction methods which provide a sharp interface between air/water phases are SLIC (Simple Line Interface Calculation) [18], PLIC (Piecewise Linear Interface Calculation) [19] and WLIC (Weighted Line Interface Calculation) [20]. SLIC method simply describes the interface as a flattened slice whose normal is pointed at only one of the three directions in space. By using the PLIC algorithm, the interface is reconstructed by a plane, which separates the two phases and is perpendicular to the interface normal $\mathbf{n}$. $\mathbf{n}$ is essentially the negative gradient of the volume fraction C. The WLIC method adds weights to the horizontal and vertical slices in SLIC.

VOF methods have been widely developed and applied to accurately capture the interface. Ref. [19] employs the VOF/PLIC method to simulate wave overtopping a levee during the storm surge of Hurricane Katrina by its incompressible Reynolds equations and $\kappa-\epsilon$ equations. Ref. [21] develops a second-order volume of fluid interface tracking algorithm in a generalized curvilinear coordinate system. In this study, an implicit algorithm based on a dual-time pseudo-compressibility method is adopted to compute water impact force on bodies. Unsteady Reynolds-averaged Navier-Stokes equations are used to solve the incompressible viscous fluid flow field. The computational efficiency is also improved by introducing pseudo-time derivatives to the equations.

One can use high resolution schemes to discrete the volume fraction equation. High resolution schemes, nevertheless, cause numerical diffusion, which affects the accuracy of the solution. The algebraic-type VOF method, namely, Tangent of Hyperbola for INterface Capturing (THINC), is therefore proposed [22] to reduce numerical diffusion. THINC scheme computes the numerical flux by utilizing hyperbolic tangent interpolation function. Jump and slope of the hyperbolic tangent function are automatically deter-