# a fractional volume of floid method for free boundary dynamics 

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# A FRACTIONAL VOLUME OF FLUID METHOD FOR FREE BOUNDARY DYNAMICS* 

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## I. INTRODUCTION

In this paper we describe an exceptionaily versatile Eulerian method to track free boundaries that undergo large deformations. The method follows regions of fluid, defined by a volume of fluid function, in contrast to a direct representation of free boundaries, such as marker particle chains. This new scheme is superior to previous free boundary methods because it requires minimum computer storage, avoids logic probiems associated with the creation or destruction of disjoint fluid regions, is applicable to arbitrarily contorting flows, and is directiy extendible to three-dimensinnal problems.

## II. THE VOF METHOD

The volume of fluid (VOF) method is based on a function $F$ whose value is unity at any point uccupled by fluid and zero otherwise. The average value of $F$ in a computational cell represeats the fractional volume of the cell occupied by fluid. In particular, a unit value of $F$ corresponds to a cell full of fluid, while a zero value indicates that. the cell contains no fluid. Cells with $!$ values between zero and one must then contain a free boundary.

In addition to defining which cells contain a bisundary, the vof method defines where fluid is located in a boundary cell. The normal direction to the boundary Lies in the direction in which the value of $F$ changes most rapidly. Because $F$ is a step function, howevers its derivatives are computed in a special way. Finally, knowing both the ncrmal direction and the value of $F$ in a boundary cell, a line cutting the cell can be constructied that approximates the interface there. This boundary location can then be used in setting boundary conditions. In addition, surface curvatures can be compulied from the $F$ distribution when surface tension forces must be considered.

The time dependence of $F$ is governed by a kinematic equation stating that the $F$ values flow with the fluid. If standard finite-difference approximations were used to compute the advection of $F$, axcessive numerir.... olearing of the $F$ function would occur and interfaces wouid lose their definition. Fortunately, the fact that fir a step function with values of er ro or onermits the use of a special fiux approxi-

[^0]mation that preserves its discontinuous nature. In particular, a type of donor-acceptor flux approximation is used that uses information about $F$ downstream as well as upstream of a flux boundar:'. In this way a crude interface shape is eatablished that can be used to compute the flux of $F$.

## III. THE SOLA-VOF CODE

The VOF method is applicable to Eulerian or the rore general Arbitrary-Lagran-gian-Eulerian (ALE) numerical formulations. We have verified the accuracy and versailify of the method by incorporsting it into a two-dimensional, finite-difference, Eulerian scheme that uses a solution algorithm (SOLA) by Hirt et al. (1975) based on the well-known Marker-and-Cell (MAC) method (Harlow and Welch, 1965). The combined code, SOLA-VOF, (described by Hirt and Nichols, 1980 and Nichols et al., 1980), uses an Eulerian mesh of rectangular cells having variable rizes $\& x_{i}$ for the ith column and $\delta y_{j}$ for the jth row. The fluid equations solved art the NavierStokes :quations in either Cartesian or cylindrical coordinates. These equations are supplemented with either the continuity cundition for incompressible fluids or the continuity condition for fluids with limited compressibility effects (e.g., acoustic waves).

The SOLA-VOF code also has a variety of additional options. Any ccmbination of cells in the mesh can be defined as obstacle cells into wifch fluid cannot flow. Instead of one fluid with a free surface, two fluids can be de'ined with different density ratios separated by a free interface. Surface tension forces are optional at the fluid interface for both the one and two fluid casen.

The basic procedure for advancing a solution through one increment: in time consists of three steps:
(1) Explicit approximations of the momentum equations are used to compute the first guess for new time- evel velocities using the initial conditions or previous time-level values for all advective, pressure, and viscous accelerations.
(2) To satisfy the incompressitie fluld contiriuitv equatior, pressures are iteratively adjusted in each cel and velocity changes induced by each pressure change are added to the velocities computed in step 1 . An iteration is needed because the change in pressure needed in one cell to satisfy the continuity equation will upset the balance in the four adjacent cellc. On the other hand, when the limited compressibility option is used the SOLA-VOF progrem automatically, and continuously, switches from an implicit to an explicit noiution for pressures as the time step is reduced below the Courant stability limit. This fenture permits more accurate results to be obtained with leas computational workl
(3) Finally, the $F$ function dufining fluid regions must be updatad to give the new fluid configuration.

Reputition of these steps will atvance a mution through any deairad time interval. At each step, of course, suitable boundary conditions mat be imposed at

We have chosen several calculational examples to illustrate the capabilities of the SCLA-VOF method.
A. Broken Dam Problem

A simply executed problem, for which experimental data is available, is the "broken dam" problem. An initially rectangular block of fluid, in hydrostatir equilibrium, collapses under the force of gravity and flows across a dry horizontal floor, as shown in Fig. 1. A comparison of the experimental data reported by Martin and Mcyce (1952) with the calculated leading edge of the fluid as a function of time, Fig. 2, shows the greatest deviation is everywhere less than a calculational cell width.
B. Collapse of a Cylindrizal Fluid Column

The collapse of a cylindrical column of fluid is similar to the "broken dam" problem, but uses the cylindrical coordinate system. Several additional features of the SOLA-VOF code are also illustrated by this calculation. Flow visualization is typically realized by plotting the velocity field with velocity vectors drawn from the center of each mesh cell containing fluid and by depicting the free surfaces with the volume fraction ( $\mathrm{F}=1 / 2$ ) contour, as seen in Fif. l. However, marker particles can be used to follow the fluid flow as in Fig. 3. In addition, this calculation demonstrates the use of obstacle cells. The capability of the code to handle highly contorted fluid configurations is exceptionally well illustrated ere. C. A Reactor Safety Application

Many bolling water reactors use a large pool of water to condense steam should a major steam leak occur. In some designs, steam would be forced into the pool through vertical pipes extending several pipe diameters below the surface of the pool. Before steam enters the pool, however, air initially in the pipes must be pushed out. The ejection of this noncondensable air forms large bubbles in the pool and displaces the pool surface upward. Several small scale experimental programs have been conducted to understand the hydrodynamic forces generated during the process. We have numerically calculated these hydrodynamic forces and compared with laboratory test data (Nichols and Hirc, 1986).

To model these experiments it was necessary to supplement the SOLA-VOF code with calculations for the gas pressure in the pipe and for the pressure in the closed space above the pool surface. These pressures are then used as free surface boundary $p$ s sures. A sequence of calculated results illustrating the fluld dynamics absociated with the air-clearing process are coitained in $\overrightarrow{\text { rig. }} 4$. D. Instability of a Liquid Column

For some applications, such as the breakip of thin liquid jet, surface tension forces mast be considered. A classic problem of this type concerns the instability of a cylindrical column of fluid. When its free surface is perturbed by radial displacements, an exponential growth in peturbation amplitude may iesult that
eventually causes the cylinder to break up into a series of discrete drops. Figure 5 illustrates a SOLA-VOF calculation of this type of surface tension driven instability. The cylinder is initially perturbed with an axisymmetric displacement of its free surface that is sinusoidal in the axial direction. Two axial wave lengths, $\lambda$, are followed, with $\lambda=4.598 \mathrm{D}$, where D is the diameter of the undisturbed liquid column. The initial perturbation amplitude is 0.001 D. A comparison of the computed amplitude growth with linear theory shows the interesting result that the linear theory is valid for large amplitude displacements. Nevertheless, nonlinear effects are important, for they are the cause of the small satellite drops that develop between the large drops.

Many additional calculations have been performed that validate various capabilities of the SOLA-VOF cade not mentioned in the above examples. Included in these are a study of bubble growth and collapse, which made use of the limited compressibility feature, and the passage of an immiscible liquid drop through a constriction in a tube. in which the tw-fluid and surface tension options were utilized to$g \in t h e r$.

## SUMMARY

We present the volume of fluid (VOF) technique as a almple and efficient means for numerically treating free boundaries embedded in a calculational mesh of Eulerian or Arbttrary-Lagrangian-Eulerian cells. It is particularly useful because it uses a minimum of stored information, treats intersectirg free boundaries automatically, and ran be readily extended to three-dimensional calculations.

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Fig. 1. Velocity vectors and free surface conf gurations compured for the broken dam problem at times $0.0,0.9,1.4$, and 2.0.


Fig. 2. Comparimon of calculated resulte with experfmental dita for the broken dam problem.


Fig. 3. Calculational results showing the collapse of a cylindrical column of fluid surrounded by a low retaining wall. Times shown are 0.0 , $1.6,2.5,3.6,4.2$, and 4.6


Fig. 4. Velocity vectors and free surface conflgurations compuied when al: Is forced through submerged vert plpe.


Fig. 5. Fluid configurations calculated for a surface tension driven instabllity of a cylindrical column of fluid. Times are approximately $0.0,6.03,6.49$, nond $\rightarrow$ n ..


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