Parallel simulation of laser-induced shock wave reflection transition *

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Parallel numerical simulation was performed to study the effects of pulsed laser energy deposition on steady regular and Mach shock wave reflections. A single laser pulse is focused upstream of the incident shock waves. It causes formation of a hot-spot region and a blast wave, which interacts in a complex way with a steady shock wave reflection pattern. It was found that the laser energy addition in the free stream may force the transition between regular and Mach reflections in the dual solution domain.

1. INTRODUCTION

Two different wave configurations, regular reflection (RR) and Mach reflection (MR) are possible in steady shock wave reflection (see Fig. 1). 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 (Fig. 2). Here $\alpha_N$ is the von Neumann criterion, $\alpha_d$ is the detachment criterion. The RR is impossible for $\alpha > \alpha_d$ and the MR is impossible for $\alpha < \alpha_N$. Whether an RR or an MR actually appears at some flow parameters is an important issue for supersonic inlets, since flow deceleration through an MR causes significant total pressure losses compared to those through an RR. The difference between $\alpha_d$ and $\alpha_N$ criteria grows rapidly with increasing flow Mach number, so it becomes even more important for scramjet propulsion and the effective design of prospective hypersonic vehicles.

Non-uniqueness of the steady state configuration in the dual solution domain and related hysteresis phenomenon in RR $\leftrightarrow$ MR transition first proposed in [1] was observed in numerical simulations [2] and some later numerical studies (see the recent review in [3]). The first experimental evidence of the hysteresis was obtained in [4]. Nevertheless, the MR dominates in the dual solution domain in most experiments. This is usually explained by the influence of wind tunnel disturbances that promote the transition to

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Figure 1. Flow schematic for regular (top) and Mach (bottom) shock wave reflections

Figure 2. Theoretical transition criteria and dual solution domain

the MR. In the recent experiments [5] performed in a low-turbulent facility the hysteresis in steady RR ↔ MR transition occurs in exact agreement with theoretical values. The effects of flow disturbances on steady RR ↔ MR transitions were studied numerically in [6]. It was found that a forced RR → MR transition in the dual solution domain may be achieved quite easily with disturbances of different types. Reverse, MR → RR transition was also observed for some special "cold-spot" density perturbation. The amplitude of this perturbation had the order of magnitude for the flow parameters in the middle of dual solution domain, so it was claimed it was impractical.

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 Rutgers University [7] 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 with a hot spot at the center. The entire pattern propagates in the free stream and interacts with the steady MR reflection. It was also observed that during this interaction Mach stem height is significantly reduced (about five times). The Mach stem returned to its original size after the interaction, so the complete MR → RR transition was not achieved in these experiments. Most likely, this was due to the influence of the wind tunnel disturbances. Nevertheless, we believe that such an energy addition may serve as a method of controlling the type of shock wave reflection. Moreover, preliminary computations performed at Rutgers [7] with the GASP code showed the possibility of a forced MR → RR transition in this case.

In this paper we perform parallel numerical simulations to investigate the unsteady
process of the interaction of a three-dimensional steady shock wave configuration (RR or MR) with a blast wave initiated in the free stream by a focused laser pulse. The main objective of this study is to investigate capability of such energy addition to force the transition between RR and MR. Another interesting issue to be studied is the mechanism of this interaction.

2. PROBLEM FORMULATION AND MODELING ISSUES

2.1. Problem formulation

We consider two symmetrical wedges at equal angles of attack $\theta$ installed into a supersonic flow with the Mach number $M$. The wedge chord is $w$, the normalized gap between trailing edges of the two wedges is $2g/w$, normalized wedge span is $b/w$. Two inclined shock waves with angles of incidence $\alpha$ are generated by the wedges. The incident shocks interact with each other on the horizontal plane of symmetry halfway between the wedges (in other words, the incident shock is reflected from the plane of symmetry). This configuration is usually used in experiments on steady shock wave reflection since boundary layer effects on the reflecting plane are eliminated in this case. The steady RR or MR shock wave configuration may appear for the flow parameters inside the dual solution domain, i.e. for $\alpha_N < \alpha < \alpha_d$. Note, since the wedges have a finite span $b$, the flow has a three-dimensional component due to the influence of the expansion waves propagating into the central portion of the flow from the wedge tips. The origin of the three-dimensional cartesian coordinates is set at the point halfway between the trailing edges at the plane corresponding to the wedge half-span. The $x$ axis coincides with the direction of the flow, $y$ and $z$ axes are, respectively, vertical and transverse coordinates.

We assume that the energy is instantaneously released in some small focal volume (this assumption corresponds well to the experiments [7], where the laser pulse duration was 10 ns). The gas in the focal volume is heated at constant density. The temperature is incremented by an amount $\Delta T$ according to

$$\Delta T(x, y, z) = \Delta T_0 \exp \left( -\frac{r}{r_0} \right)^2,$$

where $\Delta T_0$ is determined by the total energy deposited and $r_0$ is set to one-half of the radius of the focal volume of the laser pulse. We assume that the gas is perfect, and breakdown of air is not considered here. Though very simple, the proposed model yields quite satisfactory results in comparison with available experimental data on propagation of a laser-induced blast wave. The comparison will be given below.

2.2. Numerical techniques

The three-dimensional unsteady Euler equations for a perfect gas with the specific heats ratio $\gamma = 1.4$ are solved with a high-order total variation diminishing (TVD) scheme. The HLLE (Harten—Lax—van Leer—Einfeldt) solver is used for evaluation of the numerical fluxes on the inter-cell boundaries because of its robustness for flows with strong shocks and expansion waves. The variables in the “left” and “right” states on the inter-cell boundaries are reconstructed from cell averaged variables using the 4-th order formula of [8]. The reconstruction is applied to the primitive variables (density, velocity components and pressure). The use of a high-order reconstruction allows us to decrease large numerical
dissipation inherent in the HLLE solver and provide high resolution in the regions where solution is smooth without a loss of robustness near strong shock waves. The third-order explicit Runge–Kutta scheme is used for advancing solution in time. It should be mentioned that an accurate modeling of unsteady phenomena is important in this problem. In our Euler computations we replace the wedges by two inclined infinitely-thin flat plates for easier generation of the body-fitted quadrilateral grid. Due to the symmetry of the problem, the computations are performed either in a quarter of the domain (if the laser pulse is located at $y = 0$, $z = 0$), or in a half of the entire domain (if the laser pulse is located at $y \neq 0$, $z = 0$). The inflow boundary of the domain is a uniform supersonic flow with all variables imposed. The extrapolation boundary conditions are used at the other boundaries of the domain. The inviscid wall (non-permeable) conditions are used on the plates and planes of symmetry. The computations start with the uniform supersonic flow filling the entire computational domain. The computations are performed until the steady three-dimensional RR configuration is formed. To obtain an MR, the perturbation technique similar to [6] is applied. The flowfield is then advanced in time until a steady MR is formed. These steady RR or MR flowfields are used as initial data for simulation of laser energy release. A multi-block body-fitted grid is used in the simulations with the number of cells up to 30 million. Large number of cells is required to provide high grid resolution in the region of interaction.

2.3. Parallel simulation
The code is parallelized with MPI library using the domain decomposition technique. Total number of CPU used is up to 64. The entire computational domain is decomposed into equal subdomains along $x$-axis according to the number of CPU used in the computation. The data exchange is performed only between the adjacent subdomains for three halo cells from each side. Although simple, this parallelization technique yields good results in terms of parallel efficiency and scalability. Figure 3 presents the scaled speedup obtained with fixed number of grid cells per CPU ($40^3$, $80^3$ and $100^3$ in three cases).

2.4. Validation
We performed a comparison of the numerically obtained results with experiments [9]. In these experiments the laser-induced blast wave propagation in quiescent air was studied. Figure 4 shows the blast wave position as a function of time for the 112$mJ$ laser pulse. Although the blast wave in this case is apparently spherical, the numerical computations were performed with three-dimensional Euler equations to provide validation of the 3D flow solver to be used for simulations of the blast wave/RR-MR interactions. The computations were performed in a cubic domain with $40^3$ and $80^3$ cells. The agreement with the experimental data is quite good, which ensures the validity of the proposed model of the laser energy deposition.

3. RESULTS
The first case considered here is an interaction of the laser induced blast wave generated in the free stream with a steady RR configuration. The flow Mach number is $M=4$, angle of incidence $\alpha = 36$ (corresponding to $\theta = 23$) lies approximately in the middle of the dual solution domain (for $M = 4$ $\alpha_N = 33.4^\circ$, $\alpha_d = 39.2^\circ$). Geometrical parameters are
Figure 3. Scaled speedup

Figure 4. Blast wave propagation in quiescent air in experiment and computations

\[ w = 30\text{mm}, \ g/w = 0.43, \ b/w = 3.37. \] The laser energy input was 0.1J, and the laser spot was located at \( x = -0.94w, \ y = 0, \ z = 0, \) i.e. on the plane of symmetry upstream of the reflection point. First, we obtain the steady three-dimensional RR configuration. Then, at time moment \( t = t_0 \) we perform the energy release. Figure 5 presents the Mach number flow fields in two crossing planes of symmetry for the blast wave propagation in the free stream and initial stages of its interaction with an RR. The instantaneous energy release causes strong heating of the gas in the focal region (Mach number is close to zero at the central part of the hot spot). This heating causes pressure rise, followed by a formation of a spherical blast wave. At first time moments, the velocity of the leading shock is high enough so the windward front of the blast wave propagates slightly upstream of the initial laser spot location (Fig. 5a). At the successive time moments, the entire blast wave configuration with a hot spot in the center convects downstream and starts interacting with the RR (Fig. 5b). As the subsonic hot-spot reaches the shock reflection region, it breaks up completely the RR shock wave pattern. The entire process of the interaction is illustrated in Fig. 6, where the numerical schlierens in the vertical symmetry plane \( z=0 \) are given at different time moments. A complex shock-vortex pattern is formed in the region of incident shocks intersection (Fig. 6c). The flow behind a convex "bridge"-shock is subsonic. This pattern is eventually transformed into Mach stem configuration (Figs. 6d-6e). Finally, the complete transition to a steady Mach reflection occurs, which is shown in Fig. 6f. It is noteworthy that similar transition process was observed in our computations at some different flow parameters (flow Mach number, geometry, energy deposited, etc.) with the laser spot on the centerline. These results, not presented here, suggest that the RR \( \leftrightarrow \) MR transition in the dual solution domain may be achieved quite easily with a rather small flow perturbation, which is in accordance with [6].

From the practical point of view, it is more interesting to achieve a forced MR \( \rightarrow \) RR
transition. Mach reflection dominates in the dual solution domain in most experiments performed in different wind tunnels. As was discussed above, RR is observed in the whole extent of the dual solution domain only in the wind tunnels with low levels of free-stream fluctuations. Hence, the MR may be considered, in some sense, as more stable to free-stream disturbances.

The second case considered here is an interaction of the laser-induced blast wave with a steady MR. The flow parameters correspond to the experiments performed at Gasdynamics Laboratory of Rutgers University [10]: $M = 3.45$, $\alpha = 37.2^\circ$, $(\theta = 22^\circ)$, which is also approximately in the middle of the dual solution domain; $w = 25.4\text{mm}$, $g/w = 0.595$, $b/w = 2.198$. As in the previous case, we first obtain a steady MR for these flow parameters. Then, at time moment $t = t_0$ the energy release is performed. The laser energy input was 0.215 Joules, and the laser spot was located asymmetrically: $x = -0.95w$, $y = 0.72w$, $z = 0$. The sequence of events during the interaction is given in Fig. 7. Due to asymmetry of the laser spot, the blast wave at initial stages interacts with the upper incident shock only (Figs. 7a-7b). At later stages, the interaction involves the central part of the flow. As a result, the MR shock wave pattern is completely destroyed (Fig. 7c). Note in this figure the asymmetric regular intersection of the leading (windward) shocks. At later time moments, we observe formation of something similar to a very small Mach stem (Fig. 7d). Nevertheless, the MR cannot be maintained at the current flow parameters, and the entire configuration eventually transitions to regular reflection (Fig. 7e). Note the traces of the slipstreams convected downstream of the reflection point in Fig. 7e. Figure 7f presents the final steady RR configuration after the process is complete.

The fact that the Mach reflection can be transformed into regular reflection by a focused laser pulse is very interesting and important. Indeed, a small-level energy addition (0.215 Joules in this case) results in a complete change in the flow structure. The investigations of the mechanisms of such a forced transition may provide flow control schemes with many

Figure 5. Initial stages of a blast wave interaction with an RR: $t = t_0 + 10\mu s$ (a), $t = t_0 + 40\mu s$ (b)
practical applications. It is necessary to perform experiments at similar parameters in the wind tunnels with low levels of free-stream turbulence, where the transition from MR to RR is possible in the dual solution domain. The phenomena that attend the interaction are very complex. Further numerical investigations of this phenomenon are also planned with an emphasis on grid resolution effects.

![Figure 6. Laser-induced RR → MR transition at M = 4](image)

4. CONCLUSIONS

In this study we investigate numerically the effects of laser energy deposition in the free stream on steady regular and Mach reflections between two wedges in a supersonic flow. A single laser pulse focused at some small volume causes the formation of a hot spot and a blast wave propagating outwards. The results of our numerical simulations show that the laser energy deposition in the free stream may be successfully applied for controlled transition between steady regular and Mach reflections. In case of regular reflection, the laser spot initially located at the plane of symmetry forces the transition to Mach reflection. This process is attended by complex shock wave interactions. The reverse transition from Mach to regular reflection was also obtained in our computations with asymmetrical laser spot location. The latter phenomenon is very interesting and certainly requires thorough experimental and numerical investigation.
Figure 7. Laser-induced MR → RR transition at M = 3.45

REFERENCES