Stability of Regular and Mach Reflection Wave Configurations in Steady Flows

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Introduction

A HYSTERESIS phenomenon in the regular ⇔ Mach (RR ⇔ MR) reflection transition in steady flows has been discovered recently both experimentally[1] and numerically.[2]

The experiments were conducted on the SH2 hypersonic wind tunnel of the Centre National de la Recherche Scientific at Meudon, France. The SH2 wind tunnel is an open jet facility running at a constant flow Mach number of 4.96. Its run time is virtually infinite.

A schematic illustration of the experimental model inside the wind-tunnel test chamber is shown in Fig. 1a. To avoid the boundary-layer influence on the transition process, double wedge models in a symmetric configuration were used. The distance between the leading edges of the wedges was kept constant at 7.01 cm. The wedge length was 7 cm, and its width was 4 cm. Consequently, it did not span the cross section of the supersonic jet. This setup was chosen to avoid the interaction of the shock waves with the side wall boundary layers. Both the upper and the lower wedges were connected to an electric motor that could place the wedges at any fixed angle or could continuously rotate them with a rate of rotation of about 0.57 deg s^{-1}. The two wedges were mounted on a rotational mechanism that kept the inlet cross section h_{in} constant during the rotation. In addition, the wedges could be tilted sideways by 90 deg, thereby completely removing them from the supersonic jet. The reason for enabling this degree of freedom is given subsequently.

Two extreme incident shock wave angles ω_i exist for flow Mach numbers M_0 greater than 2.20. They correspond to the detachment and von Neumann transition criteria[3] and are labeled here as ω_i^D and ω_i^N, respectively. MR wave configurations are theoretically impossible for $\omega_i < \omega_i^N$, and regular reflection wave configurations are theoretically impossible for $\omega_i > \omega_i^D$. In the range $\omega_i^N \le \omega_i \le \omega_i^D$ both RR and MR wave configurations are theoretically possible. For the flow Mach number of the wind tunnel that was used in the course of the experiments reported in this study, i.e., $M_0 = 4.96$, the values of these two extreme incident shock wave angles are $\omega_i^N = 30.9$ deg and $\omega_i^D = 39.3$ deg.

In the aforementioned experimental study,[1] both RR and MR wave configurations were observed for identical values of ω_i inside the theoretical dual solution domain $\omega_i^N \le \omega_i \le \omega_i^D$. Furthermore, the values of ω_i at which the RR → MR and the MR → RR transitions took place were determined by conducting experiments in which ω_i was continually changed. These experiments revealed that

$$\omega_i^{tr}(\mathrm{MR} \to \mathrm{RR}) = 30.9 \text{ deg} = \omega_i^N$$

$$\omega_i^{tr}(\mathrm{RR} \to \mathrm{MR}) = 37.2 \text{ deg} < \omega_i^D = 39.3 \text{ deg}$$

Consequently, the experimental dual solution domain for $M_0 = 4.96$ was found to be

$$\omega_i^N = 30.9 \text{ deg} \le \omega_i \le 37.2 \text{ deg} < \omega_i^D = 39.3 \text{ deg}$$

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In another set of experiments the stability of the RR and MR, which were established inside the experimental dual solution domain, was investigated by continuously changing the wedge angles in discrete steps of about 1 deg. At each position the lower reflecting wedge was completely removed from the flowfield by tilting its holding arm sideways by 90 deg. This resulted in a situation in which only an oblique straight shock wave emanating from the leading edge of the upper wedge was left in the flowfield. At this stage the lower wedge was brought back to its original position and the flowfield was allowed to reach its steady-state conditions. Based on video camera records, it was found that there was a single critical incident shock wave angle value, $\omega_i^{cr} = 35.5$ deg, below which the stable wave configuration was found to be that of an RR and above which the stable wave configuration was found to be that of an MR. Consequently, from a stability point of view the domain $\omega_i^{tr}(\mathrm{MR} \to \mathrm{RR}) < \omega_i < \omega_i^{tr}(\mathrm{RR} \to \mathrm{MR})$ in which both RR and MR wave configurations were found to exist can be divided into two subdomains; RR is stable in the domain $\omega_i^{tr}(\mathrm{MR} \to \mathrm{RR}) < \omega_i < \omega_i^{cr}$, and MR is stable in the domain $\omega_i^{cr} < \omega_i < \omega_i^{tr}(\mathrm{RR} \to \mathrm{MR})$. Recall that for $M_0 = 4.96$ it was found that $\omega_i^{tr}(\mathrm{MR} \to \mathrm{RR}) = 30.9$ deg, $\omega_i^{cr} \approx 35.5$ deg, and $\omega_i^{tr}(\mathrm{RR} \to \mathrm{MR}) = 37.2$ deg. Note that the latter two values were found to depend on the dimensions of the wedges.[1]

Present Study

To have a more accurate estimation of the value of ω_i^{cr}, a pressure-measurement-based experimental procedure was developed. This was done by mounting a pitot tube along the symmetry line at the location shown in Fig. 1b. The probe was connected to an electric pressure transducer (located outside the flowfield) that continuously recorded the pressure while the lower wedge was moved in and out of the flow. The influence of the pitot tube on the measured flowfield was checked and found to be negligibly small.

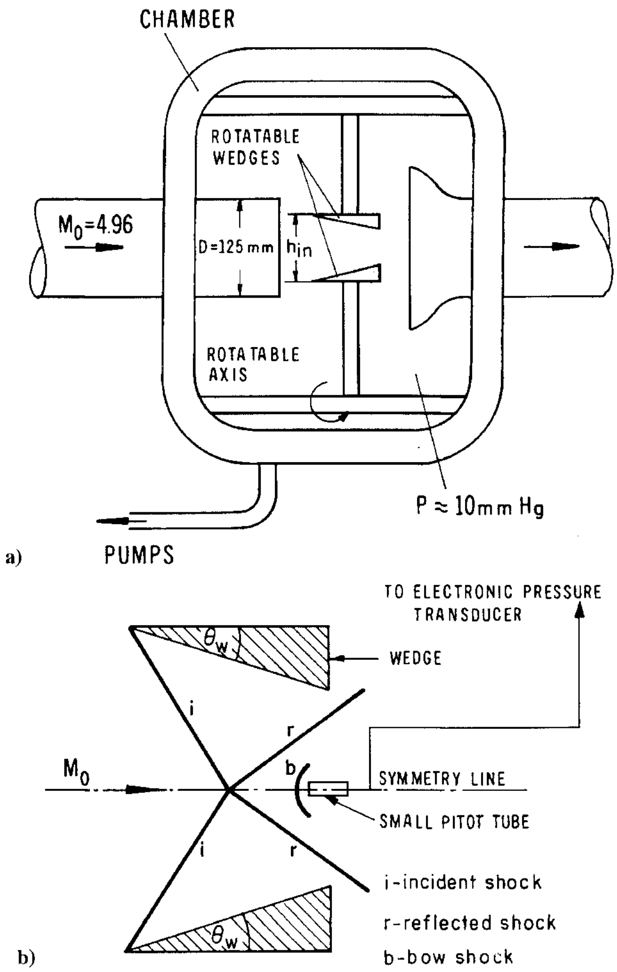

Fig. 1 Schematic illustration of the experimental setup: a) wedges inside the test section and b) location of the pressure transducer.

Since the pressure at the location of the pitot tube depends on the type of wave reflection that exists ahead of the tube, recording the pressure at that location showed which type of reflection actually took place. Note that in the investigated case P(RR) > P(OS) > P(MR), where P(RR) is the pitot pressure appropriate to an RR, P(OS) is the pitot pressure appropriate to an oblique shock (i.e., the lower wedge is tilted sideways), and P(MR) is the pitot pressure appropriate to a Mach reflection.

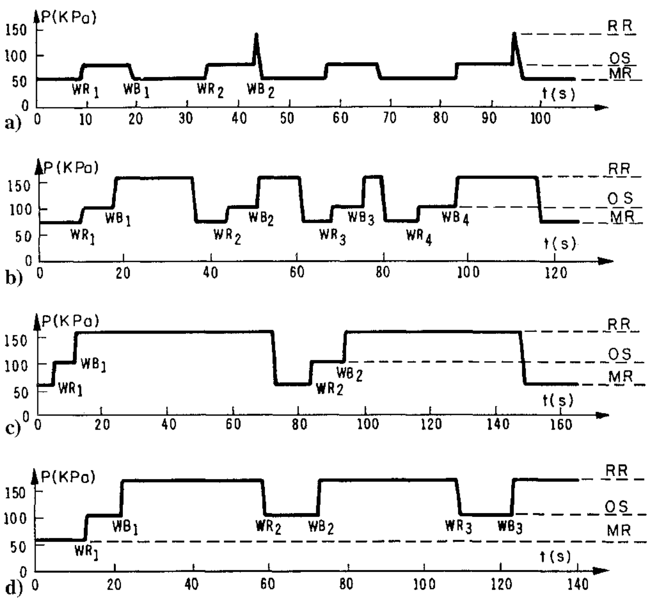

Fig. 2 Continuous pressure histories as recorded by the pressure transducer shown in Fig. 1b for four different incident shock wave angles ω_i: a) 38.6, b) 35.1, c) 34.8, and d) 34.0 deg.

Typical pitot pressures are shown in Fig. 2 for four different values of ω_i. WR indicates the time when the lower wedge was removed from the flowfield, and WB indicates the time when the lower wedge was reinserted. In Fig. 2a, in which $\omega_i = 38.6$ deg, a Mach reflection was first established (at $t = 0$) in the flowfield, with a pitot pressure of about 50 kPa. When the lower wedge was removed (at WR_1), the pressure jumped to about 80 kPa, which is the pressure appropriate to an oblique shock wave, i.e., P(OS). When the lower wedge was brought back into the flowfield (at WB_1), the pressure dropped immediately back to about 50 kPa, which, as mentioned earlier, is the pressure appropriate to a Mach reflection, i.e., P(MR). A second removal of the lower wedge (at WR_2), again caused the pressure to jump from P(MR) to P(OS). However, when the lower wedge was brought back to its original position (at WB_2), a jump from P(OB) to a pressure appropriate to an RR, P(RR), was first observed. However, this regular reflection immediately terminated and reverted to a Mach reflection. This is clearly evident in Fig. 2a, where the pressure is seen to drop immediately from P(RR) to P(MR). The results show that the stable wave configuration for $\omega_i = 38.6$ deg is that of a Mach reflection. The reason for obtaining a transient RR, for these conditions, is explained subsequently.

Figure 2b shows the results for $\omega_i = 35.1$ deg. Again we started (at $t = 0$) with a Mach reflection. As shown earlier, removal of the lower wedge (at WR_1) caused a sudden jump in the pressure from P(MR) to P(OS). When the lower wedge was reinserted at WB_1, the pressure jumped from P(OS) to P(RR) and remained at that level for about 18 s until it suddenly changed to P(MR). The reflection went through a spontaneous transition from a regular to a Mach reflection. The same results were obtained when the process was repeated at WR_2, WR_3, and WR_4. The durations of the RR configurations were 9, 4, and 18 s. It is concluded that the stable reflection configuration for $\omega_i = 35.1$ deg is that of a Mach reflection.

Figure 2c shows the results for $\omega_i = 34.8$ deg. In general, the results are similar to those shown in Fig. 2b. Wedge removal (at WR_1) resulted in a jump from P(MR) to P(OS). When the lower wedge

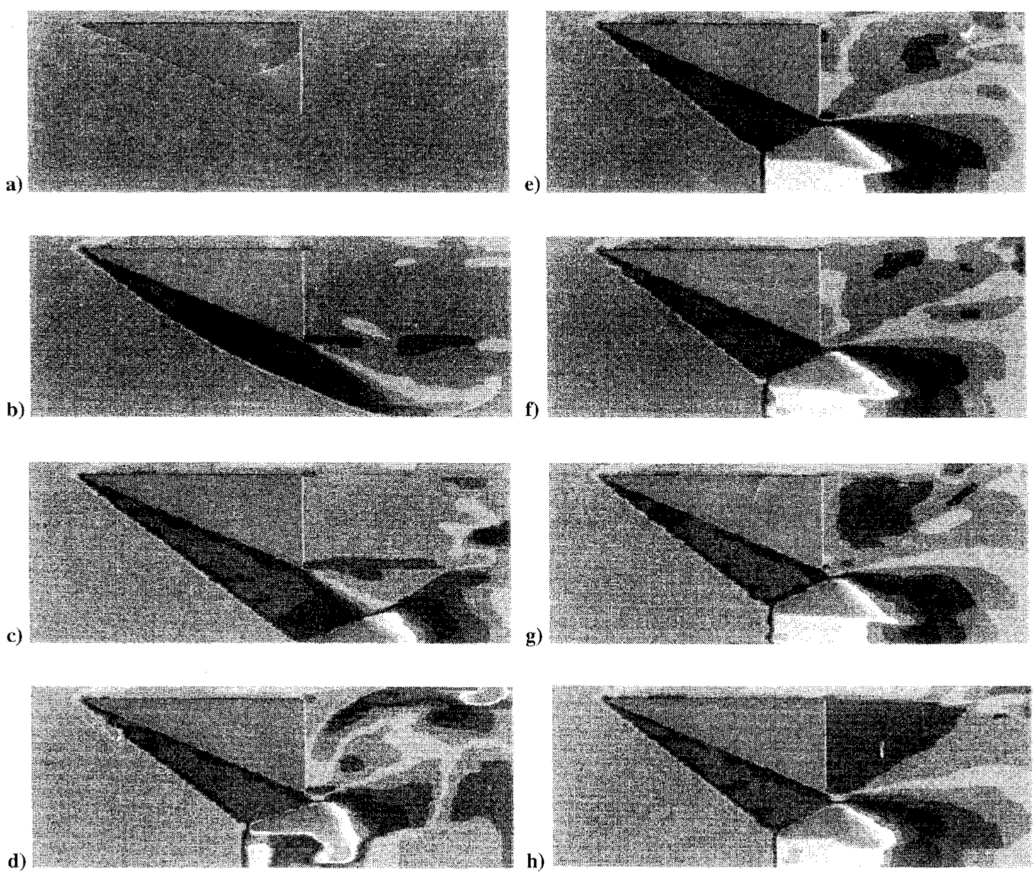

Fig. 3 Evolution of a stable MR for $M_0 = 3.49$ and $\theta_W = 23$ deg from the initiation of a supersonic flow over the reflecting wedge: a) formation of the oblique shock wave (note that it is not straight at this early stage), b) transient RR (note that the oblique shock wave is now straight), and c–h) MR. The configuration shown in panel f is the one corresponding to the stable MR.

was reinserted (at WB_1), the pressure jumped to P(RR), indicating the formation of an RR. The pressure then dropped suddenly to P(MR), again indicating a spontaneous transition from a regular to a Mach reflection. The process was repeated at WR_2. Consequently, the stable reflection for $\omega_i = 34.8$ deg is again an MR.

In spite of the similarity just described in the observed processes in Figs. 2b and 2c, there was one noticeable difference between them, namely the time duration of the existence of the RR from the moment of its formation (at WB) until its spontaneous transition to a Mach reflection. Whereas, as can be seen in Fig. 2b, the four transient regular reflections, which were formed at WB_1, WB_2, WB_3, and WB_4, lasted for about 18, 9, 4, and 18 s, respectively, the two transient regular reflections, which were formed at WB_1 and WB_2 (see Fig. 2c), existed for about 60 and 55 s, respectively. Consequently, it is apparent from Figs. 2a–2c that as ω_i approached the value appropriate for the transition from a stable MR to a stable RR, the duration of the transient RR increased.

A different sequence of events is evident in Fig. 2d for $\omega_i = 34.0$ deg. The pressure appropriate to the initially established Mach reflection P(MR) jumped, as expected, to P(OS) when the lower wedge was removed (at WR_1). When the lower wedge was reinserted (at WB_1), the pressure jumped to P(RR), indicating the establishment of an RR. However, unlike the cases recorded in Figs. 2a–2c, the RR this time was stable and did not change spontaneously to a Mach reflection. Once an RR was established, the removal of the lower wedge (at WR_2) resulted in a drop in the pressure from P(RR) to P(OS), and the return of the lower reflecting wedge, at WB_2, resulted in a jump back to P(RR). Hence, based on the results shown in Fig. 2d the stable reflection for $\omega_i = 34.0$ deg is an RR. In summary, the results shown in Figs. 2a–2d indicate that Mach reflection wave configurations were stable for $\omega_i \geq 34.8$ deg and that RR wave configurations were stable for 34.0 deg. Averaging between these two values results in $\omega_i^{cr} \approx 34.4$ deg, in contrast to the value obtained in Ref. 1, i.e., $\omega_i^{cr} = 35.5$ deg, which was based on continuous (video) photography.

The reason for the formation of a transient RR before the establishment of a stable MR for $\omega_i > \omega_i^{cr}$ is understood if one inspects the numerical simulation of the evolution of an MR as shown in Fig. 3, which is taken from Ref. 4. As can be seen, the oblique shock wave, which is formed at the leading edge of the wedge, reflects first at the symmetry line as an RR (see Figs. 3a and 3b). This RR then changes to a Mach reflection (Fig. 3c), which after a while reaches its steady-state position and configuration.

Based on the numerical simulation shown in Fig. 3, one can conclude that even when the initial conditions are appropriate to a stable MR the evolution to the stable MR starts with a transient RR. When $\omega_i \gg \omega_i^{cr}$, as is the case in Fig. 2a, the duration of the transient RR is extremely short. In fact, it is so short that sometimes it is not even recorded. However, as ω_i approaches ω_i^{cr}, as is the case in Figs. 2b and 2c, the duration of the existence of the transient RR increases. The mechanism(s) causing the termination of the RR in this case is(are) yet to be understood.

Conclusions

The stability of RR and MR in the dual solution domain was investigated experimentally. A pressure-measurement-based method was applied.

It was found that the dual solution domain, i.e., $\omega_i^{tr}(\text{MR}\rightarrow\text{RR}) \leq \omega_i \leq \omega_i^{tr}(\text{RR}\rightarrow\text{MR})$, is divided by a critical angle, say, ω_i^{cr}, into two subdomains. RR is stable in the subdomain $\omega_i^{tr}(\text{MR}\rightarrow\text{RR}) < \omega_i < \omega_i^{cr}$, and MR is stable in the subdomain $\omega_i^{cr} < \omega_i < \omega_i^{tr}(\text{RR}\rightarrow\text{MR})$.

In addition, it was found that even when the stable wave configuration is an MR, it was preceded, in the vicinity of the critical angle ω_i^{cr} by a transient RR wave configuration that spontaneously changed to an MR. The average duration of the temporal regular reflection was found to increase as the value of ω_i^{cr} was approached from above. At the flow Mach number $M_0 = 4.96$, it was found that $\omega_i^{tr}(\text{MR}\rightarrow\text{RR}) = 30.9$ deg, $\omega_i^{tr}(\text{RR}\rightarrow\text{MR}) = 37.2 < \omega_i^D = 39.3$ deg, and $\omega_i^{cr} \approx 34.4$ deg, in contrast to the value 35.5 deg, which was reported previously. The average time duration of the existence of the transient regular reflections Δt was found to be 0 for $\omega_i \geq 38.6$ deg, 12.5 s for 35.1 deg, 57.5 s for 34.8 deg, and $\rightarrow \infty$ for ≤ 34.4 deg. Finally, both $\omega_i^{tr}(\text{RR}\rightarrow\text{MR})$ and ω_i^{cr} depend on the dimensions of the wedges.

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References

[1]Chpoun, A., Passerel, D., Li, H., and Ben-Dor, G., "Reconsideration of Oblique Shock Wave Reflections in Steady Flows, Part I, Experimental Investigation," *Journal of Fluid Mechanics*, Vol. 301, 1995, pp. 19–35.

[2]Vuillon, J., Zeitoun, D., and Ben-Dor, G., "Reconsideration of Oblique Shock Wave Reflections in Steady Flows, Part II, Numerical Investigation," *Journal of Fluid Mechanics*, Vol. 301, 1995, pp. 37–50.

[3]Ben-Dor, G., *Shock Wave Reflection Phenomena*, Springer–Verlag, New York, 1991.

[4]Vuillon, J., Zeitoun, D., and Ben-Dor, G., "Numerical Investigation of Shock Wave Reflection in Steady Flows," *AIAA Journal*, Vol. 34, No. 6, 1996, pp. 1167–1173.

Correlation of Separation Angles Induced by Glancing Interactions

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Introduction

GLANCING shock-wave/turbulent-boundary-layer interaction, in which an oblique shock wave glances across a boundary layer growing along an adjacent wall (see Fig. 1), constitutes one of the most important phenomena of three-dimensional interference. Several studies of this phenomenon have been conducted recently with the objective of correlating the glancing-interaction features induced by unswept sharp fins (USF) at different Mach numbers with various wedge angles,[1] and subsequently deducing relationships between the interactions produced by several geometrically dissimilar shock generators such as USF, swept sharp fins, and semicones (SC).[2] The families of swept sharp fins and SC induce conical inviscid shock waves, which have curvature, whereas the USF induces a planar shock wave. However, in most of the previous studies, shock-wave strength given solely by inviscid shock angle has been considered to correlate the interaction features even when the types of shocks differ.

In this study, angles of primary separation lines induced by three disparate families of shock generators (Fig. 1)—USF, SC, and swept triangle fins (STF)—are emphasized, and relationships among the three families are investigated by considering the inviscid pressure field in the interaction region. A correlation law useful for predicting the separation angles, which takes into account the shock-curvature effect, is then postulated.

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