TN

BW

MP

CI

KINETIC SIMULATIONS OF UNSTEADY SHOCK-BOUNDARY LAYER INTERACTIONS

Allocation: Illinois/52 Knh
PI: Deborah A. Levin[1]

[1]University of Illinois at Urbana-Champaign

EXECUTIVE SUMMARY

Hypersonic flow over configurations such as a double wedge at continuum-like free stream conditions has been a challenging problem because of the multiple shock–shock and shock–boundary layer interaction, separated flows near the hinge, shear layer, and three-dimensional effects. These conditions generate a mesh that is highly nonuniform because of very high levels of refinement near the surface due to extremely high flow gradients in temperature and pressure. The octree cells lying in this region are highly refined as compared to those in the free stream and inside the geometry leading to a high degree of load imbalance among the processors, which can cause significant increases in communication time. In addition, these flows are unsteady in nature but provide an opportunity to study flow stability mechanisms and identify near-transition behavior. However, large sizes of additional particle data must be collected in order to analyze the time-dependent signals.

RESEARCH CHALLENGE

Hypersonic compressible flows are characterized by significant gradients in fluid density, high fluid temperatures, and a large degree of nonequilibrium. The multiscale nature of these problems makes it a challenge in terms of flow physics and computational intensity. This work was motivated by the study of laminar shock wave boundary layer interaction (SWBLI) problems, which are especially difficult to accurately model due to complex shock interactions, flow separation, three-dimensional effects, and shear layers. All these effects play a significant role on aerothermodynamic quantities such as heat transfer, skin friction, and pressure loads over different angular sections. The particle-based Direct Simulation Monte Carlo (DSMC) method is a good candidate to simulate such flows because it solves the Boltzmann transport equation exactly; hence, it is valid even in strong shock regions where the continuum assumptions inherent in the derivation of Navier–Stokes equations fail. However, the extent of its applicability to such problems has been limited by the high computational requirements arising from the need to simulate a large number of particles to satisfy DSMC requirements such as having the cell size comparable to the local mean free path, a time step that is smaller than the local mean collision time, and sufficient numbers of particles per cell to perform collisions.

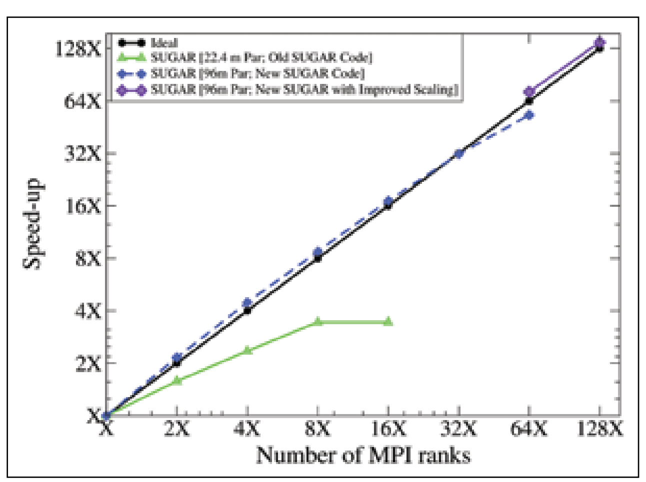

Figure 1: Strong scaling performance of the improved SUGAR DSMC code.

METHODS & CODES

We have developed a three-dimensional MPI-parallelized DSMC code known as Scalable Unstructured Gas-dynamic Adaptive mesh Refinement (SUGAR). The code uses new techniques to simulate hypersonic, compressible flows such as an octree-based adaptive mesh refinement (AMR) implementation for capturing multiscale physics, linearized representation of an unstructured grid using Morton-Z space filling curve for efficient access of computational cells, an accurate cut-cell algorithm to compute correct volume of intersected computational cells, algorithmic improvements for efficient gas–surface interactions, and array-based data structures for optimal use of cache memory utilization [1].

A great deal of work has been done to improve the scalability of the code. In brief, the improvement in the strong scaling, as compared to the original SUGAR version presented at the Blue Waters conference approximately two years ago, is shown in Fig. 1, where a near-ideal scaling is now obtained for a 128 times increase in the number of processors for hypersonic flow over a hemisphere with 96 million computational particles (with X=32 for the blue and purple lines). The result presented two years ago (green line with X=128) achieved poor parallelization, and exhibited very long run times well. In addition, 87% weak scaling was obtained for 8,192 processors for a hemisphere flow with 24 billion particles.

RESULTS & IMPACT

We have recently simulated an even more computationally challenging flow over a double wedge using 768 nodes, with 24 billion particles and 1.8 billion computational cells. The double wedge geometry has the forward and aft angles of 30° and 55°, with a length of 50.8 mm for the first wedge. The flow conditions corresponded to a free stream Mach number, velocity, static pressure, and unit Reynolds number of 7.14, 3,812 m/s, 0.78 kPa, and 52,200, respectively. For this simulation shown in Fig. 2, the VHS model and the majorant frequency scheme were used and gas–surface interactions were modeled using the Maxwell's model with full momentum and energy accommodation.

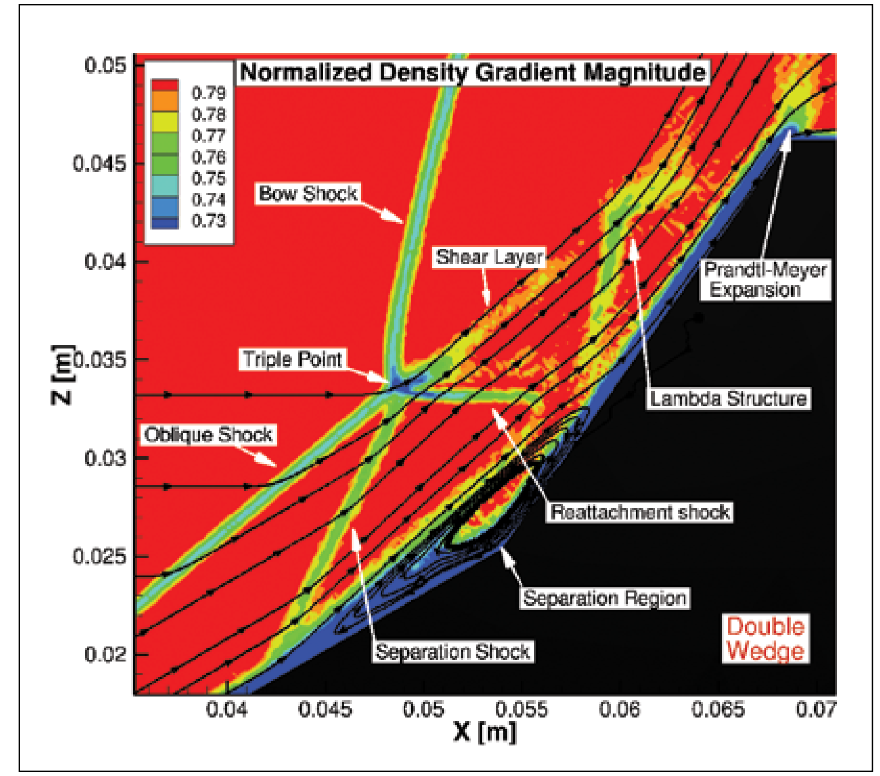

Figure 2: Shock–shock interactions for hypersonic flow over a double wedge at an early time in the evolution of the unsteady flow.

Fig. 2 shows the resolution of the highly complex shock physics that occurs in this domain of hypersonic shock–boundary layer interaction flows. An oblique shock is formed at the leading edge of the lower wedge and a bow shock forms in front of the upper wedge. As the flow moves up the lower wedge, an adverse pressure gradient is formed and the boundary layer separates, which generates a separation shock. These three shocks meet at the triple point, and with their interaction a transmitted shock (also known as the reattachment shock) is formed. The reattachment shock impinges on the upper wedge and the thickness of the boundary layer reduces at the impingement point. This point is usually where the boundary layer reattaches to the surface. The zone embedded among the hinge, separation point, and the reattachment point is the separation zone where recirculation is observed. Note that the flow downstream of the bow shock is subsonic, but the flow going through the oblique, separation, and reattachment shocks remains supersonic. Therefore, a contact surface, also known as the shear layer, is formed across which the pressure is constant; however, the velocities and temperatures are different. The reattachment shock, after reflecting off the boundary layer, forms expansion waves, which reflect at the contact surface and coalesce to form a compression wave. Even though this flow is still laminar, it is unsteady, and future calculations on Blue Waters will enable us to use global linear stability analysis to understand the different excitation and decaying eigenmodes as well as the nature of the disturbance in terms of acoustic, entropy, or vortical waves [2].

WHY BLUE WATERS

The time-accurate, large-scale DSMC simulations performed to obtain the results shown in Fig. 2 require on the order of 100,000 node-hours to reach a steady state of 1 millisecond. These are the first simulations that enable the hypersonic laminar shock boundary layer interaction community to understand the role of slip in a fully 3D simulation. In addition, we have made extensive use of the CPMAT and Perf-tools profiler on Blue Waters for testing these algorithmic improvements.

PUBLICATIONS AND DATA SETS

[1] Sawant, S., O. Tumuklu, R. Jambunathan, and D. A. Levin, Novel Use of AMR Unstructured Grids in DSMC Compressible Flow Simulations. *AIAA Aviation Forum* (AIAA, Denver, Colo., June 5–9, 2017).

[2] Tumuklu, O., D. A. Levin, and V. Theofilis, On the temporal evolution in laminar separated boundary layer shock-interaction flows using DSMC. *55th AIAA Aerospace Sciences Meeting* (AIAA, Grapevine, Texas, January 9–13, 2017).