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Variable High-Order Multiblock Overlapping Grid Methods for Mixed Steady and Unsteady Multiscale Viscous Flows, Part II: Hypersonic Nonequilibrium Flows

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Abstract. The variable high-order multiblock overlapping (overset) grids method of Sjögreen & Yee [CiCP, Vol. 5, 2009] for a perfect gas has been extended to nonequilibrium flows. This work makes use of the recently developed high-order well-balanced shock-capturing schemes and their filter counterparts [Wang et al., J. Comput. Phys., 2009, 2010] that exactly preserve certain non-trivial steady state solutions of the chemical nonequilibrium governing equations. Multiscale turbulence with strong shocks and flows containing both steady and unsteady components is best treated by mixing of numerical methods and switching on the appropriate scheme in the appropriate subdomains of the flow fields, even under the multiblock grid or adaptive grid refinement framework. While low dissipative sixth- or higher-order shock-capturing filter methods are appropriate for unsteady turbulence with shocklets, second- and third-order shock-capturing methods are more effective for strong steady or nearly steady shocks in terms of convergence. It is anticipated that our variable high-order overset grid framework capability with its highly modular design will allow for an optimum synthesis of these new algorithms in such a way that the most appropriate spatial discretizations can be tailored for each particular region of the flow. In this paper some of the latest developments in single block high-order filter schemes for chemical nonequilibrium flows are applied to overset grid geometries. The numerical approach is validated on a number of test cases characterized by hypersonic conditions with strong shocks, including the reentry flow surrounding a 3D Apollo-like NASA Crew Exploration Vehicle that might contain mixed steady and unsteady components, depending on the flow conditions.

AMS subject classifications: 65Z05, 65M06, 65M50, 65M55, 65M60, 65M99, 65Y99

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Key words: Unstructured mesh, hypersonic flows, thermo-chemical nonequilibrium, residual distribution schemes, double cone.

1 Motivation, objectives and validation process

The time-accurate unsteady 3D compressible flow solver ADPDIS3D is supported by a grant from the Department of Energy (DOE) SciDAC multi-institute program through the Science Application Partnership (SAP) initiative. The objective of this grant is to develop, implement and validate this variable high-order 3D multiblock overlapping (overset) grid solver for problems involving turbulence with strong shocks and density variations. ADPDIS3D includes capabilities for both Direct Numerical Simulation (DNS), resolving all scales of the flow fields, and Large Eddy Simulation (LES), modeling the small turbulent scales. One of the unique features of the solver is its ability to perform DNS and LES computations in non-trivial geometries through the use of overset curvilinear grids. ADPDIS3D contains a large number of high-order finite difference schemes and shock-capturing schemes. These schemes can be used to perform accurate unsteady computations for flow speeds that range from nearly incompressible to hypersonic speeds [19, 27, 29–31, 34]. Importantly, the code implements many innovative low dissipative algorithms that adaptively use numerical dissipation from shock-capturing schemes as postprocessing filters on non-dissipative high-order centered schemes [19, 27, 29–31, 34]. These filter schemes were especially designed for improved accuracy over standard high-order shock-capturing schemes in capturing turbulence with strong shocks and density variations. For multi-dimensional curvilinear grids, the metrics are evaluated at the same high-order as the spatial base scheme with high-order freestream preservation [22].

Recently, these filter schemes were proved to be well-balanced schemes [34] in the sense that these schemes exactly preserve certain non-trivial steady-state solutions of the chemical nonequilibrium governing equations. With this added property the filter schemes can better minimize spurious numerics in reacting flows containing both steady shocks and unsteady turbulence with shocklet components than standard non-well-balanced shock-capturing schemes. For a description of the algorithms and their performance, including results of a detailed LES computation of temporal-evolving mixing layers, see e.g. [6, 19, 27, 29–31, 34]. Furthermore, ADPDIS3D contains three choices of solvers: standard compressible flow, compressible non-ideal MHD [27], and chemical nonequilibrium hypersonic flows [34]. For a more detailed description see [18, 19]. In order to improve numerical stability, a preprocessing step by conditioning the governing equations via entropy splitting [25], Ducros et al. splitting [4] or system form of the Tadmor entropy conserving form [5] is included in the procedure.

Multiscale turbulence with strong shocks and flows containing both steady and unsteady components require mixing of numerical methods and switching on the appropriate scheme in the appropriate subdomains of the flow fields, even under the multiblock grid or adaptive grid refinement framework. It is a non-trivial task to find adaptive