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HYSTERESIS PHENOMENA IN SHOCK WAVE REFLECTIONS IN STEADY FLOWS

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ABSTRACT

The state-of-the-art regarding the hysteresis phenomenon in the regular↔Mach reflection transition in steady flows as it has been established in the past decade is summarized.

GENERAL PRESENTATION OF REGULAR AND MACH REFLECTIONS

As indicated in Ref. 1 two shock-wave-reflection configurations are possible in steady flows, regular reflection (RR) and Mach reflection (MR). Schematic illustrations of the wave configurations of an RR and an MR are shown in Figs. 1a and 1b, respectively.

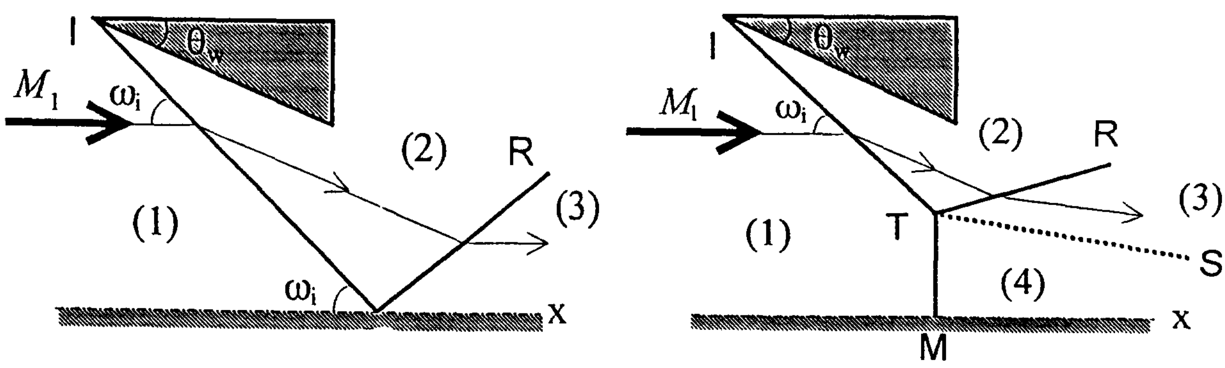

Figure 1: Schematic illustration of a) regular reflection (RR), and b) Mach reflection (MR).

The RR consists of two shock waves, the incident, i, and the reflected, r, shock waves. They meet at the reflection point, R, which is located on the reflecting surface. The angle of incidence, ω_i, of a regular reflection is sufficiently small so that the streamline deflection, θ_1, caused by the incident shock wave, i, can be canceled by the opposite streamline deflection, θ_2, caused by the reflected shock wave, r. Therefore, the boundary condition of a regular reflection is $\theta_1-\theta_2=0$.

The MR consists of three shock waves, the incident, i, the reflected, r, and the Mach stem, m, and one slipstream, s. They all meet at the triple point, T. Unlike an RR where the net deflection of the streamlines is zero, in an MR the net deflection of the streamlines is non-zero, in general. Since the streamlines on both sides of the slipstream must be parallel to each other, their boundary condition is $\theta_1-\theta_2=\theta_3$.

It should be noted here that the above mentioned boundary conditions are based on local considerations in the vicinities of the reflection point R of an RR and the triple point T of an MR. In order for these conditions to be global the shock waves and the slipstream must be straight so that the flow regions bounded by them are uniform.

TRANSITION CFRITERIA AND THE DUAL-SOLUTION DOMAIN

As indicated by Ref. 2 two extreme angles of incident are associated with the oblique reflection of shock wave. They are the *von Neumann,* ω_i^N, and *the detachment,* ω_i^D, angles (ω_i^D is larger than ω_i^N). For a given incident flow Mach number M_0, ω_i^N is the smallest incident angle for which an MR is possible and ω_i^D is the largest incident angle for which an RR is possible. Consequently, an MR is impossible for $\omega_i < \omega_i^N$ and an RR is impossible for $\omega_i > \omega_i^D$. For incident angles in the range $\omega_i^N \le \omega_i \le \omega_i^D$, which is known as the dual-solution domain, both RR and MR are theoretically possible. Since both RR and MR are theoretically possible in the dual-solution domain the RR↔MR transition could take place at any incident angle, ω_i, inside that range. Consequently, the von Neumann and the detachment angles are the lowest and the largest possible values of ω_i for transition.

The dual-solution domain, for which both RR and MR are possible, is shown in Fig. 2 in the (M_0,ω_i)-plane. The detachment and the von Neumann criteria divide the (M_0,ω_i)-plane into three domains: only an RR is theoretically possible; only an MR is theoretically possible; and both an RR and an MR are theoretically possible.

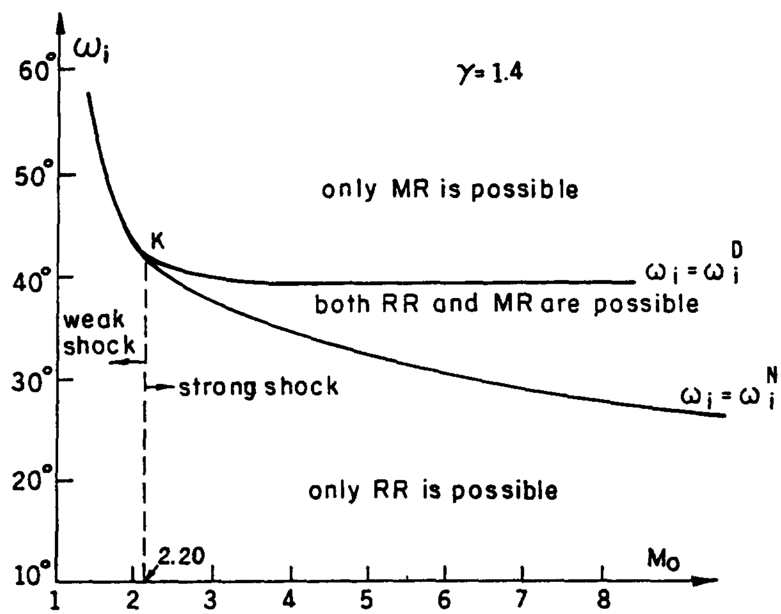

Figure 2: Domains of possible reflection configurations in the (M_0,ω_i)-plane.

THE HYSTERESIS PROCESS IN THE RR↔MR TRANSITION

Based on the existence of the dual-solution domain the possibility of a hysteresis in the RR↔MR transition was hypothesized in Ref. 3. However, since experimental attempts failed to confirm the hysteresis it was concluded in Ref. 4 that the RR is unstable inside the dual-solution domain and that its transition to MR occurs at the von Neumann condition, i.e., at $\omega_i = \omega_i^N$.

By applying the principle of minimum entropy production Ref. 5 showed analytically that, in contrary to the results and conclusion of Ref. 4, RR is stable in most of the dual-solution domain.

Ref. 6 succeeded to experimentally record the hysteresis process for the first time. Using an FCT based numerical code the dependence of the finally established wave configuration inside the dual-solution domain on the distance, h, between the trailing edge of the reflecting wedge and the reflecting surface was investigated by Ref. 7. They showed that for a given incident flow Mach number, M_0, and reflecting wedge angle, θ_W, the reflection is an MR when $h_{min}<h<h_{tr}$ and an RR when $h_{tr}<h<h_{max}$. The value of h_{tr}, at which the RR↔MR transition takes place, was found to linearly decrease with M_0.

In a following numerical study by Ref. 8 the hysteresis process was confirmed for the first time. Since then Refs. 9-13 re-confirmed it using a variety of numerical codes.

The hysteresis process in the RR↔MR transition as obtained numerically by Ref. 13 is shown in Fig. 3. The angle of incidence, ω_i, was changed from an initial value smaller than ω_i^N, for which only an RR is theoretically possible, to a value larger than ω_i^D, for which only an MR is theoretically possible, and back to the initial value. The obtained hysteresis that is shown in the figure is self-explanatory.

All the above mentioned studies were limited to the case in which the triple point T of the MR was free of downstream influences. This fact together with the conclusion of Ref. 13 that the transition between RR and MR can be promoted or suppressed anywhere in the range $\omega_i^N \leq \omega_i \leq \omega_i^D$ by suitable choice of downstream boundary conditions motivated Refs. 14 and 15 to study, analytically and numerically, the downstream-pressure effects. The results of this study, which revealed a downstream-pressure-induced hysteresis, are shown in Fig. 4.

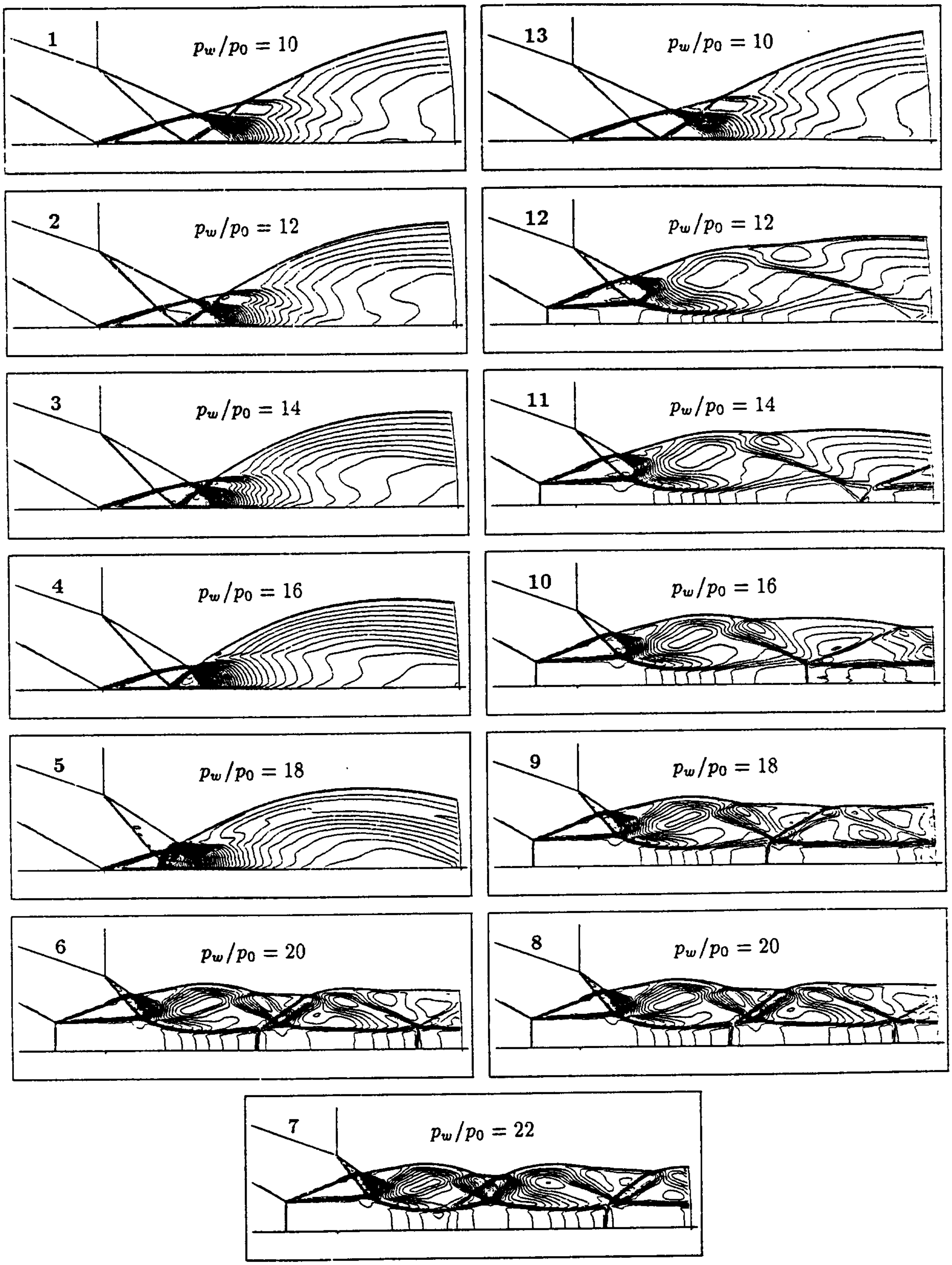

Figure 4: Downstream-pressure-induced hysteresis in RR↔MR reflection transition for M_0=4.96 and ω_i=29.5 deg.

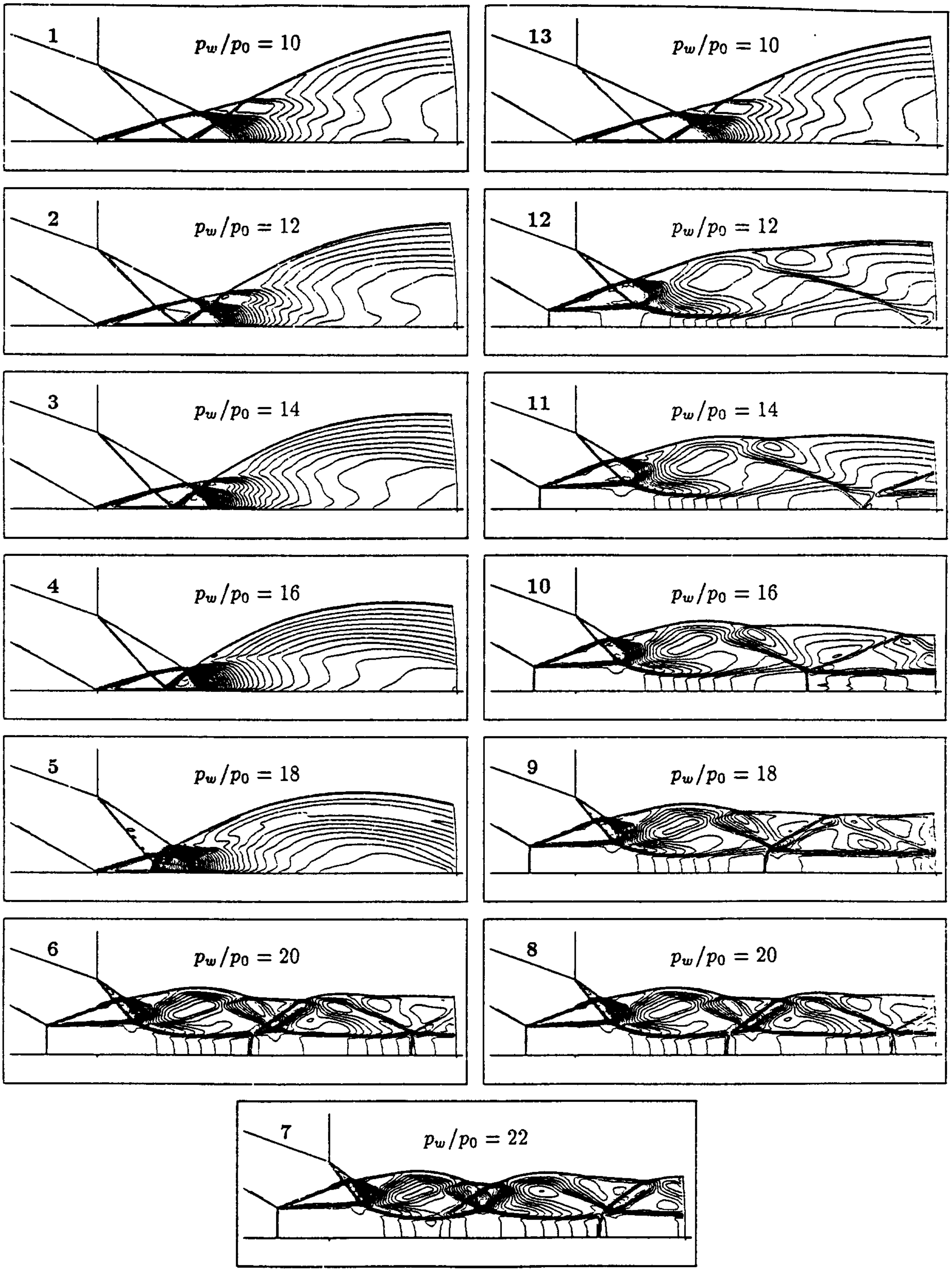

Figure 4: Downstream-pressure-induced hysteresis in RR↔MR reflection transition for M_0=4.96 and ω_i=29.5 deg.

SUMMARY AND CONCLUSIONS

The conclusions of the above-described analytical, experimental and numerical studies comprise, in fact, the new state-of-the-art regarding the reflection of oblique shock waves in steady flows, which is summarized in the following:

1. Regular reflection is theoretically impossible in the domain $\omega_i < \omega_i^D$.
2. Mach reflection is theoretically impossible in the domain $\omega_i < \omega_i^N$.
3. Inside the dual-solution domain $\omega_i^D \leq \omega_i \leq \omega_i^N$ both regular and Mach reflections are stable.
4. The RR↔MR transition can take place anywhere inside the dual-solution-domain.
5. There is a hysteresis in the RR↔MR transition.
6. The finally established wave configuration inside the dual-solution domain depends on both geometrical parameters and downstream pressure effects.
7. It was shown that for a given incident flow Mach number, M_0, and reflecting wedge angle, θ_W, the reflection, inside the dual-solution domain, is either an MR or an RR depending on the distance, h, between the reflecting-wedge-trailing-edge of the and the reflecting surface.
8. A downstream-pressure-induced hysteresis was found.

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