Wall-Modeled Lattice Boltzmann and Navier-Stokes Approaches for Separated Flows

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Lattice Boltzmann (LB) and hybrid Reynolds-averaged Navier-Stokes/large eddy simulation (RANS/LES) methods within the Launch Ascent and Vehicle Aerodynamics (LAVA) solver framework are applied to NASA's Revolutionary Computational Aerosciences (RCA) standard test cases for separated flows. A detailed comparison between the performance and accuracy of the two emerging numerical methodologies for turbulence resolving simulations, i.e. the LB and hybrid RANS/LES methods will be presented. This contribution addresses the RCA technical challenge to identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error for standard turbulence separated flow test cases. Results for the 2D NASA wall-mounted hump[1] and the axisymmetric transonic bump[2] including time-averaged pressure coefficient, skin friction, and velocity profiles, as well as resolved and modeled Reynolds stresses for both numerical approaches will be presented and differences between LB and hybrid RANS/LES will be discussed.

I. Introduction

The NASA Revolutionary Computational Aerosciences (RCA) sub-project has created a technical challenge to identify and down-select critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error for standard test cases of turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions. In an effort to address this technical challenge, the Lattice Boltzmann (LB) and hybrid Reynolds-averaged Navier-Stokes/large-eddy simulation (RANS/LES) methods within the Launch Ascent and Vehicle Aerodynamics (LAVA) solver framework are applied to the RCA standard test cases for separated flows. The first test case is the 2D NASA wall-mounted hump[1] with a reference Mach number of 0.1 and Reynolds number of 0.936 million based on the 0.42 m chord. The second test case is the axisymmetric transonic bump[2] with a reference Mach number of 0.875 and Reynolds number of 2.763 million based on the 0.2032 m chord. Both test cases have been previously studied using both numerical approaches by other researchers,[3–7] but no detailed comparison of the advantages and disadvantages between the two approaches has been performed. In this work, a detailed comparison between the performance and accuracy of the two emerging numerical methodologies for turbulence resolving simulations will be presented.

II. Computational Methodology

The LAVA solver framework[8] is utilized for the computational study. LAVA offers flexible meshing options and was developed with the intent of modeling highly complex geometry and flow-fields. The framework supports Cartesian and curvilinear structured grids as well as unstructured arbitrary polyhedral meshes. Overset grid technology[9] is used to couple the solutions across different overlapping meshes. In this study,

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the Cartesian grid approach is used with the LB method and the structured curvilinear overlapping grid methodology is used for the hybrid RANS/LES method. The Cartesian grids are automatically generated within the framework and the Pointwise$^{\text{TM}}$ and Chimera Grid Tools (CGT)[10] software packages are used to generate the curvilinear grids.

II.A. Lattice Boltzmann

The LB method is a mesoscopic approach wherein simplified kinetic equations that retain just enough detail to satisfy the desired macroscopic equations of fluid motion (weakly compressible, isothermal Navier-Stokes equations in the present context) are solved.[11] The local state of fluid motion is described by density distribution functions $f(\vec{x}, t, v)$, which upon being normalized by the local density represent the probability of finding particles moving with velocity v in an infinitesimal volume dx about $\vec{x}$. The familiar macroscopic variables such as density and the components of momentum are determined from the density distribution functions through moment summations.

The LB equation governs the space-time evolution of density distribution functions $f(\vec{x}, t, v)$. The density distribution function $f(\vec{x}, t, v)$ at a particular node of the lattice defines the fraction of mass contained in a control volume surrounding the node which moves at velocity v. For example, $f(\vec{x}, t, 0)$ defines the fraction of mass contained in the control volume which is at rest. The equation is solved numerically through an extremely efficient *collide at nodes and stream along links* algorithm. In a single time step the virtual, computational particles collide at a node relaxing towards the local *equilibrium* and subsequently hop on to the neighboring nodes of the lattice. The velocity space is commonly discretized into 15, 19 or 27 speeds on a regular cubic lattice in 3D, where the notation $DdQq$ describes a lattice in d dimensions with q discrete velocities. More details can be found in Barad *et al.*[12] Boundary condition and wall model details will be included in the presentation.

II.B. Hybrid RANS/LES

The compressible hybrid RANS/LES equations are solved using a low-dissipation high-order finite-difference formulation applied to the curvilinear transformed system of equations in strong conservation law form.[13] The Spalart-Allmaras (SA)[14] turbulence model is used as the base RANS closure model. Two zonal hybrid RANS/LES modeling approaches will be assessed. Implicit second-order backward differencing is used for time integration and the discretized equations are marched in pseudo-time until a sufficient reduction in the residual has been achieved for each physical time-step (approximately 3 to 4 orders of residual reduction is achieved in the present computations). The nonlinear system of equations are linearized at each pseudo time-step and an alternating line-Jacobi relaxation procedure is applied. Local pseudo time-stepping is used to accelerate convergence. Domain decomposition and the Message Passing Interface (MPI) are used to enable a scalable parallel algorithm. Details of the numerical method and turbulence modeling can be found in Housman *et al.*[15,16]

III. Summary

Results from the application of the LB method using Cartesian grids and the hybrid RANS/LES method using structured overlapping grids on RCA separated flow test cases will be presented. Accuracy, efficiency, and robustness will be compared between the two approaches. Successes and challenges inherent to each method will be discussed as well as a roadmap towards achieving the RCA goals.

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