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PLIC-VOF Improvement Using Signed Distance Function for Incompressible Interfacial Flow

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In this paper, a new algorithm was proposed for the 2D coupling of the Volume of Fluid (VOF) and Level Set (LS) methods, which was used for the computation of free surface tracking. This method was also coupled with the second-order advection solution of momentum equations. At the first step, the interface was reconstructed from the volume fraction function via a Piecewise Linear Interface Calculation (PLIC) scheme within the computational domain. Then the level set signed distance function was obtained near the interface, and the new normal vector was calculated. This method was associated with a geometrical treatment to evaluate the normal vector through the use of the signed distance function. On the basis of the new normal vector, the interface was reconstructed again. Then the VOF procedure should be repeated by the new normal vector. Through the employment of an iterative method, a more accurate signed distance function and consequently the interface normal vector could be achieved. This procedure should be repeated once for fine mesh and three times for coarse mesh. Several numerical tests, such as Zalesak's problem, shearing flow, and dam break, were conducted in order to verify the accuracy, efficiency, and capability of the present model. The results showed that the new model was more efficient than the VOF method.

INTRODUCTION

The numerical simulation of interfacial flows is the most important topic in marine engineering, environmental science, geophysics, and fundamental physics. The first attempt to calculate the flow with the free surface was made by Harlow and Welch (1965), who developed the Marker and Cell (MAC) method. Thereafter, different techniques were introduced in interfacial and free surface flows that fall into two main categories: surface-tracking methods (surface fitting) and volume-tracking methods (surface capturing). In the first category, the interface is represented and tracked explicitly by being marked with special marker points or by being attached to a mesh surface that is forced to move with it. In the second category, the fluids on each side of the interface are marked by either massless particles or an indicator function. The surface-capturing or volume-tracking methods are implicit with respect to the interface. In these methods, multiphase distribution is described by the use of a special function. An extensive review of surface-tracking and volume-tracking methods is presented by Ubbink (1997) and Gopala and van Wachem (2008).

The most known volume-tracking method is the Volume of Fluid (VOF) method presented by Hirt and Nichols (1981). Another common volume-tracking method is the Level Set (LS) method pioneered by Osher and Sethian (1988). Among the free surface modeling methods, the VOF and LS methods are probably the most widely used methods in the literature. Each method has its own advantages and drawbacks.

In the VOF method, fluid volumes are initialized in each computational cell from the specified interface geometry. The volume data are retained as volume fractions, i.e., the color function, whose value is unity at any point occupied by fluid and otherwise zero. Cells with color function values between zero and one contain a free surface:

$$F = \begin{cases} 1 & \text{Fluid \#1} \\ 0 & \text{Fluid \#2} \\ 0 < F < 1 & \text{Interface} \end{cases} \tag{1}$$

Since a unique interface configuration does not exist once the exact interface location is replaced with discrete volume data, detailed interface information cannot be extracted until an interface is reconstructed. The interface is tracked by evolving fluid volumes forward in time with solutions of an advection equation as follows:

$$\frac{\partial F}{\partial t} + u_i \frac{\partial F}{\partial x_i} = 0 \tag{2}$$

If the flow is incompressible, then the above advection equation can be written as follows:

$$\frac{\partial F}{\partial t} + \frac{\partial (F u_i)}{\partial x_i} = 0 \tag{3}$$

The reconstructed interface is then used to compute the volume fluxes necessary to integrate the volume evolution equations. The VOF method has an excellent mass conservation property, but it lacks accuracy in the direct calculations of the normal and curvature due to the discontinuous spatial derivatives of the VOF function near the interface. Moreover, the implementation of the VOF method is not straightforward since a complicated geometrical procedure is needed for the interface reconstruction. The most published volume-tracking algorithms fall into one of three interface reconstruction categories: piecewise constant, piecewise constant/stair-stepped, and piecewise linear (Rider and Kothe, 1998).

In the LS method, the interface is described by the level set function, which is defined as a signed distance function. The value

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