HYSTERESIS-RELATED PHENOMENA IN SHOCK WAVE REFLECTION

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Summary The results of our recent numerical and experimental investigations of hysteresis-related phenomena in the shock wave reflection transition are presented. It is demonstrated that the existence of more than one stable configuration and the hysteresis seem to be a universal feature of the interaction of flow discontinuities. A wide range of problems is considered, including various aspects of shock wave reflection in supersonic gas flows, shock and detonation wave interaction in chemically reacting flows, and reflection of steady bore waves (hydraulic jumps) in supercritical shallow water flows.

INTRODUCTION

In 1979 H.Hornung et al. put forward a hypothesis that the transition between steady regular and Mach configurations of shock waves should be accompanied by a hysteresis [1]. Though the first experiments did not confirm this conjecture, in 1995 the hysteresis was observed in both numerical simulations [2] and wind-tunnel experiments [3]. Numerous investigations of this phenomenon undertaken during the last eight years allow one to understand that, within the so-called *dual solution domain*, the supersonic flow with interacting shock waves can indeed be considered as a bi-stable system. For identical flow parameters, either a regular or a Mach steady shock wave configuration can be obtained, depending on the initial conditions. It was demonstrated especially unambiguously by numerical simulations owing to the absence of flow disturbances, which are unavoidable in any experimental facility. Though both regular reflection (RR) and Mach reflection (MR) are stable to infinitesimal flow disturbances, finite-amplitude perturbations can induce the transition between them. It is most likely that the free-stream disturbances are responsible for an earlier (as compared to theoretical criteria and results of numerical simulations) transition to MR, which was observed in several wind-tunnel experiments.
The goal of the present paper is to describe the most recent results of investigations of the shock reflection hysteresis and related phenomena, including simulations of chemically reacting flows and shallow water flows. We would like to particularly demonstrate the universal nature of non-uniqueness of steady configurations and hysteresis behaviour upon the interaction of flow discontinuities in different physical systems.

SHOCK WAVE REFLECTION TRANSITION AND HYSTERESIS

Experiments in low-noise wind tunnel

Experimental observation of the shock wave reflection hysteresis is hampered by the influence of flow disturbances inherent in experimental facilities. To reduce their effects to minimum, we have performed experiments in a low-noise wind tunnel, which was usually used to investigate the laminar-turbulent transition. The free-stream Mach number is M = 4. As a result, for the first time, the hysteresis phenomenon has been observed, which is very close to that predicted theoretically and obtained in numerical simulations. Thus, the transition to MR occurs at the shock wave angle of incidence a = 38.2º while the theoretical *detachment angle* is a_d = 39.2º. The back transition to RR is observed at a = 34.0º while the theoretical *von Neumann angle* is a_N = 33.4º. These results confirm very clearly that the transition between RR and MR under ideal conditions where flow disturbances are absent (maybe, in a flight experiment with a low-turbulent atmosphere) should occurs exactly as was earlier predicted theoretically and observed in numerical simulations.

Numerical simulations of transition controlled by laser energy deposition

It was previously established [4] that, in numerical simulations, flow disturbances of some special type could induce the transition between regular and Mach configurations. It opens the possibility of active control of such bi-stable configurations. The most available tool for flow control can be the generation of flow disturbances with laser energy deposition. A laser pulse focused upstream of the steady shock wave configuration causes formation of a hot-spot region and a blast wave, which interacts in a complex way with the steady configuration. This interaction can induce the transition to another configuration. Preliminary experiments on the influence on laser energy deposition on steady shock wave patterns were performed at Rutgers University [5]. In the present paper, the results of 3D numerical simulations of the blast wave/steady shock configuration interaction are described. Figure 1 shows the sequence of events during the interaction with MR. As a result, the steady Mach configuration is completely destroyed and the transition to RR is forced.

Numerical simulations of asymmetric reflection with reflected shock wave of strong family

A number of interesting features can be observed in asymmetric interaction of two shock waves. In addition to the hysteresis phenomenon and the so-called *inverse Mach reflection*, a unique situation is possible in this case where regular reflection with a reflected shock of a strong family is formed. It can be obtained with no special downstream boundary conditions because the subsonic zone behind the reflected shock is closed and the flow is rapidly accelerated again up to supersonic velocities by the expansion fan emanating from the trailing edge of the wedge.

CHEMICALLY REACTING FLOWS

A shock wave propagating in a combustible mixture causes an abrupt increase in temperature and, consequently, can induce ignition and lead to formation of a detonation wave (DW), a united complex of a shock wave and a reaction zone moving through the ambient media with an extremely high velocity (normally, 2-3 km/s). Theoretically, standing detonation waves can also exist, provided the incoming flow velocity exceeds the so-called *Chapman-Jouguet velocity* D_{CJ}. A theoretical analysis of the properties of oblique standing detonation waves was performed several decades ago. For many years, this subject has aroused a great interest because of possible applications of standing detonation waves for design of a new type of engines exploiting detonation instead of slow combustion. However, experimental evidence of their existence is scarce and ambiguous owing to difficulties in performing such experiments. We have performed a theoretical analysis of MR with a detonation wave as a Mach stem and numerical simulation of the transition to such a configuration from nonreacting RR. The computations are performed for hydrogen/oxygen and hydrogen/air gas mixtures. The existence of MR with a detonation wave is shown within a wide range of incoming flow Mach numbers, and a hysteresis is observed during the transition.

SHALLOW WATER FLOWS

It is well known that there is an analogy between the compressible Euler equations and those governing shallow water motion. The Froude number $Fr = u/\sqrt{gh}$, where u is the flow velocity, g is the acceleration of gravity, and h is the water depth, plays the same role as the Mach number, and supercritical flows with $Fr > 1$ resemble, in many aspects, supersonic flows. In particular, there are jumps in the water depths and bore waves, which are counterparts of shock waves. The interaction of steady oblique bore waves (hydraulic jumps) can lead to either regular or Mach reflection, depending on the Froude number and the angle of incidence a. Our theoretical analysis shows that the dual solution domain where both types of reflection are possible exists at $Fr > Fr_* = 2.95$. Numerical simulations confirm that, if a first increases and then decreases, the transition to Mach reflection and the back transition to regular reflection occur at different values of a, so that the hysteresis phenomenon is observed.
It can be assumed that experiments on the bore wave reflection transition would enable us to elucidate important features concerning the role of flow disturbances in inducing the transition, because it should be much easier to detect and measure disturbances in a supercritical hydraulic flume flow than in a supersonic wind tunnel flow.

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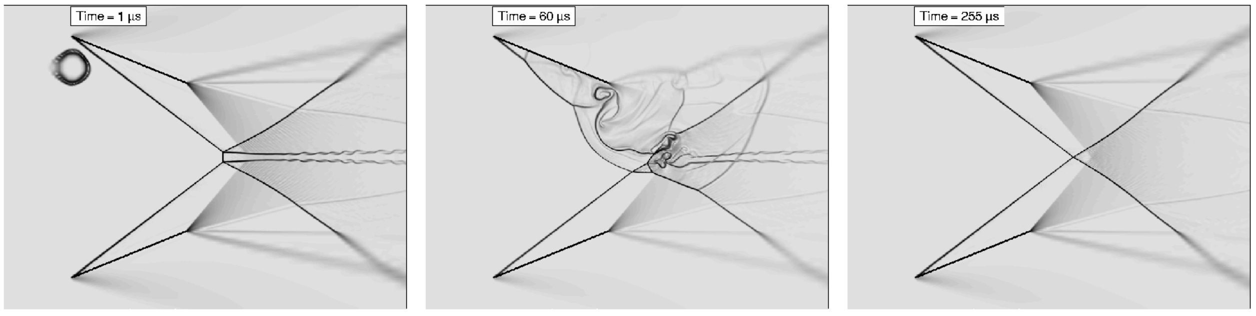

Fig.1. Interaction of a laser pulse of 0.215 J with a steady Mach configuration in a supersonic flow at M=3.45.