Experimental Investigation into Converging Cylindrical Shock Wave Reflection

B.J. Gray and B.W. Skews

1 Introduction

The behaviour of a planar shock wave that encounters an inclined wedge is well known, and Ben-Dor [1] gives a detailed description of the various reflection patterns that form under these circumstances. If the angle of incidence between the shock and the wedge is low enough, then the two shock pattern known as regular reflection (RR) will occur. For a given Mach number, there is a critical incident angle (known as the maximum-deflection angle) above which no reflected wave exists that is capable of deflecting the flow so that it runs parallel to the boundary. In these cases, regular reflection is not possible, and a Mach reflection (MR) must occur, which is characterised by the presence of a third shock (the Mach stem), and a slipstream, as shown in Fig. 1(a).

Introducing curvature along a shock front has several significant effects on the behaviour of the shock. Perhaps the most significant of these effects is the manner in which the Mach number of a curved shock wave increases as the radius of curvature decreases [2].

Another difference between a curved and planar shock waves is that the angle of incidence of a curved shock wave changes as the shock wave propagates up the wedge. In particular, for a converging shock wave, the incident angle decreases as the shock propagates up the wedge. This behaviour is similar to behaviour of a planar shock wave encountering a concave curved wall or cavity [3]. At some point, the incident angle passes from the MR domain into the RR domain, and the Mach reflection becomes an inverse Mach reflection (IMR). The triple point of an IMR moves back toward the surface and eventually reattaches, resulting in a pattern similar to RR. However, the residual slipstream and Mach stem are still present, and follow at some distance behind the reflection point, forming a transitioned regular reflection (TRR) such as the one shown in Fig. 1(b).

B.J. Gray · B.W. Skews
Flow Research Unit, University of the Witwatersrand, Johannesburg, 2050, South Africa

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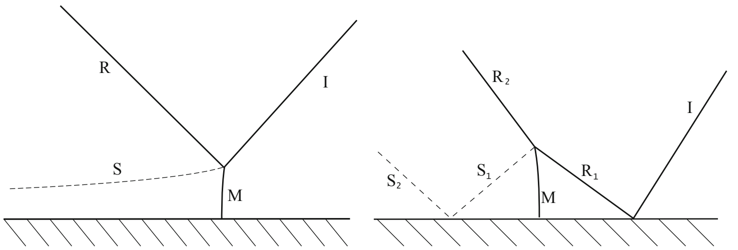

Fig. 1 Two possible reflection patterns, showing the incident wave (I), reflected waves (R), Mach stem (M) and slipstreams (S)

There has been some research into the propagation and reflection of cylindrical and spherical waves [4], and focusing phenomena as a shock wave converges [5], but there is little research data available on the reflection behaviour of curved shock waves, particularly converging shock waves.

Previously, the conditions for transition between various reflection patterns when a converging cylindrical shock wave segment encounters an inclined wedge was studied numerically by these authors [6]. This paper aims to investigate the behaviour of these shock waves experimentally, and draw a comparison with the numerical results.

2 Apparatus and Methodology

A facility which attaches to the end of a conventional shock tube has been designed that is capable of producing shock waves of arbitrary shape inside a narrow propagation chamber. A narrow slit is machined into a flange which is attached to the end of the shock tube. The test section — consisting of converging top and bottom walls and a curved back wall matching the shape of the slit — is positioned perpendicular to the shock tube axis.

After passing through the slit, the planar wave from the shock tube is transformed into a converging cylindrical shock in the test section. A wedge is fitted in the path of the shock wave at the end of the test section. Glass windows on either side of the chamber allow the shock wave to be photographed using a schlieren optics setup, in which the knife edge was aligned perpendicular to the wedge.

Two sets of tests were carried out under identical conditions with a 30° wedge — the first using a Photron SA5 high speed camera shooting at 100 000 frames per second, and the second using a Nikon D40X 10.2 megapixel camera for higher resolution photos. The high speed footage was used to measure the speed of the shock as it propagated up the wedge by tracking the position of the shock in each frame.

3 Results

The driver pressure was set to generate a planar shock wave before the slit with Mach numbers of 1.25, 1.3, and 1.35, which had strengthened once they reached the wedge apex to Mach numbers of approximately 1.5, 1.6 and 1.7 respectively. The initial reflection pattern was found to be MR for all three Mach numbers, but as the shock wave propagated up the wedge (decreasing the incidence angle), the triple point trajectory was turned back toward the surface. Toward the top of the wedge, the triple point collided with the wedge, resulting in a TRR.

Figs. 2 to 6 show schlieren photographs taken after various delays in five separate tests for wedge angle of 30° and Mach number and radius at the apex of approximately 1.5 and 100 mm. A 3.3x zoomed image of the reflection is shown to the right of each photo. The shock is moving from left to right, and the time since the shock passed the apex has been estimated from the delay.

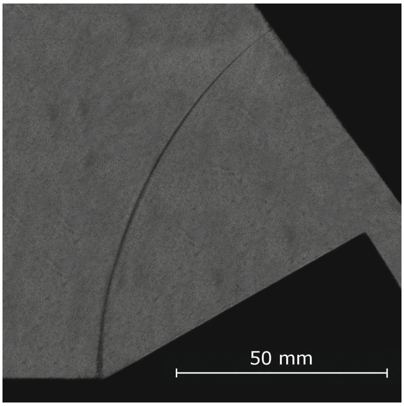

Fig. 2 Shock wave shortly before encountering the wedge apex

The incident angle between the shock wave and the wedge surface at which the triple point first makes collides with the surface was measured from the photographs. These are shown in Table 1.

Table 1 Comparison between measured incident angle at transition to TRR and incident angle predicted by numerical simulations in [6]

M_{apex}	$\theta_{experiment} \pm 2.5°$	$\theta_{numerical}$
1.5	30°	27.5°
1.6	27°	25.4°
1.7	25°	24.0°

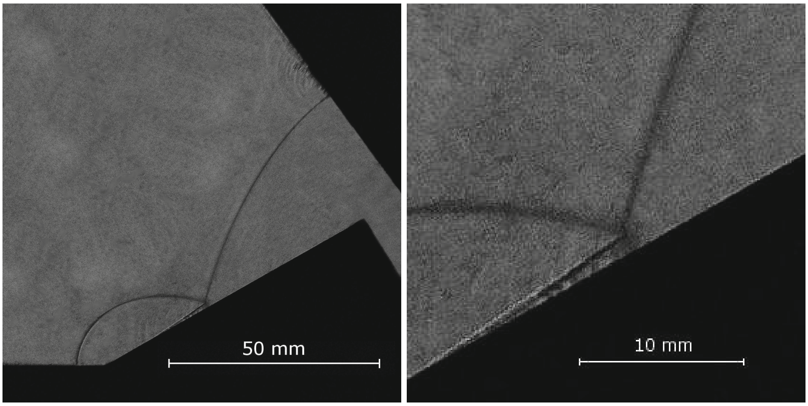

Fig. 3 Direct Mach reflection (DiMR) 40μs after the apex

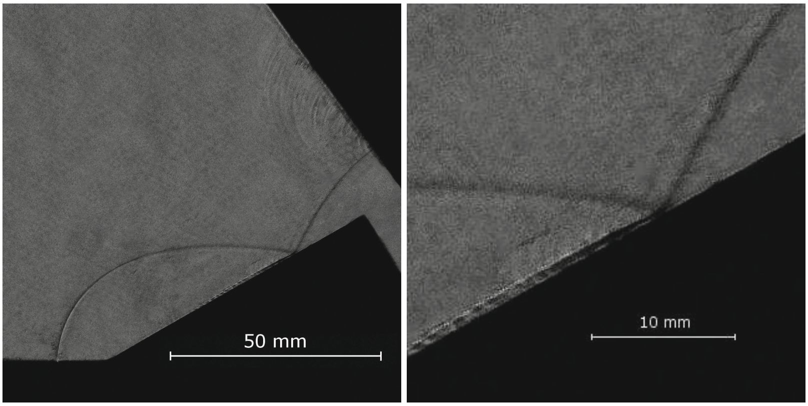

Fig. 4 Triple point starts moving towards the wedge, forming Inverse Mach reflection (IMR) 60μs after the apex

4 Discussion

The results obtained through experiment show reasonable agreement with the results of the numerical simulations [6]. A higher initial Mach number leads to the Mach reflection persisting higher up the wedge, and a lower incident angle when transition occurs.

However there is a significant degree of uncertainty in the measurement of the transition angle, for two reasons. Firstly, motion blur leads to a slight ambiguity in the shock position. Secondly, it is challenging to identify the exact point in time at which the triple point collides with the wedge. In most cases, the angle was obtained by interpolating between two images, such as those in Figs. 4 and 5, which introduces further uncertainty into the measurement.

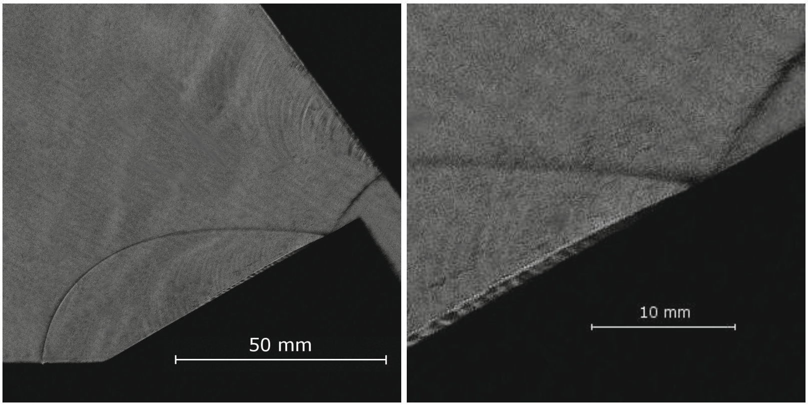

Fig. 5 Triple point collides with the wedge, causing the onset of a Transitioned Regular reflection (TRR) 65μs after the apex

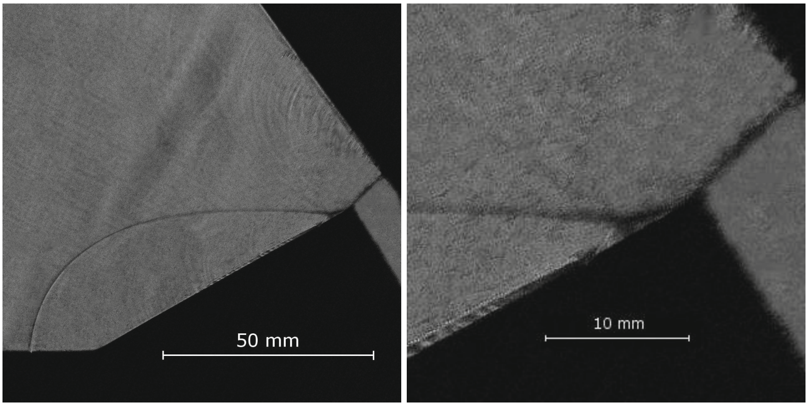

Fig. 6 Transitioned Regular reflection (TRR) well established by the end of the wedge 70μs after the apex

Although the measured angles shown in Table 1 appear to be consistently higher than those obtained in the numerical analysis, given the small number of data points and the uncertainty of the measurements, it is impossible to draw any meaningful conclusion from this.

A regular periodic disturbance is clearly visible in the slipstreams in Figs 3 to 5 which is likely a Kelvin-Helmholtz instability, although images with a higher resolution would be needed to confirm this. The instability is significantly more pronounced than in slipstreams resulting from Mach reflection of a planar wave. This is likely due to the fact that, in the case of a converging cylindrical shock, the triple point is accelerating along a curved trajectory, rather than propagating at a constant speed along a straight line as in the reflection of a planar shock wave.

5 Conclusions

A converging cylindrical shock wave of 100 mm radius encountering a wedge inclined at an angle of 30° initially forms a MR. As the wave propagates up the wedge, the triple point of the Mach reflection gradually starts moving back toward the wedge surface, eventually colliding with the surface, resulting in a TRR. The limited number of tests carried out suggest that the incident angle at which transition to TRR occurs does decrease as the Mach number of the initial shock wave is increased. Further experiments involving a greater range of Mach numbers and wedge angles are currently planned.

References

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