MODAL DECOMPOSITIONS OF SHOCK INTERACTIONS

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EXECUTIVE SUMMARY

Hypersonic flows involving Edney type IV/V shock wave boundary layer interaction (SWBLI) systems are characterized by complex multilength-scale features that include the triple point, separation bubble, shear layer, and shocklets. These features lead to a complex flow dynamics that is characterized by thermal nonequilibrium downstream of the bow shock as a result of the small residence time of the flow, a low-frequency unsteadiness associated with the laminar separation bubble (caused by a strong pressure rise along the surface), the potential growth of the Kelvin–Helmholtz instability in the shear layer at the contact surface downstream of the triple point, periodic oscillations of the triple point, and Goertler vortices (secondary flows that appear in a boundary layer flow along a concave wall) owing to curved streamlines on the outer side of the separation bubble. The PI seeks to understand these phenomena using the particle-based direct simulation Monte Carlo (DSMC) method, which is valid for a greater range of local Knudsen numbers than Navier–Stokes equations. This work is important because the accurate modeling of SWBLIs is crucial to design hypersonic vehicles with the best possible performance.

RESEARCH CHALLENGE

Given the complexities of the 3D finite span simulation, it is pertinent first to understand the behavior of the 2D base flow under self-excited, spanwise homogeneous perturbations by simulating flow over the double wedge of a chosen span length with periodic flow domain boundaries in the spanwise direction. Such perturbations could be generated inside the laminar separation bubble and grow, or the shock system may amplify the disturbances naturally present in the free stream. Growing perturbations may have a range of different wavelengths; however, this work involves the wavelength for which the growth is maximum since the spanwise periodic flow structures will exhibit this particular wavelength. The spanwise periodic case can shed light on the stability of the base flow under self-excited perturbations, the wavelength of spanwise periodic structures, their origin, and their time-accurate temporal behavior. In addition, the perturbations present in the separation bubble may have a range of dominant frequencies. One of the broader objectives of this research is to find out if there is a link between the frequency of shock oscillation and the characteristic frequency associated with the growth and shrinkage of the separation bubble. The second challenge of this work is the development and verification of a linear stability analysis framework that takes into account thermal nonequilibrium, thereby extending its application to hypersonic SWBLI systems.

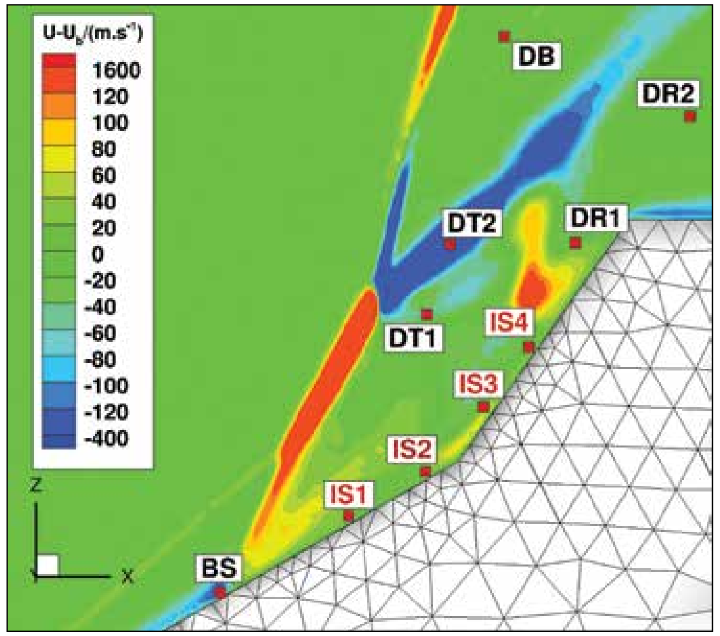

Figure 1: Location of numerical probes in the hypersonic flow over the double wedge showing the difference between the instantaneous and steady state streamwise velocity fields.

METHODS & CODES

The scalable unstructured gas-dynamics adaptive mesh refinement (SUGAR) DSMC code was developed and optimized on Blue Waters by making several improvements in the data structure of particles and how they are accessed from computational cells [1]. Two key findings are summarized here. First, with profiling and comparison with an older Cartesian grid code with two-level mesh adaption, SMILE, the PI found that the significant computational bottleneck was not the collision step (the usual problem) but rather the particle-mapping step to an unstructured grid. This led to the conclusion that since particle selection and mapping are performed extensively in DSMC, the previous use of the recursive pointer approach was unacceptably high. The SUGAR computational tool instead utilizes linearized data structures based on Morton Z space-filling curves. In this approach, only the leaves of an octree are stored with each leaf cell assigned a unique Morton index with which it can be accessed. During the mapping phase, based on a particle's position, maximum depth of the root, and its minimum node position, a unique Morton index is computed that is the particle's leaf cell index.

RESULTS & IMPACT

A number of key results from this work were presented in a poster at the recent International Union of Theoretical and Applied Mechanics (IUTAM) Transition meeting [2]. Toward the goal of studying the stability of base flows under self-excited perturbations, a preliminary spanwise periodic case was simulated with a span length of 72 mm, which is twice the size of the separation length defined; *i.e.*, the distance between the separation and reattachment points. The case started from a precomputed 2D base flow field extruded in the spanwise direction and was run for 0.25 ms, such that one cycle of the low-frequency wave through the oblique bow shock was captured. To compute the frequency of this wave, a numerical probe was placed downstream from the bow shock at the point labeled "DB" in Fig. 1. Fig. 2 (left) shows the L_2 norm of instantaneous residual kinetic energy at probe location DB. Planes 1 to 5 listed in the legends of Fig. 2 (left} correspond to data sets obtained at the same X and Z coordinates of the probe DB but at different spanwise (Y) coordinates of 1, 15.4, 29.8, 44.2, 58.6 mm, respectively. As the changes in the bow shock are felt downstream in the residual kinetic energy at probe DB, two peaks can be identified after the initial transient period of 0.05 ms. Based on the difference between the time at which those two peaks occur, the corresponding shock frequency, fs, is calculated as 8 kHz. At probe locations IS1, IS2, IS3, and IS4, which lie inside the separation bubble, the residual kinetic energy grows linearly, whereas at all other probe locations it decays linearly (not shown). Fig. 2 (center) shows the unsteady dynamics in the residual kinetic energy at probe location IS1, where the frequency of fluctuations inside box one is approximately 21 times larger than the shock frequency. The zoom of the data in box two, shown in Fig. 2 (right), reveals differences in the residual history among spanwise shifted locations of five copies of probe IS1 indicating spanwise flow perturbations. A detailed analysis of the frequencies associated with the separation bubble and an estimate of the spanwise wavelength can be found in the PI's recently presented work [3].

WHY BLUE WATERS

These simulations show for the first time that self-excited perturbations are present even at two orders of magnitude lower unit Reynolds number in hypersonic flow. They also show that the estimate of the spanwise wavelength of flow structures of 7.2 mm [3] is reasonable. With this estimate, the size of the simulation can be reduced by decreasing the span length to 28.8 mm from 72 mm. Such numerical investigations can only be performed with petascale computational assets such as Blue Waters, where this research has used about 60 billion particles and 4.5 billion computational cells. Such runs require about 86,000 Blue Waters node-hours to simulate an unsteady flow for 0.1 ms.

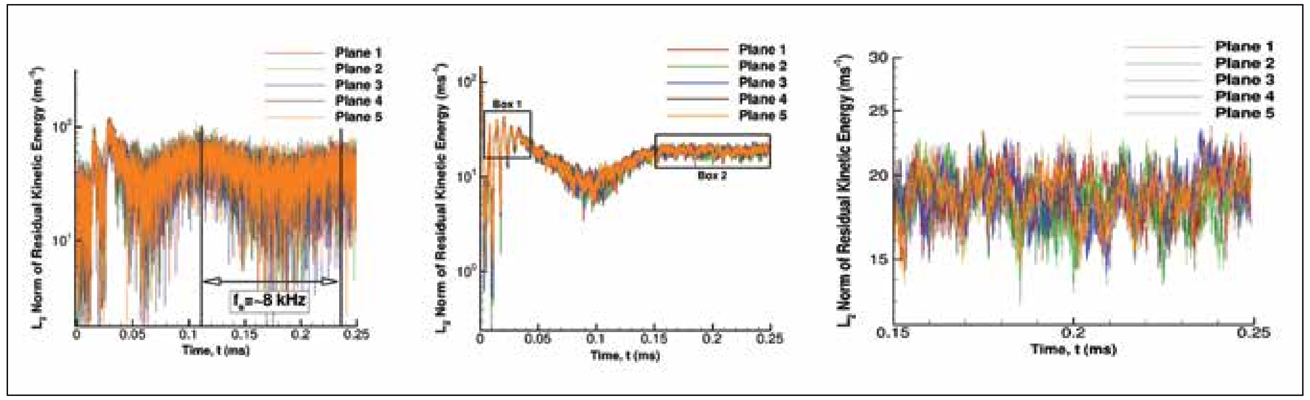

Figure 2: The time history of L_2 norm of residual kinetic energy at probe locations DB (left) and IS1 (center), shown in Fig. 1 and zoomed (right) at the rectangular box marked in the center figure. DB and IS indicate portions of the flow field that are downstream of the strong bow shock and in the separation bubble, respectively.