Block-Based Adaptive Mesh Refinement Finite-Volume Scheme for Hybrid Multi-Block Meshes

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Abstract: A block-based adaptive mesh refinement (AMR) finite-volume scheme is proposed and developed for solution of hyperbolic conservation laws on two-dimensional hybrid multi-block meshes. A Godunov-type upwind finite-volume spatial-discretization scheme, with piecewise limited linear reconstruction and Riemann-solver based flux functions, is applied to the quadrilateral cells of a hybrid multi-block mesh and these computational cells are embedded in either body-fitted structured or general unstructured grid partitions or subdomains of the hybrid grid. A hierarchical quadtree data structure is used to allow local refinement of the individual subdomains based on heuristic physics-based refinement criteria. An efficient and scalable parallel implementation of the proposed algorithm is achieved via domain decomposition. The hybrid mesh approach readily allows for the use of body-fitted structural mesh blocks in the vicinity of bodies and solid surfaces, where the structured nature and orthogonality of the grid to the boundary can provide added accuracy and solution efficiency and the use of general unstructured partitions to fill the remaining computational domain and connecting the structured mesh. The use of unstructured grid topology to connect the body-fitted blocks near solid boundaries greatly simplifies the initial grid generation process. The performance of the proposed parallel hybrid AMR scheme is demonstrated through application to the solution of the Euler equations of compressible gas dynamics for a number of flow configurations and regimes in two space dimensions. The efficiency of the AMR procedure and accuracy, robustness, and scalability of the hybrid mesh scheme are all assessed.

Keywords: adaptive mesh refinement (AMR), hybrid mesh, domain decomposition, upwind fintie-volume methods

1 Introduction and Motivation

Computational fluid dynamics (CFD) has proven to be an important enabling technology in many areas of science and engineering. Nevertheless, further advances in numerical methods are required to enable the more routine use of high-fidelity analysis tools for practical engineering applications. A recent assessment of the needs for large-scale and high-performance scientific computing indicates that a number of fundamental issues in discretization design must be addressed [1]. One of the issues identified was the need for greater automation of mesh generation via adaptive mesh refinement (AMR) to reduce the time to generate high-quality meshes and for the treatment of complex geometries. The present study represents further steps toward addressing this need.

Computational grids that automatically adapt to the solution are very effective in treating problems with disparate length scales, providing the required spatial resolution while minimizing memory and storage requirements. Groth and co-researchers [2, 3] have developed a block-based parallel AMR method for body-fitted multi-block mesh with arbitrary mesh block connectivity. The block-based approach has been shown to enable efficient and scalable parallel implementations for a variety of complex flows, as well as allow for local refinement of body-fitted mesh with anisotropic stretching. The latter aids in the treatment of complex flow geometry and flows with thin boundary and shear layers and/or discontinuities and shocks. While the block-based AMR approach aids in the automation of the grid generation process, certainly greater efficiencies and reduction of human input are possible.

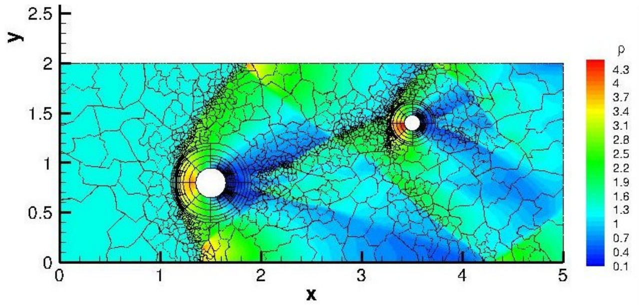

Figure 1: Predicted distribution of density for supersonic flow past two cirular cylinders with a Mach number of M=2.0. The The final adapted mesh contains 656 solution blocks and 138,513 computational cells with 5 levels of refinement and an overall refinement efficiency of 0.81892.

Hybrid meshing techniques have received considerable interest in recent years [4, 5, 6] for providing greater flexibility in meshing complex geometries. They permit the use of body-fitted structural mesh blocks in the vicinity of bodies and solid surfaces, where the structured nature and orthogonality of the grid to the boundary can provide added accuracy and solution efficiency. Conversely, general unstructured partitions can be used to fill the remaining computational domain and connecting the structured mesh. The generation of unstructured grids can be readily automatically and requires less human intervention. The use of unstructured grid topology to connect the body-fitted blocks near solid boundaries can potentially greatly simplify the initial grid generation process.

2 Scope

To this end, a block-based AMR finite-volume scheme is proposed herein for solution of hyperbolic conservation laws on two-dimensional hybrid multi-block meshes. A Godunov-type upwind finite-volume spatial-discretization scheme, with piecewise limited linear reconstruction and Riemann-solver based flux functions, is applied to the quadrilateral cells of a hybrid multi-block mesh and these computational cells are embedded in either body-fitted structured or general unstructured grid partitions or subdomains of the hybrid grid. A hierarchical quadtree data structure is used to allow local refinement of the individual subdomains based on heuristic physics-based refinement criteria. The data structure permits an efficient and scalable parallel implementation of the proposed algorithm via domain decomposition. In addition, the nature of the structured blocks is exploited to reduce computational overhead and storage. The performance of the proposed parallel hybrid AMR scheme is demonstrated through application to the solution of the Euler equations of compressible gas dynamics for a number of flow configurations and regimes in two space dimensions. The efficiency of the AMR procedure and accuracy, robustness, and scalability of the hybrid mesh scheme are all assessed.

The final version of the paper will encompass a description of the finite-volume and AMR techniques, an in-depth discussion of the the hybrid meshing procedure and data structure, and a discussion of numerical results and performance of the hybrid solution method relative to those obtained using fully structured and unstructured grids. Sample numerical results for the interacting supersonic flow past two circular cylinders obtained using the proposed parallel AMR hybrid-mesh finite-volume scheme are shown in Figure 1.

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