Parallel Simulation of Laser-Induced Shock Wave Reflection Transition

D.V.Khotyanovsky[1], D.D.Knight[2], A.N.Kudryavtsev[1], M.S.Ivanov[1]

[1]Institute of Theoretical and Applied Mechanics,
Russian Academy of Sciences, Siberian Division,
4/1 Institutskaya str, Novosibirsk, 630090, Russia

[2]Rutgers - The State University of New Jersey,
98 Brett Road, Piscataway, NJ 08854-8058, U.S.A

Two different wave configurations, regular reflection (RR) and Mach reflection (MR) are possible in steady shock wave reflection. For strong shock waves (i.e. for flow Mach numbers M>2.2) there exists a range of angles of incidence $\alpha_N < \alpha < \alpha_D$ (dual solution domain) where both reflection types are theoretically possible. Here α_N is the von Neumann criterion, α_D is the detachment criterion. The RR is impossible for $\alpha > \alpha_D$ and the MR is impossible for $\alpha < \alpha_N$. The difference between these criteria grows with increasing flow Mach number M, e.g. at M=4 α_N=33.4˚, α_D=39.2˚, and at M=10, α_N=25.2˚, α_D=39.7˚. In the range $\alpha_N < \alpha < \alpha_D$(*dual solution domain*) both steady RR and MR are possible. Part of the dual solution domain is in the range of the operating conditions of supersonic air intakes, so it is practically important to obtain a deeper understanding of this problem. This is even more pronounced for the effective design of prospective hypersonic vehicles. Mach reflection is much worse in terms of total pressure recovery, which makes it crucial for air-breathing engines to provide flow deceleration through an RR rather than MR.

The existence of two possible steady shock wave configurations at the same flow parameters implies the possibility of flow control by means of some energy addition into the free stream. In the experiments performed at Gasdynamics Laboratory of the Rutgers University[1] the impulse laser energy deposition upstream of the shock reflection configuration was studied. It was observed that the laser pulse focused in some small volume results in formation of a blast wave, which propagates in the free stream and interacts with the steady MR reflection. It was observed that during this interaction Mach stem height is reduced significantly. In principle, such energy addition may serve as a method of controlling the type of shock wave reflection.

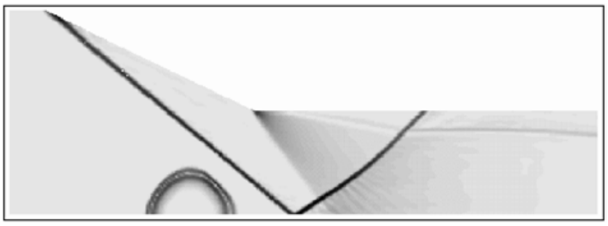
In this study we perform 3D unsteady numerical simulation of the interaction of a steady shock wave reflection with a laser-induced blast wave propagating in the free stream. We assume that in some focal region there is an instantaneous laser energy release, which results in an abrupt isochoric heating of the gas in this region. Numerical simulation is performed with 3D unsteady Euler equations with perfect gas model. Initial temperature distribution in the laser spot has the Gaussian shape. Although very simple, this model gives satisfactory results, which is confirmed by the comparison with the experimental data on blast wave locations at different time moments.

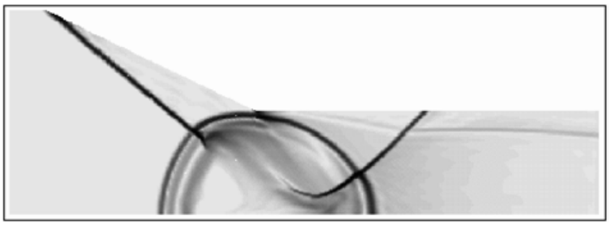
The essential features of this problem is flow three-dimensionality and unsteadiness. Correct simulation of the complex process of the blast wave interaction with steady shock wave reflection poses several problems for CFD methods. These are mainly related to strong shock waves and very low density regions observed in different areas of the flow; unsteady phenomena, and non-uniqueness of steady solution. The three-dimensional unsteady Euler equations are solved with the high-order total variation diminishing (TVD) scheme. The HLLE (Harten-Lax-van Leer-Einfeldt) solver [2] is used to calculate the numerical fluxes on the intercell boundaries because of its robustness for flows with strong shock waves and expansions. The flow variables on the inter-cell boundaries is reconstructed from cell averaged values using the 4-th order formula [3]. The use of high order reconstruction formula allows us to decrease a large numerical diffusion inherent to the HLLE solver and provide a high resolution of the smooth part of the solution without loss of robustness near strong shock waves. A multiblock body-fitted structured grid may be used in simulations. The third order explicit TVD Runge-Kutta scheme[4] is chosen as a time stepping method. It should be noted that an accurate modeling of unsteady phenomena can prove to be important in this problem.

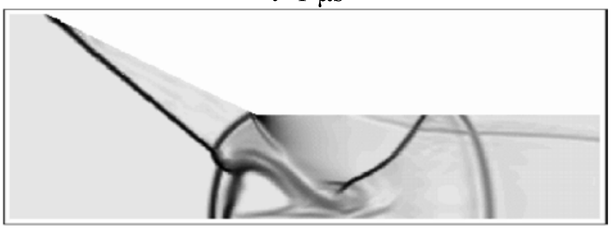
The code is made parallel in a distributed memory fashion using MPI subroutines. We rely upon MPI library since it is most portable and widely used message passing software. Since our code is explicit in time, its parallelization is rather straightforward. The entire computational domain is decomposed into subdomains of equal size. The data corresponding to each subdomain are allocated to each processor. To perform the computation in each subdomain, the data in a few adjacent grid cells from the left and from the right should be provided. This is achieved with the MPI "send" and "receive" operations. Though very simple, this parallel implementation is quite efficient in terms of parallel speedup. The following table presents scaled speedup of the parallel computation of a test problem (uniform flow in a rectangular channel). The computations were run on Intel Pentium III 800 MHz Linux cluster of the Institute of Theoretical and Applied Mechanics with the Fast Ethernet 100 Mbit-per-second connection.

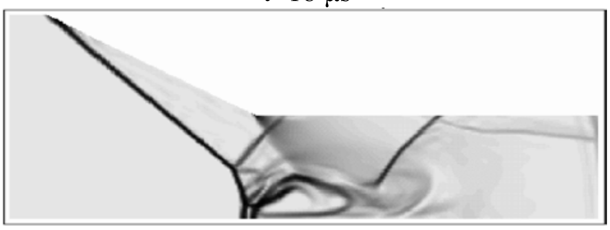
N_{CPU}	Number of cells N_x x N_y x N_z	Size of the domain L_x x L_y x L_z	Wall clock time in seconds
1	40x120x40	1x3x1	1360
2	40x240x40	1x6x1	1378
4	40x480x40	1x1x1	1430
8	40x960x40	1x24x1	1536

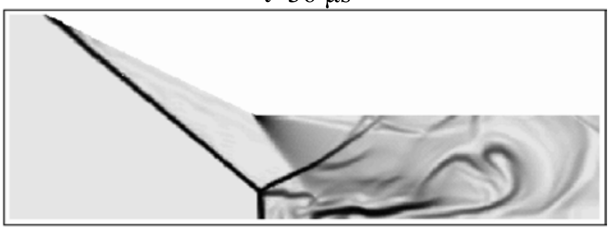
In the following figures we present our results on laser energy deposition ahead of the steady regular shock wave configuration. The flow conditions are: Mach number M=4, stagnation temperature T_0=293 K, stagnation pressure P_0 = 1.2x10^6 Pa. Symmetrical double-wedge model has the following dimensions: wedge chord is w = 30 mm, the non-dimensional gap between two wedges is g/w = 0.43, the wedge span is b/w = 3.37. Laser energy input was 317mJ. We assume that the laser pulse was focused upstream of the RR on the symmetry plane at point, which is 0.31w upstream of the trailing edges of the wedges. In this arrangement we use mirror boundary conditions on the plane of symmetry. Sequence of images given below (numerical schlieren in the vertical plane of symmetry) illustrates the process of an interaction of a laser induced blast wave with steady RR. Finally, we obtain a steady Mach reflection in this case. Total number of cells in the domain was 4.6 million.

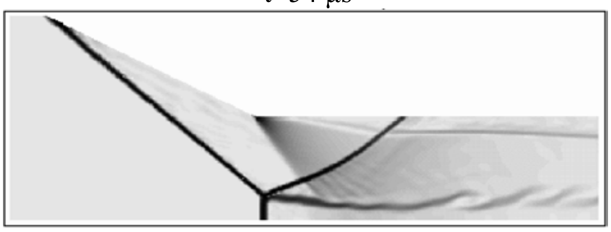

t=1 μs


t=18 μs


t=36 μs


t=54 μs


t=90 μs


t=296 μs

Acknowledgements.

This work was supported by the Russian Foundation for Basic Research under grants 03-01-00244 and 03-07-90403. Some computations were performed at National Center for Supercomputing Applications (NCSA), U.S.A.

References

1. R. Adelgren, H. Yan, G. Elliott, D. Knight, T. Beutner, A. Zheltovodov, M. Ivanov, and D. Khotyanovsky. Localized flow control by laser energy deposition applied to Edney IV shock impingement and intersecting shocks. AIAA paper 2003-0031.
2. B. Einfeldt, C.D. Munz, P.L.Roe, B.Sjögren (1991) On Godunov-type methods near low densities, J. Comput. Phys., V. 92, pp.273-295.
3. S. Yamamoto, H. Daiguji (1993) Higher-order-accurate upwind schemes for solving the compressible Euler and Navier-Stokes equations, Computers and Fluids, V. 22, pp. 259-270.
4. C.-W. Shu, S. Osher (1988) Efficient implementation of essentially non-oscillatory shock capturing schemes, J. Comput. Phys., V.77, pp. 439-471.