Journal of Computational Physics 374 (2018) 692–723

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

A parallel direct cut algorithm for high-order overset methods with application to a spinning golf ball

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ARTICLE INFO

Article history:
Received 21 November 2017
Accepted 20 May 2018
Available online 4 August 2018

Keywords:
Overset
CFD
Flux reconstruction
Discontinuous Galerkin
GPU
Golf ball

ABSTRACT

Overset methods are commonly employed to enable the effective simulation of problems involving complex geometries and moving objects such as rotorcraft. This paper presents a novel overset domain connectivity algorithm based upon the direct cut approach suitable for use with GPU-accelerated solvers on high-order curved grids. In contrast to previous methods it is capable of exploiting the highly data-parallel nature of modern accelerators. Further, the approach is also substantially more efficient at handling the curved grids which arise within the context of high-order methods. An implementation of this new algorithm is presented and combined with a high-order fluid dynamics code. The algorithm is validated against several benchmark problems, including flow over a spinning golf ball at a Reynolds number of 150,000.

1. Introduction

Overset grids are a commonly used technique within the field of computational fluid dynamics (CFD) to enable the simulation of cases which involve the relative motion of several distinct bodies [1]. The idea is to generate a distinct mesh around each body and then overlay these meshes on top of a background grid. The relevant system of governing equations are then solved on each grid, with a hole cutting algorithm being used to transfer data between grids as required. Also known as the Chimera grid approach, this technique has enabled the accurate simulation of complex problems of engineering interest, including entire rotorcraft configurations with relative motion between one or more rotors in addition to a fixed fuselage.

One of the many advantages of this approach, compared with say deforming grids, is that it is possible to employ multiple solvers: an unstructured near-body solver to allow for easier mesh generation around each body, and a high-order Cartesian off-body solver with adaptive mesh refinement (AMR) for speed and simplicity. In most production codes used for complex geometries, such as the CREATE-AV HELIOS software [2], the near-body solvers are typically 2nd or 3rd order accurate in space. Higher-order near-body solvers are available, but only for (multi-block) structured grids currently, such as with the OVERFLOW code using 5th order accurate finite differences [3,4]. For the best possible performance, accuracy, and applicability to a wide range of complex geometries, however, a higher-order unstructured near-body solver is preferable. As shown by Wissink [5] and by Nastase et al. [6], without a high-order near body solver, vortical structures and other flow features incur high amounts of diffusion before (or while) passing into the high-order off-body solver, causing a large increase in error.

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https://doi.org/10.1016/j.jcp.2018.05.036
0021-9991/

High order methods have a number of attractive attributes. Not only are they less dissipative, enabling the simulation of vortex-dominated flows with fewer degrees of freedom than a lower-order method, but they have also been shown to give remarkably good results when used to perform implicit large eddy simulations (ILES) and direct numerical simulations (DNS) [7,8]. Popular examples of high-order schemes for unstructured grids include the discontinuous Galerkin finite element method, first introduced by Reed and Hill [9], and spectral difference (SD) methods originally proposed under the moniker 'staggered-grid Chebyshev multidomain methods' by Kopriva and Kolias in 1996 [10] and later popularized by Sun et al. [11]. In 2007 Huynh proposed the flux reconstruction (FR) approach [12]; a unifying framework for high-order schemes for unstructured grids that encompasses both the nodal DG schemes of Hesthaven and Warburton [13] and, at least for a linear flux function, any SD scheme. More recently, Romero et al. [14] proposed a simplified formulation of the FR approach, direct flux reconstruction (DFR), which exactly recovers the nodal DG version of FR.

Within the context of overset grids, high-order methods of the discontinuous variety are particularly attractive. By their nature, they involve a large amount of structured computation within each element, while relatively little data is needed from surrounding elements. In addition to providing high-order accuracy on unstructured grids, this compactness provides a significant advantage over finite difference and finite volume methods for overset grids. As described in detail by Galbraith [15], the artificial boundary (AB) approach is an entirely natural extension of these methods to handle element interfaces which may overlap another grid. For codes which utilize the message passing interface (MPI) paradigm for parallelization, only relatively minor modifications must be made to handle overset grids, since the AB faces appear identical to inter-processor boundaries.

A number of high-order solvers have been integrated into overset-grid frameworks in recent years, using both the traditional volume-interpolation approach [6,16,17] and the surface-based AB approach [15,18–20]. Research has focused on the DG and FR methods, with studies focusing on their use as either a near-body solver, an off-body solver, or both. Brazell and Kirby et al. [17,21] have developed an advanced overset-capable DG solver, with the focus on an off-body AMR solver capable of both h- and p-adaptivity to track flow features of interest and match the resolution of the near-body grid. Crabill et al. [19] previously showed an unstructured FR solver suitable for use on both near- and off-body moving grids, and Duan and Wang [20] more recently developed a similar capability for both mixed-element unstructured and semi-structured strand grids.

These studies and others indicate that high-order methods can maintain their order of accuracy on overset grids with a relatively small increase in absolute error. However, to date no group has presented an overset method capable of solving large-scale, dynamic Navier–Stokes problems on moving overset grids which uses high-order unstructured solvers throughout the domain. For static cases, the only requirement is that the overset interpolation process should add only a small amount of overhead to the underlying solver. In the case of moving grids, however, the entire overset connectivity must constantly be recomputed, so both the connectivity and interpolation together should not add a significant amount of overhead. This requires novel algorithms to perform the high-order overset connectivity quickly.

Furthermore, modern hardware is shifting towards the use of highly parallel accelerators such as Intel's line of Xeon Phi co-processors and NVIDIA's line of Graphical Processing Units (GPUs). These accelerators provide the potential for an order of magnitude improvement in terms of performance-per-Watt over conventional CPUs, but require algorithms that map well to their hardware architecture. In particular, algorithms which conserve memory bandwidth are essential since, on these platforms, memory bandwidth is typically the limiting factor. Fortunately, high-order finite element-type methods (such as DG and FR) map extremely well onto these architectures, but limited work has been done to map overset methods onto them [22].

In this work, we outline the development of a high-order GPU-accelerated solver capable of running on moving overset grids with curved elements. The underlying numerical solver, ZEFR, is able to run on tensor–product elements using the DFR scheme. ZEFR was developed in the Aerospace Computing Laboratory as a simple but high-performance CFD code for the purpose of developing new algorithms and applying them to useful test cases. The code is written in a combination of C++ and CUDA and can effectively target NVIDIA GPUs. Distributed memory systems are handled using the MPI standard. All overset-related connectivity and interpolation is handled within the external Topology Independent Overset Grid Assembler (TIOGA) library [23], to which modifications have been made for the present work. TIOGA handles the construction of binary search trees, the inter-process communication map, and approximate geometry representations, as well as performing donor searches and interpolation of solution data between grids. Our key advancement lies in a novel overset domain connectivity algorithm inspired by the work of Galbraith [15,18], Sitaraman [24], and others, and has been developed specifically to leverage the considerable speedup possible with modern hardware. The proposed method is simple, robust, and fast for arbitrary configurations of curved-element grids.

The remainder of this paper is as follows. In Section 2, the application of the AB overset method to DFR will be discussed, along with a review of existing overset grid assembly methods. Section 3 will discuss the additional work necessary to handle moving grids within the AB framework. In Section 4, existing direct cut methods will be reviewed, and our novel Parallel Direct Cut hole-cutting method will be presented. In Section 5 we present the results of several test cases run with our new method, including the challenging problem of a spinning golf ball at a realistic Reynolds number of 150 000. The performance and robustness of the method are also considered. Finally, in Section 7 conclusions are drawn.