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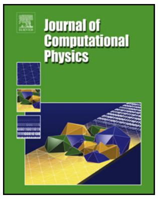

Simulation of moving boundaries interacting with compressible reacting flows using a second-order adaptive Cartesian cut-cell method

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ABSTRACT

A high-order adaptive Cartesian cut-cell method, developed in the past by the authors [1] for simulation of compressible viscous flow over static embedded boundaries, is now extended for reacting flow simulations over moving interfaces. The main difficulty related to simulation of moving boundary problems using immersed boundary techniques is the loss of conservation of mass, momentum and energy during the transition of numerical grid cells from solid to fluid and vice versa. Gas phase reactions near solid boundaries can produce huge source terms to the governing equations, which if not properly treated for moving boundaries, can result in inaccuracies in numerical predictions. The small cell clustering algorithm proposed in our previous work is now extended to handle moving boundaries enforcing strict conservation. In addition, the cell clustering algorithm also preserves the smoothness of solution near moving surfaces. A second order Runge–Kutta scheme where the boundaries are allowed to change during the sub-time steps is employed. This scheme improves the time accuracy of the calculations when the body motion is driven by hydrodynamic forces. Simple one dimensional reacting and non-reacting studies of moving piston are first performed in order to demonstrate the accuracy of the proposed method. Results are then reported for flow past moving cylinders at subsonic and supersonic velocities in a viscous compressible flow and are compared with theoretical and previously available experimental data. The ability of the scheme to handle deforming boundaries and interaction of hydrodynamic forces with rigid body motion is demonstrated using different test cases. Finally, the method is applied to investigate the detonation initiation and stabilization mechanisms on a cylinder and a sphere, when they are launched into a detonable mixture. The effect of the filling pressure on the detonation stabilization mechanisms over a hyper-velocity sphere launched into a hydrogen–oxygen–argon mixture is studied and a qualitative comparison of the results with the experimental data are made. Results indicate that the current method is able to correctly reproduce the different regimes of combustion observed in the experiments. Through the various examples it is demonstrated that our method is robust and accurate for simulation of compressible viscous reacting flow problems with moving/deforming boundaries.

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1. Introduction

Several engineering devices involve moving or deforming solid boundaries in a compressible reacting flow environment. Examples of such applications include propulsion systems with moving components such as Internal Combustion (IC) engines, hypersonic propulsive devices such as Oblique Detonation Wave (ODW) engines and solid rocket motors involving regressing propellant surfaces. Numerical simulations can be effectively employed to study the performance and optimization of these systems. However, in comparison to simulations with fixed boundaries, moving boundary simulations are difficult mainly due to a continuously changing physical domain. Additional complexities arise due to the interaction of the moving boundary with a reacting flow. The boundary motion in a reacting flow can result in compression or the expansion of the flow in the vicinity of the boundary which can have a significant effect on the flame propagating characteristics. In the case of hypersonic propulsion applications, a body moving at supersonic speed in a reacting flow can initiate and sustain an oblique detonation that can propel the body further accelerating it to hypersonic speeds [2]. All these factors thus make numerical simulations of moving boundary reacting flow problems, particularly challenging.

Both body conforming and non-body conforming approaches have been used in the past to study moving boundary problems. One of the body conforming methods for solving such flow problems involving moving surfaces is the Arbitrary Lagrangian Eulerian (ALE) scheme [3,4], which deploys a body-fitted unstructured mesh. In this approach, the mesh needs to be regenerated as the body moves such that it conforms to the body at all times. The mesh regeneration, however, can often lead to mesh tangling, especially when the body undergoes large structural displacements. Besides, generating a body conforming mesh, by itself can be quite challenging for a 3D and a complex geometry. Another popular structured mesh approach for simulation of moving boundaries is the Overset or Chimera [5] technique. In this approach, the embedded boundary is resolved by using a local structured meshed that overlay a background mesh. Fluid state variables are exchanged between the overlapping grids and the moving boundaries are handled by moving the associated mesh with it while the background mesh remains stationary. Henshaw and Schwendeman [6] employed the overset technique with success for simulation of moving boundaries in high-speed reactive and non-reactive flow. The main limitation of the overset technique is that if the boundary shape is complex, mesh generation becomes difficult.

The most attractive alternative in such scenarios is the use of Cartesian grid based immersed boundary (IB) methods, which does not require any mesh generation and hence is free of mesh tangling issues for complex and moving/deforming boundaries [7,34,8–10]. The challenge associated with any of the Cartesian grid based IB methods, however, is in achieving a smooth solution at the moving boundaries [11]. The three major Cartesian based IB methods that have been applied successfully for moving boundary problems are the Ghost cell Finite difference Method (GFM) [12–14], immersed interface method (IIM) [15] and the cut-cell methods [16,17]. In addition, there are several variants of sharp interface methods based on direct forcing approach [18] that have also been studied for moving body problems.

GFM is a finite difference based method and does not ensure strict conservation at the boundaries. The non-conservation of mass, momentum and energy can lead to spurious pressure oscillations at the boundaries, which is even more amplified as the boundary moves or deforms, whereby the fluid nodes change to solid nodes and vice versa [11]. A number of studies have been reported on applying the ghost fluid method (GFM) along with different correction schemes to mitigate the oscillation issue for complex moving/deforming boundaries. Chen et al. [19] employed a cut-cell based method, viz. the Pressure Saturated Computational cell (PSC) method in conjunction with GFM, to enforce conservation at the boundaries and thereby reducing the pressure oscillations. Lee and You [20] used a fully implicit time integration along with mass source/sink algorithm so as to address both the sources of oscillations in GFM based methods that were identified by Lee et al. [11]. Recently, Bergmann et al. [21] used a penalty correction to impose the right pressure boundary conditions in the GFM and suppressed the oscillations by using face-centered velocity. They have applied it for complex moving geometries in an incompressible medium. Mittal et al. [22] employed a multi-dimensional ghost-cell methodology, which was shown to simulate incompressible flow past 3D stationary, moving, as well as deforming bodies. One of the main challenges associated with extending the GFM method to moving boundaries is the problem of the “freshly cleared cells”, i.e. cells in the fluid region which were inside the solid region and got uncovered due to boundary motion [23]. These cells do have a time history of state variables and therefore require interpolation from neighboring cells. The interpolation can result in artifacts near the moving boundary which can be amplified for high speed reacting flow problems. The issue of non-conservation is also a major drawback for the GFM method. Especially, in the case of high-speed flows, loss of conservation can lead to an incorrect prediction of flow physics such as shock speed, detonation velocity, etc.

In contrast to GFM methods, cut-cell methods enforce strict conservation of mass, momentum and energy. However, there have been a limited number of studies reported on applying the cut-cell method to moving boundaries. Schneiders et al. [17,24] extended the work done by Hartmann et al. [25] for solving compressible viscous flow using cut cell method, to moving boundaries. In these studies, a variant of the flux redistribution technique previously developed by Pember et al. [26] was used for handling the small cell problem. The blending of a stable non-conservative update based on interpolation with an unstable conservative update based on time integration was done to achieve stability of the small cells and achieve a smooth temporal variation of surface forces on the boundary. The mass deficit/surplus due to the non-conservative update is distributed to the neighboring cells. However, the effect of flux distribution on the accuracy of the surface shear stress predictions was not discussed. Moreover, the cases demonstrated were restricted to bodies moving at low subsonic velocities. The capability of the method to handle large displacements at high speed was not addressed. In summary, all the aforementioned studies using immersed boundary methods or cut-cell methods are either of low accuracy (first or pseudo-