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Short Note

Analytical and geometrical tools for 3D volume of fluid methods in general grids

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Abstract

It is well known that volume of fluid (VOF) methods in three-dimensions, especially those based on unsplit advection schemes, involve highly complex geometrical operations. The objective of this work is to propose, for general grids and three-dimensional Cartesian geometry, simple and efficient geometrical tools for volume truncation operations that typically arise in VOF methods and an analytical method for local volume enforcement. The results obtained for different tests and grid types show that the proposed analytical method may be as much as three times faster than Brent's iterative method. Advection tests were carried out using hexahedral grids obtained from deformation of a cubic grid to assess the accuracy of the proposed tools in combination with a recently proposed unsplit PLIC–VOF method.
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1. Introduction

One of the most widely used methods for simulating interfacial flows is the volume of fluid (VOF) method. Algebraic formulations in VOF methods are being replaced by purely geometrical procedures with PLIC (piecewise linear interface calculation) reconstruction of the interface, which provide second-order accuracy. Numerous successful implementations of high-order PLIC–VOF methods have been developed in two dimensions (2D) during the last two decades (see for example the reviews of Scardovelli and Zaleski [14] or Rider and Kothe [13] and the references therein). However, the great complexity of the geometrical operations involved in these methods makes their extension to three dimensions (3D) relatively difficult (successful implementations of high-order PLIC–VOF methods in 3D can be found in [2,4,5,8–10,12]).

Two basic operations are involved in any geometrical PLIC–VOF method: volume truncation and the enforcement of local volume conservation. The first typically arises in the computation of the fluid volume advected through cell boundaries, a volume obtained from the intersection between the reconstructed interface

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and the donating flux regions constructed at cell boundaries. In spatially varying velocity fields, the use of unsplit advection schemes gives rise to discretized flux regions that are generally irregular convex polyhedra (polygons in 2D), thus introducing additional complexity.

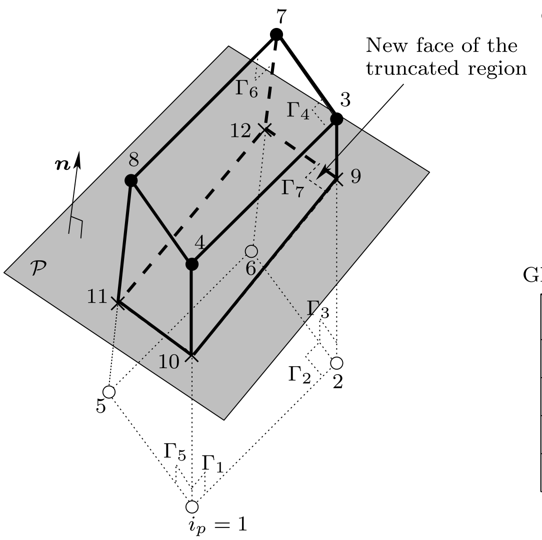
The second operation consists of determining the position of a planar interface (with a given orientation) that produces a truncated polyhedron of a given volume. This problem is usually encountered as part of the interface reconstruction step, in which local volume conservation is enforced in each interfacial cell of the computational domain. The solution to this problem may also be useful in the advection step, to ensure that the volume of the flux region constructed at a given cell boundary satisfies the local conservation constraint given by the computed volumetric flux through the cell boundary (see Refs. [4,6,7]). The analytical solution to this problem eliminates the need to iterate, generally reducing CPU time. Scardovelli and Zaleski [15] and Yang and James [18] solved this problem analytically for orthogonal hexahedral and tetrahedral grids, respectively. However, for general grids, or even for orthogonal hexahedral grids when an unsplit advection scheme is used and the flux regions constructed at cell boundaries are non-orthogonal, a more general analytical method is needed.

The tools for volume truncation operations and the analytical method to enforce local volume conservation in general grids are described in Sections 2 and 3, respectively. The proposed analytical method is assessed in Section 4 by comparing its efficiency with that of an iterative method typically used in PLIC–VOF methods. The source codes and pseudo-codes for the proposed algorithms are available for download at [19].

2. Polyhedron truncation procedure

In this section, a general procedure for obtaining the truncated polyhedron resulting from the intersection between a plane $\mathscr{P}$ and a generic convex polyhedron Ω, either regular or irregular, will be described. A relatively similar procedure can be found in the work of Stephenson and Christiansen [17], although few implementation details are given by these authors. The truncation procedure is carried out in 2D and 3D problems using two different algorithms, the corresponding codes and pseudo-codes of which are available at [19]. The output of the algorithms is the set of ordered vertices of the truncated polyhedron or polygon.

Let us consider a polyhedron of J faces, with I_j vertices in each face j, and a plane $\mathscr{P}$, defined by $\boldsymbol{n}\cdot\boldsymbol{x}+C=0$, where $\boldsymbol{n}$ is the unit-length vector normal to $\mathscr{P}$, $\boldsymbol{x}$ is the position vector of a generic point on $\mathscr{P}$ and C is a constant. Fig. 1 shows an example of the arrangement of polyhedron vertices using a global



Global i_p vertex indices for the original polyhedron

i \ j	1	2	3	4	5	6
1	1	2	3	4	1	6
2	2	1	2	3	4	5
3	3	5	6	7	8	8
4	4	6	7	8	5	7

Global i_p vertex indices for the truncated polyhedron

i \ j	1	2	3	4	5	6	7
1	9	−−	3	4	10	11	9
2	3	−−	9	3	4	8	10
3	4	−−	12	7	8	7	11
4	10	−−	7	8	11	12	12

Discarded face (column 2); New face (column 7)

Fig. 1. Truncation of a polyhedron by a plane $\mathscr{P}$. Symbols • and ∘ denote vertices with positive and negative ϕ values, respectively, and × denotes the intersection point between plane $\mathscr{P}$ and a polyhedron edge.

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