7th Australasian Hydraulics and
Fluid Mechanics Conference,
Brisbane, 18-22 August, 1980

Investigation of Transition Conditions for Shock Wave Reflexion in Steady Flow

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SUMMARY Experiments were conducted in a supersonic wind tunnel at Mach numbers from 2.8 to 5.0 to determine the transition condition from regular to Mach reflexion and vice versa in steady flow. The programme was carried out to test the hypothesis that the unstable condition of regular reflexion at shock wave angles greater than that predicted by the von Neumann condition can be maintained if the shock wave angle is increased smoothly in steady flow.

For the conditions of the tests the transition from regular to Mach reflexion or vice versa was independent of whether the shock wave angle was increased or decreased. The results provide support for the von Neumann condition as the correct criterion for transition in steady flow, contrary to information given by textbooks.

1 INTRODUCTION

The last decade has seen a strong revival of interest in the subject of transition from regular to Mach reflexion of shock waves. Though this effect is of considerable practical importance in supersonic aerodynamics, especially of engine intakes, and in the gasdynamics of explosions, the revival of interest in transition to Mach reflexion has come mainly from research groups at or connected with universities. The aim of these groups was to improve the understanding of some of the unexplained discrepancies between theory and experiment in this complex phenomenon.

The configuration of a regular shock reflexion in steady flow is shown in figure 1a. A supersonic stream encounters an oblique shock at an angle α as shown and is deflected towards the reflecting wall. The reflected shock provides the means of turning the flow back to its original direction parallel to the wall. As α is increased, there comes a point at which the configuration changes to the "Mach reflexion" shown in figure 1b where the incident shock intersects normal and reflected shocks at a triple point. The length of the nearly normal shock or Mach "stem" S is controlled by the geometry of the upper boundary of region B. This boundary is unable to influence the reflexion point in the regular reflexion configuration, figure 1a, because the flow is everywhere supersonic. In the Mach reflexion, however, the flow after the Mach stem is subsonic, so that upstream influence is possible in region D.

To explain the mechanism by which the boundary of region B influences the flow, consider the top half of the symmetrical configuration (see figure 2) often used in experiments. In this configuration the wall is replaced by a plane of symmetry, thus avoiding the complication of a viscous boundary layer on the wall. The expansion fan from the trailing edge of the shock-generating wedge eventually strikes the streamline F which has passed through the triple point. This causes the pressure to drop in the streamwise direction in region D, thus accelerating the flow, eventually, to supersonic conditions again. As a result, the cross-sectional area of the stream tube between the two triple-point streamlines F and F' decreases initially to a minimum at a sonic throat and then increases again in the region of accelerating supersonic flow. A subsonic pocket is thus formed in the otherwise supersonic flow. The size and shape of this pocket are controlled by the distance between the Mach stem and the sonic throat, which in turn depend only on the geometry, and thus on the scale, of the upper boundary of region B. However, until the subsonic pocket is set up, it is not possible for any information about the boundary of B to be transmitted to the reflexion point. Clearly, in the absence of a subsonic pocket, the flow in the vicinity of the reflexion point must not contain a length, as is indeed the case in regular reflexion.

The theory of Mach reflexion is clear on two results (Courant and Friedrichs, 1948): that Mach reflexion is not possible when $\alpha < \alpha_N$, where α_N is

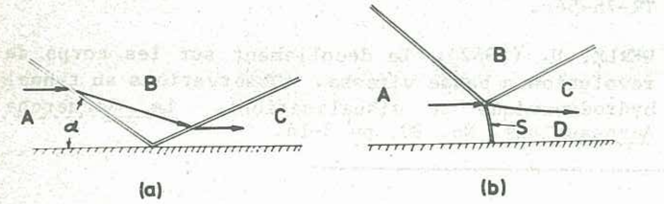

Figure 1 a) Regular and b) Mach reflexion

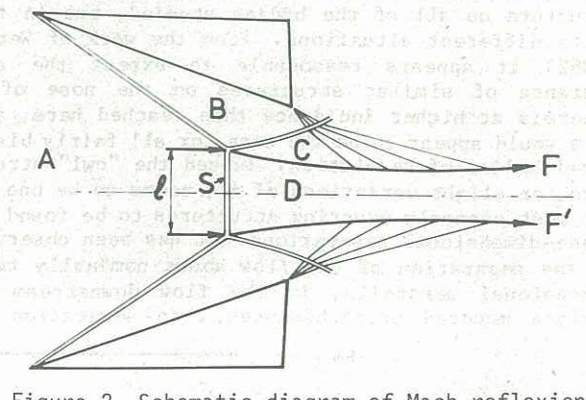

Figure 2 Schematic diagram of Mach reflexion with symmetrical arrangement of models

that incident shock angle for which the pressure after the regularly reflected shock (region C) is equal to the pressure reached from A via a normal shock; and that regular reflexion is not possible for $\alpha < \alpha_d$, where α_d is the value of α for which the regularly reflected shock is at the condition of maximum streamline deflexion. In the region $\alpha_N < \alpha < \alpha_d$, both configurations are possible. Figure 3 illustrates the regions of possible regular and Mach reflexion as functions of Mach number.

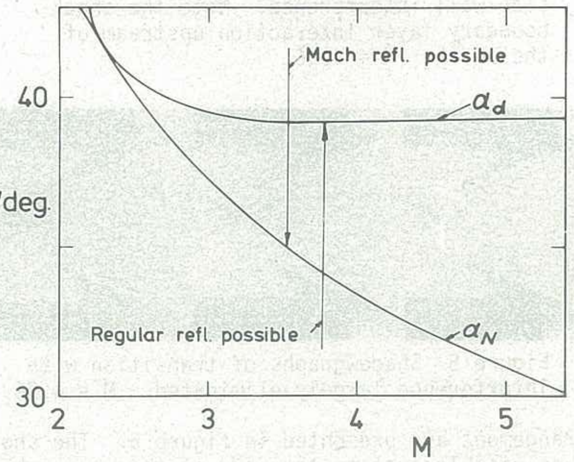

Figure 3 The detachment and von Neumann conditions as functions of M, for specific heat ratio $\gamma = 7/5$.

Experimental results supporting the upper curve $\alpha = \alpha_d$ or the "detachment criterion", as the condition for transition to Mach reflexion are numerous. However, these have been obtained either in the pseudosteady flow of a plane, moving shock reflected off a fixed wedge, or have been restricted to steady flow at Mach numbers, $M \leq 3$, where the difference between α_N and α_d is relatively small. Where steady flow measurements have been made at high Mach number (Hornung and Kychakoff, 1977, Hornung, Oertel and Sandeman, 1979) they support the lower curve $\alpha = \alpha_N$, or the "von Neumann criterion". These are limited to one value of the Mach number (M=16), however, in a monatomic perfect gas (argon), and to dissociating flows.

Through a simple Galilean transformation the flow near a *regular* pseudosteady reflexion may be transformed to a steady flow. However, it is important to observe that such a transformation, applied to a pseudosteady *Mach* reflexion does not result in a steady flow, because the region influencing the reflexion point grows linearly with time. On the basis of pseudosteady reflexion data, textbooks such as Liepmann and Roshko (1957), Landau and Lifshitz (1959), Becker (1966) and Whitham (1974), give $\alpha = \alpha_d$ as the transition criterion for steady flow.

The small separation of the α_N and α_d curves at lower Mach numbers has caused Henderson and Lozzi (1975) to be persuaded that α_N is the correct criterion for all cases. This has been shown to be incorrect by Hornung, Oertel and Sandeman (1979) who demonstrated that, in the pseudosteady case, α_d (or the sonic condition very close to it) is the correct criterion, while α_N applied in steady flow. They proposed the following mechanism for the transition in steady flow: It is necessary for a length scale to be communicated to the reflexion point for the flow pattern to exhibit a length (such as the Mach stem length). The geometry of the boundary of region B in figure 3 must therefore be able to influence the flow near the reflexion point. Consider the case $\alpha_N < \alpha < \alpha_d$, where both reflexion configurations are possible, and assume that the regular reflexion actually occurs. Then, through some unsteady disturbance, let a Mach reflexion be set up temporarily. This allows a communication path to be set up, as explained in the discussion of figure 2, suggesting that Mach reflexion is stable in $\alpha_N < \alpha < \alpha_d$.

In order to test this mechanism, Hornung et al. (1979) proposed an experiment in which the configuration of figure 2 was to be investigated in a facility with sufficient running time to allow α to be increased through the region $\alpha_N < \alpha < \alpha_d$ from below and from above during the run, to avoid the disturbances associated with tunnel starting, and thus to examine whether any hysteresis effect exists. Such an effect would support the proposed mechanism. (It should be mentioned here that, although this mechanism of a temporary disturbance can cause a Mach reflexion to become stable in steady flow, it cannot do so in pseudosteady flow. This is consistent with the experimental observation that $\alpha = \alpha_d$ is the transition condition for pseudosteady flow.)

The purpose of the experiments described in this paper was, firstly, to obtain a more complete set of data for steady flow transition by measuring the transition angle at four supersonic Mach numbers up to M=5, and secondly, to measure the transition angle while increasing and while decreasing α through the range $\alpha_N < \alpha < \alpha_d$ during steady conditions, in order to examine the suggestion that a hysteresis effect may occur.

2 EXPERIMENT

The blowdown wind tunnel S3 of the Weapons Systems Research Laboratory of the Defence Research Centre, Salisbury, South Australia is the facility which is most suitable for our experiment in Australia. A calibration and a detailed description are given by Robinson (1970) and by Robinson and Landers (1967). The tunnel has a rectangular test section 152 mm × 178 mm.

Air, dried to a water content of 150 ppm by weight, is supplied to the control valve of the tunnel at pressures up to 8 MPa. This air is heated to the required reservoir temperature (up to 370°K) as it flows through the regenerative heater into the settling chamber. The heater stores enough energy prior to the run to maintain the reservoir temperature constant to within ± 3°K for the duration of the run (typically 30 s). The reservoir pressure (2.76 MPa maximum) is controlled to within ± 1% automatically during the run. The Mach number is determined by interchangeable nozzle blocks designed for M = 2.8, 3.5, 4.0 and 5.0 in the test diamond centred on the maximum cross-section. The variation of M over the region covered by the model of the present experiment is less than 0.5% at all four Mach numbers.

The tunnel is equipped with an incidence change mechanism and a good quality schlieren/shadowgraph system, the windows of which give coverage of the region between the top and bottom surfaces of the test section. The schlieren system is fitted with a 35 mm camera equipped with an automatic expose/film-wind mechanism which allows exposures to be taken at a rate of up to 3 frames per second with the spark light source triggered from the camera. A schlieren image is displayed in the control room on closed circuit television to give the operator the information necessary to make sensible decisions about experimental procedure.

For the purposes of our experiment, the model consisted of a double wedge arrangement similar to that of figure 2, with a system for adjusting the incidence of the wedges symmetrically using the incidence change mechanism. This enabled the wedge incidence to be varied continuously during a run at a minimum rate of 1.8 deg/s thus giving a resolution of approximately 0.6 deg/frame.

The location of the pivot pins for the wedges was chosen in such a manner that the gap between the trailing edges does not change excessively with wedge angle, and that the aerodynamic forces produce a slight incidence, reducing moment. It was not possible to reduce backlash in the system to less than ± 1 deg. However, the accuracy of determination of wedge angle from photographs is estimated to be ± 0.25 deg.

Initially, the wedges extended to within 2 mm of the sidewalls in the spanwise direction provoking an undesirable interaction with the sidewall boundary layer. Subsequently the span of the wedges was reduced to 102 mm, giving 25 mm clearance from the sidewall. Whilst the modification eliminated the undesirable interaction with the sidewall boundary layer, oil flow studies showed that the flow over one tip of each wedge was affected by blockage in the side support arms. This was subsequently corrected and satisfactory shock waves were generated by the wedges. Because of the finite span of the wedges however, only portion of the shock front centred on the tunnel axis is plane, and the shock-interaction pattern is not two dimensional.

The experimental conditions are given in table I. These conditions could not be reproduced exactly in repeat runs, but the effect of the run-to-run variation on the present experiment is not significant.

TABLE I

EXPERIMENTAL CONDITIONS

M	$T_o/°K$	p_o/MPa
2.84	300	0.31
3.49	300	0.49
3.98	300	0.76
4.96	365	1.54

3 RESULTS

The first series of experiments was performed with the model which provides only a narrow spanwise gap between it and the window. It was immediately clear that no hysteresis effect occurred, the transition being independent of the direction of incidence change. An example of the shadowgraph pictures taken is presented in figure 4. This shows strong evidence of an interaction of the wedge shock with the sidewall boundary layer in the form of a feature slightly upstream of the shock. The more sharply defined line may be identified as the wedge shock by comparing its incidence to that calculated from the wedge incidence and the free stream Mach number. The measured transition angle, α_{tr}, was slightly but significantly smaller than α_N throughout the Mach number range tested.

The experiments were then repeated with models with the span reduced to 102 mm to move the boundary layer interaction further downstream. Following modifications to the support arms, this was successful in producing well-defined shock fronts, and examples of shadowgraph photographs taken with this

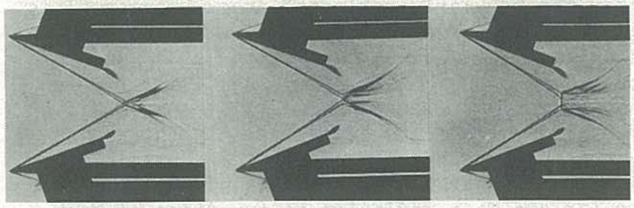

Figure 4 Shadowgraphs of transition with side-wall interference. Note the shock-boundary layer interaction upstream of the shock. M = 4.96.

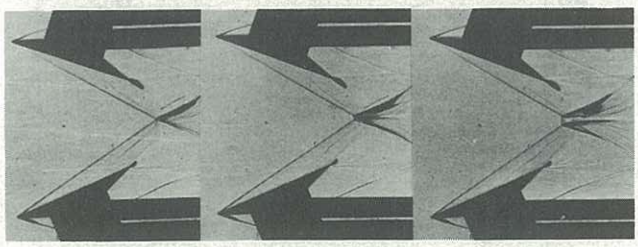

Figure 5 Shadowgraphs of transition with interference largely eliminated. M = 4.96.

arrangement are presented in figure 5. The shock waves visible just to the rear of the wedge shocks originate from the side support arms adjacent to the sidewalls. These should have no effect on the wedge shock interaction.

The transition angles were again observed to be identical with α increasing and α decreasing. The angles were obtained plotting the Mach stem length ℓ against α, fitting a straight line to the measurements and extrapolating to $\ell = 0$. An example of such a plot is given in figure 6. As can be seen, the extrapolated value of α_{tr} agrees well with the calculated value of α_N which is marked by an arrow.

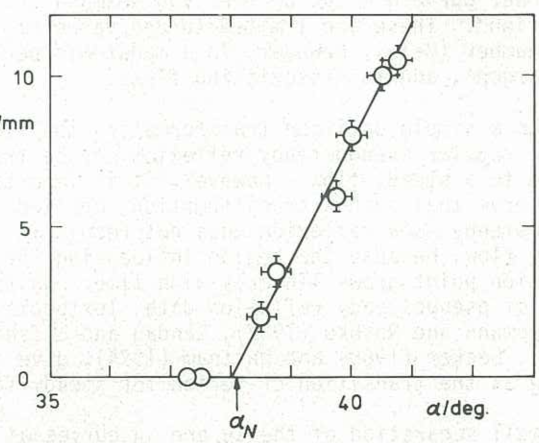

Figure 6 Example of determination of transition angle. M = 2.84.

Figure 7 presents the experimental data for α_{tr} as a function of M in relation to the two curves α_N and α_d; data of Henderson and Lozzi (1975) are included. This demonstrates clearly, that the von Neumann criterion gives the correct transition angle in steady flow over the whole Mach number range, a result which is not unambiguously demonstrated by Henderson and Lozzi's data because of the proximity of α_N and α_d at lower Mach number. The large separation of the two curves at M=5 (8.5 deg) and the excellent agreement of α_{tr} with α_N of our data support this result more convincingly.

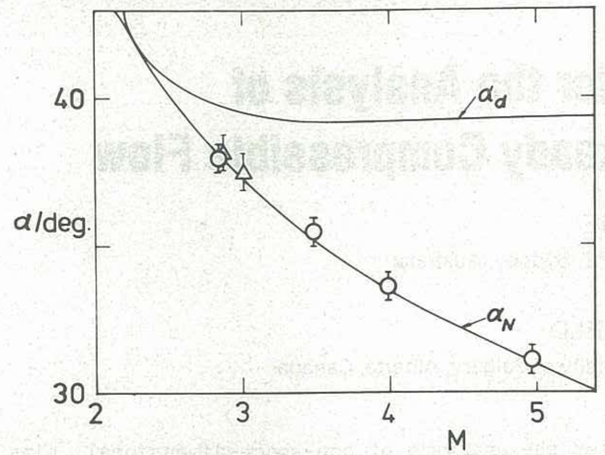

Figure 7 Comparison of measured transition angles with theory. ○ , present experiments, △ , Henderson & Lozzi.

4 CONCLUSIONS

It has been demonstrated that, in steady flow, the transition from regular to Mach reflexion of shock waves occurs at the von Neumann condition and not at the detachment condition. This has been done more convincingly than in previous work by performing experiments in the Mach number range $2.8 \leq M \leq 5$, at the upper end of which the separation of α_N from α_d is 8.5 deg, such that the experimental error is not significant. This result is contrary to information given by gasdynamics textbooks.

The hysteresis effect predicted by Hornung, Oertel and Sandeman (1979), that the unstable state of regular reflexion in the range $\alpha_N < \alpha < \alpha_d$ might be achieved by a continuous adjustment of wedge incidence during the run, could not be confirmed.

ACKNOWLEDGEMENTS

The first author acknowledges the permission of the Chief Superintendent, Weapons Systems Research Laboratories to publish this paper. Both authors express their appreciation to Mr K.D. Thomson for his cooperation and encouragement of the project, and to members of the staff of Aerodynamics Research Group, particularly J. Beniulis who designed the model, and A. Paine and B. Ralph who conducted the experiments.

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