Experimental investigation of strong shock reflection and hysteresis in various wind tunnels

M.S. Ivanov, A.N. Kudryavtsev, S.B. Nikiforov, A.D. Kosinov, and A.A. Pavlov

Institute of Theoretical and Applied Mechanics, Novosibirsk 630090, Russia

Abstract. Experimental studies of reflection of steady shock waves was performed in three different wind tunnels. The 3D structure of regular and Mach reflections as well as the influence of 3D effects on the transition between these two shock-wave configurations was investigated in detail using laser sheet visualization. In particular, spanwise variation of the Mach stem height was measured, and the results are in close agreement with numerical predictions. Changing the width/length aspect ratio of the test model $b/w$, it was shown that the transition from regular to Mach reflection for $b/w > 2$ is not virtually affected by 3D effects. The size of the hysteresis loop was different in different wind tunnels. While in the T-313 wind tunnel no (or very small) hysteresis was observed, the experiments performed in the T-326 and T-325 facilities gave clear evidence of this phenomenon. The results obtained in the low-noise wind tunnel T-325 were particularly demonstrative, showing the hysteresis loop, which is quite close to that predicted theoretically and obtained in numerical simulations. Thus, the quality of wind tunnel flow (the level of free-stream disturbances) is critically important for reproducing the shock wave reflection transition hysteresis in wind-tunnel experiments.

1 Introduction

The transition between regular (RR) and Mach (MR) shock wave reflections, having more than a century’s history of research, still remains one of the last unsolved problems of classical gas dynamics. The existence of two possible solutions at the same flow conditions and the related hysteresis phenomenon make this problem one of the most interesting and challenging research tasks.

The transition from one reflection type to the other at a fixed free-stream Mach number $M$ occurs at a certain incident shock angle $\alpha_{tr}$. The analysis of two-shock and three-shock configurations made by von Neumann in his classical work [1] allowed him to derive two principal criteria for strong ($M > 2.2$) shock waves – the von Neumann (or mechanical equilibrium) criterion, $\alpha_N$, and the detachment criterion, $\alpha_D$, at which the transition from regular to Mach reflection may occur. Regular reflection is impossible for $\alpha > \alpha_D$, and Mach reflection is impossible for $\alpha < \alpha_N$. In the range $\alpha_N < \alpha < \alpha_D$ (dual solution domain), both reflection types are theoretically possible. The difference ($\alpha_D - \alpha_N$) increases considerably with increasing $M$.

The theoretical possibility of the existence of two different shock configurations for $\alpha_N < \alpha < \alpha_D$ implies the question: which criterion is correct for the transition between these configurations? Previous results obtained in [2,3] are contradictory. As we consider here a case where steady incident shocks generated by a double-wedge model are reflected from the plane of symmetry (the plane of symmetry replaces a reflecting wall in order to eliminate boundary-layer effects), the following question also arises: may the finite span of the test model and accompanying 3D effects affect the transition from regular to Mach reflection and back?
Our goal was to clarify such discrepancies. That is why we performed our tests in different wind tunnels and with model of different spans.

2 Experimental facilities and techniques

2.1 Wind tunnels

All experiments were performed in supersonic and hypersonic wind tunnels of the Institute of Theoretical and Applied Mechanics. Below, a more detailed description of wind tunnels and experimental conditions is given. T-313 is a supersonic blowdown wind tunnel with a closed test section $600 \times 600 \times 1200$ mm. The experiments were conducted at a flow Mach number $M = 4$ with a stagnation temperature of 290K, stagnation pressure of $10^6$ Pa, and $Re_1 = 50 \times 10^6 \text{m}^{-1}$. T-326 is a free-jet wind tunnel with a 200 mm round jet. The experiments were conducted at $M = 6$ with a stagnation temperature of 400K and stagnation pressure of $2 \times 10^6$ Pa. The unit Reynolds number was $Re_1 = 11.8 \times 10^6 \text{m}^{-1}$.

In order to clarify possible influence of flow disturbances, a set of experiments was performed in a low-noise supersonic blowdown wind tunnel T-325 with a closed test section $200 \times 200 \times 600$ mm. A detailed description of this facility and hot-wire measurements of free-stream fluctuations can be found in [4]. Our experiments were conducted at a flow Mach number $M = 4$ and unit Reynolds number $Re_1 = 12.8 \times 10^6 \text{m}^{-1}$. Under these conditions, the level of mass flow fluctuations in the range of frequencies from 50Hz up to 300kHz does not exceed 0.2%.

2.2 Techniques

In our experiments on hysteresis, we used schlieren and shadowgraph techniques to visualize shock-wave configurations. Flowfield images were captured by a JAI CV-M10 CCD camera with a resolution of $782 \times 582$ pixels. The CCD camera worked in the progressive scan mode with a frame rate of 25 Hz. The images were grabbed by a Leutron Vision PicPort-Stereo-H4d frame grabber and then stored on a computer hard disc as bitmap graphical files. In some runs, flow images were also recorded by a VCR.

In order to investigate the 3D structure of the shockwave configuration, we developed laser sheet visualization in the streamwise direction. Our modification allowed us to traverse the test section of T-313 in the spanwise direction scanning the flowfield from the central plane up to the side wall. The maximum angle between the laser sheet and the wind tunnel axis did not exceed 3.8°. Slices of the flow pattern were grabbed by the CCD camera mounted outside the test section.

In addition to flow visualization in T-326 and T-325, total pressure measurements were performed. A Pitot tube was mounted behind the reflection point of shock waves at the place where the flow was supersonic for both regular and Mach configurations, so that any upstream influence of the probe was excluded. The signal of the sensor was synchronized with that from the slide-wire potentiometer. The data were acquired by a 12-bit four-channel ADC located inside a Pentium III PC. The pressure sensor and the potentiometer were plugged in two channels with the same sampling rate of 20 KHz.
3 Results

3.1 Experiments in T-313

In the experiments conducted in the blowdown wind tunnel T-313, we tried to investigate simultaneously both the RR-MR-RR transition and the influence of 3D effects on it. For this purpose, we investigated models with different aspect ratios $b/w$ ($b$ is the spanwise length and $w$ is the width of the wedge). For each span, a series of RR-MR-RR transitions was performed. The results showed that the transition to Mach reflection arose slightly (0.6 to 1.0°) higher than $N$. The angles of forward and backward transition are similar: $F_{tr} = 34°:45°$, $B_{tr} = 34°:42°$ for $b/w = 3.75$; $F_{tr} = 34°:01°$, $B_{tr} = 33°:72°$ for $b/w = 2.00$; $F_{tr} = 34°:93°$, $B_{tr} = 34°:71°$ for $b/w = 1.00$. The sole exception is $b/w = 0.66$ ($F_{tr} = 39°:83°$, $B_{tr} = 38°:07°$), where three-dimensional effects are very strong.

We also conducted a detailed investigation of the 3D structure of RR and MR using the laser sheet visualizations (Fig. 1). This allowed us to measure the Mach stem height variation along the spanwise coordinate $z$, which is shown in Fig. 2 for MR at $\alpha = 37°$ and $b/w = 3.75$. For comparison, the Mach stem heights obtained in our 3D Euler simulations are also given. It is quite evident that experimental and numerical data are in close agreement. Note, the Mach stem height is almost constant in the vicinity of the central plane, i.e., $z/w = 0$. That is, the central part of the flow is almost free of 3D effects for the large enough span $b/w = 3.75$. It is also confirmed by a comparison with the Mach stem height obtained in 2D computations (see Fig. 2).

3.2 Experiments in T-326

The experiments conducted in the T-326 free-jet wind tunnel give clear evidence of the hysteresis phenomenon. The difference between $\alpha_{tr}^F$ and $\alpha_{tr}^B$ reaches approximately 3° for $b/w = 2.5$ and 2°:2.5° for $b/w = 1.0$. It should be noted that three-dimensional effects for $M = 6$ are not as strong as for smaller $M$ because of decreasing the Mach cone angle. The direct transition is accompanied by a substantial jump of the Mach stem height, and the reverse one is continuous.
The time history of the total pressure obtained during one of our runs in T-326 is shown in Fig. 3. In our runs we started from the angle of attack lower than the von Neumann criterion and then increased the angle of attack until the transition to MR occurred. After that, we decreased the angle of attack to force the regular reflection. The angles of attack of the wedges, $\theta$, are also plotted in the figure. For reference, the lines corresponding to the theoretical criteria $D = 39.5$ and $N = 29.0$ are also plotted. We may suggest that some disturbances inherent in the flow cause the transition from RR to MR in the middle of the dual solution domain.

In Fig. 4, we give similar Pitot measurements for a wind tunnel test where the wedge angle was piecewise-constant during the run. In the beginning, for $t < 9.5 \text{ s}$, when the angle of the wedge is $\theta = 23.3^\circ$ ($\alpha = 32.2^\circ$), we observe the RR configuration. Then the wedge angle is changed at a small value to $\theta = 23.5^\circ$ ($\alpha = 32.4^\circ$), and RR persists. When the angle is increased again to $\theta = 23.8$ ($\alpha = 32.8^\circ$), RR is maintained for three seconds and, after that, a sudden transition to MR happens while the angle is kept constant.

### 3.3 Experiments in T-325

To explain the whole variety of experimental facts, we suggested that the transition to Mach reflection is strongly affected by free-stream disturbances, which are inevitably present in any experimental facility. Namely, within the dual solution domain between $\alpha_N$ and $\alpha_D$, the regular reflection configuration is stable to infinitesimal disturbances; however, finite-amplitude disturbances can force the transition to Mach reflection. The threshold amplitude of disturbances capable of initiating the transition decreases as $\alpha$ increases and vanishes as $\alpha$ approaches $\alpha_D$.

The transition from regular to Mach reflection produces an abrupt decrease in total pressure (see Fig. 5). Comparing two signals, the moment of the transition and, consequently, the corresponding angle of attack of the wedge can be determined with a high accuracy. From here, the incident shock angle can be calculated using simple gas-dynamic relations. The transition angles in multiple passes with increasing and decreasing wedge
angle demonstrated remarkable repeatability, which was obviously absent in earlier experiments [6,12].

3.4 RR-MR transition time

In our experiments, we tried to investigate the process of transition from regular to Mach reflection in details. We used a CCD camera switched in a special mode. In this mode, only a two-pixel height linear fragment (slim area in Fig. 6 RR or MR) of the image along the axis of symmetry is captured every 64 µs. This linear fragment is displayed on the top of the frame, the next captured fragment is displayed on the same frame below the first one, and so on. A part of the whole frame containing the process of transition is shown in the middle of the figure and marked as “Transition”. In the upper part of the “Transition” region, the regular reflection is observed. The process of transition is show inside the white frame, followed by the steady Mach reflection in the bottom part. It can be seen from the figure that the transition from RR to MR occurs in 10-15 rows, which is about 1 ms.

4 Conclusions

Regular and Mach reflections of steady shock waves were studied experimentally in three different wind tunnels. The influence of 3D effects resulting from the finite length of the wedge on RR-MR-RR transition was investigated by changing the aspect ratio of the wedge model. It was shown, that the influence of 3D effects is negligible for aspect ratios larger than 2.0.

A detailed experimental investigation of the 3D structure of steady regular and Mach reflections between the wedges of different spanwise aspect ratios was performed with the laser sheet visualization in the T-313 wind tunnel. The Mach stem height variation in the transverse direction was measured and agrees well with numerical predictions.
The hysteresis phenomenon was also investigated in detail. In the T-313 wind tunnel, no or very small hysteresis was observed. In the T-326 wind tunnel, the forward RR-MR transition occurred in the middle of the dual solution domain and the angle of the reverse MR-RR transition was slightly (0.5°) higher than the von Neumann criterion.

It was shown earlier, that 3D effects do not influence shock reflection if the aspect ratio is large enough; thus, the only reason for an earlier transition from RR to MR in experiments is the level of free-stream disturbances in the wind tunnel. The experiments in a really low-noise wind tunnel (T-325) immediately allowed us to confirm this hypothesis. The transition occurred in close agreement with theoretical predictions. Thus, it is necessary to take into account the quality of the wind-tunnel flow when comparing the transition conditions in different wind tunnels.

In our experiments, the time of transition from regular to Mach reflection was estimated using an original approach. In this approach, a CCD camera switched in a special mode captured the process of transition, which gave us the time of transition equal to approximately one millisecond.

References