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MEASUREMENTS OF GLANCING SHOCK WAVE/BOUNDARY LAYER INTERACTION FROM MACH 1.9 TO 3.8

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ABSTRACT

Surface pressure measurements have been made to investigate glancing shock wave/turbulent boundary layer interaction over the Mach number range, 1.95 to 3.74. They indicate a growth of upstream influence at low Mach numbers that is consistent with the interaction characteristics theory of Stalker. At higher Mach numbers it appears that significant separation occurs, even though the angle of the shock generating wedge is only 5°.

INTRODUCTION

The present high level of interest in aerospace planes has focused attention on shock wave/boundary layer interactions, both in external flow over a hypersonic aerospace plane and in the inlet to its airbreathing scramjet propulsion system. An important class of shock wave boundary/layer interaction is one in which sweepback is a key element. The flow is then three-dimensional. The configuration of interest in this paper is shown in Figure 1. A planar shock wave generated by a wedge is swept back across a two-dimensional, turbulent boundary layer on a flat plate. The leading edge of the wedge is normal to the plate. If the deflection angle of the wedge is small (not more than about 5°) large regions of separated flow are not expected to occur and the interaction is regarded as weak.

This three-dimensional interaction has been studied at free stream Mach numbers up to about 3 (Settles and Dolling (1986) review experiments) but investigators disagree over some basic aspects of the flow. In particular, there is debate over whether the flow away from the generating wedge, adopts a generally cylindrically symmetric or conical form. For weak interactions a theory developed by Stalker (1984) from the 'triple-deck' model of Lighthill (1953) predicts that disturbances propagate upstream along shock wave/boundary layer interaction characteristics, the direction of which is determined by the properties of the boundary layer and the main stream. For the geometry considered here, Stalker's model predicts that the flow adopts a cylindrically symmetric pattern and that interaction initiation effects from the leading edge of the wedge take the form of termination of the upstream flow pattern along shock wave/boundary layer interaction characteristics. The structure of this interaction is shown in Figure 2.

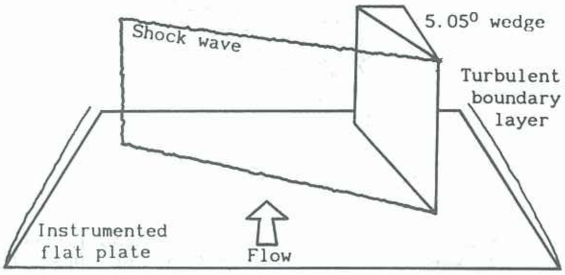


Figure 1 Experimental flow geometry

Validation of Stalker's theory has been obtained at a Mach number of 1.85 and a wedge angle of 5° (Mee et al, 1986) but not at the higher Mach numbers associated with the intake flow of a hypersonic scramjet. The interaction characteristics theory predicts that a high Mach number, glancing shock/wave boundary layer interaction is basically different to one at moderate supersonic speeds. The reason for this is that the rate at which the extent of the high Mach number interaction spreads normal to the shock as one passes downstream from the origin of the interaction is likely to be of the same order as the rate at which it spreads due to boundary layer growth. This is expected to increase surface flow deflections and encourage separation (Mee et al, 1986).

This paper reports new measurements of weak, glancing shock wave/turbulent boundary layer interaction over the Mach number range of 1.95 to 3.74. The measurements are used to evaluate Stalker's interaction characteristics theory.

STALKER'S THEORY

The theory of Stalker (1984) is based on the two-dimensional 'triple-deck' model of Lighthill (1953). The external supersonic stream is the outer deck, with the boundary layer represented by a rotational, compressible, inviscid flow as the middle deck and a viscous, incompressible flow as the inner deck adjacent to the wall.

The theory predicts that perturbations to flow quanties along the interaction line (intersection of the plane of the shock wave with the wall) are propagated upstream of this line with exponential decay along a series of parallel shock wave/boundary layer interaction characteristics (Figure 2). The three-dimensional perturbations equations for continuity, momentum and energy are applied to the middle deck. A number of assumptions are made, in particular, the assumption that the cylindrically symmetric Prandtl- Meyer relation can be used to relate pressure at the edge of the boundary layer to the vertical deflection angle there, and that a simple power law Mach number profile in the turbulent boundary layer is adequate.

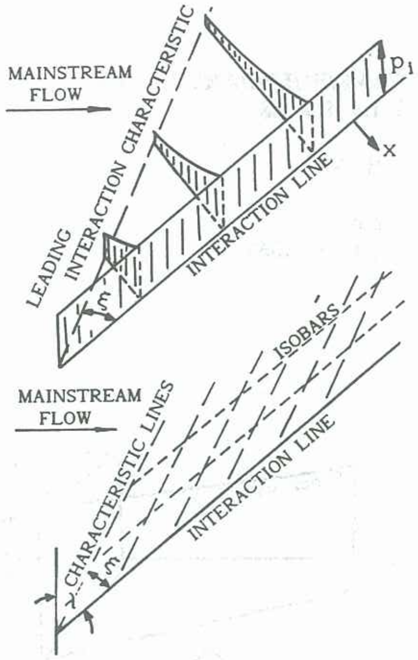
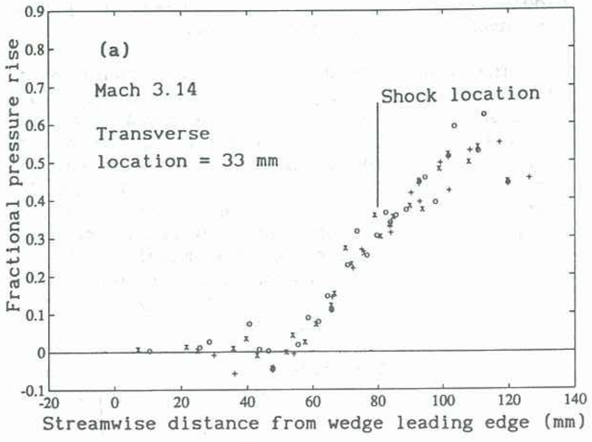


Figure 2 Structure of the interaction proposed by Stalker. Top: distribution of upstream pressure disturbance. p_1 is the pressure perturbation at the interaction line. Bottom: plan view showing parallel characteristic lines.

The theory predicts that perturbations in flow quantities, for example, pressure, will decay upstream from the interaction line as $e^{\kappa x}$ (where x is normal to the interaction line (Figure 2)) until the leading interaction characteristic is encountered. Across this, flow properties take their undisturbed values, implying a sudden jump in flow properties across the leading characteristic. The measure of upstream influence κ^{-1} and the angle ξ of the characteristics to the interaction line are predicted by Stalker.

EXPERIMENTS

The experiments are described in detail by Stacey (1989). They were conducted in the Department's supersonic blowdown wind tunnel fitted with a variable Mach number asymmetric sliding block nozzle. The model fully spanned the 101 mm wide test section. The glancing shock wave was generated by a 5.05° wedge bolted directly to the surface of the measuring plate. The model geometry is shown in Figure 1. Surface static pressures on the plate were measured with a 32-channel piezoelectric transducer module with



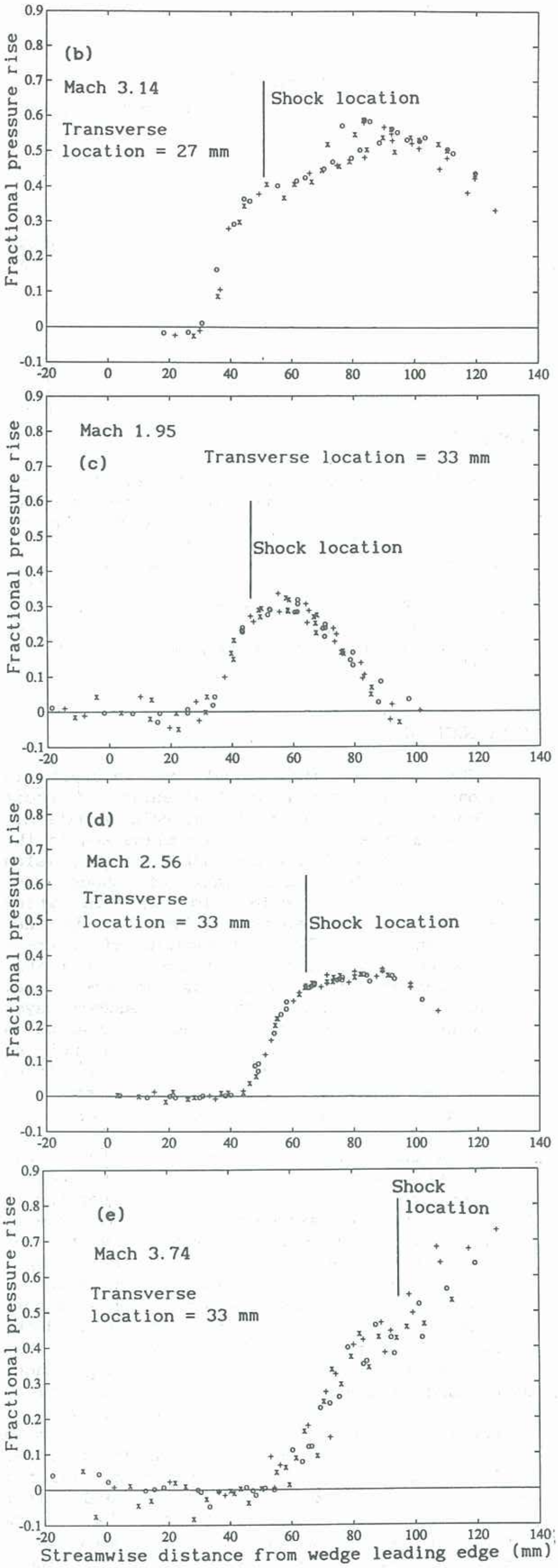


Figure 3 Representative streamwise pressure distributions: (a) and (b) are at two different transverse stations at Mach 3.14, (a), (c), (d) and (e) are at one transverse location and cover all Mach numbers tested. Transverse location is measured normal to the flow from the wedge leading edge.

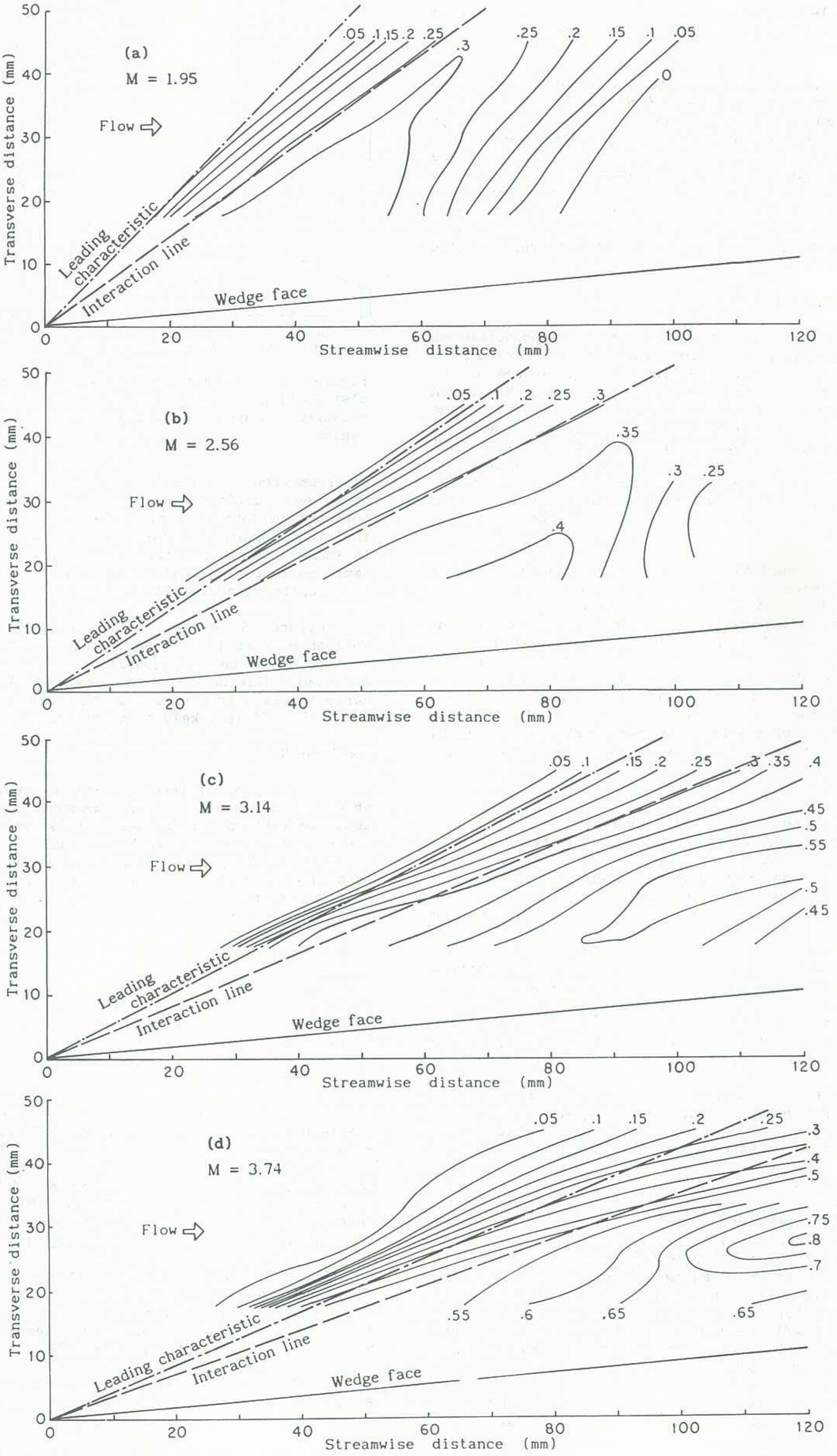


Figure 5. Upstream pressure perturbation distributions taken normal to the shock from measurements near the spanwise limit of the data region.

multiplexed output. Mach number was established by simultaneously measuring stagnation chamber pressure.

Tests were conducted for several streamwise wedge positions at four Mach numbers; 1.95, 2.56, 3.14 and 3.74, corresponding to Reynolds numbers of 7.5×10^6 to 1.0×10^7 at the interaction line. Two wedge angles were used; 5.05° and 0°. The purpose of the 0° wedge tests was to provide a control for assessing the pressure change due solely to the 5.05° shock wave. The mere presence of a wedge, (without a shock), can change the pattern of the (second order) nonuniformities in the flow.

Data Reduction

Mee et al (1986) show that the principle of superposition holds for weak interactions such as those considered here. Thus, the pressures on the plate surface for the 5.05° shock case are given in terms of a fractional rise above the corresponding value for the 0° 'shock' case. It was convenient to collapse the data initially into plots of streamwise pressure distribution. Examples of these plots are shown in Figure 3. Pressure levels read from these plots were then used to form the contour plots of Figure 4.

The variation in the streamwise position of the wedge (needed to obtain fine spatial resolution of pressure measurements with fixed pressure tappings) results in a variation in the thickness of the boundary layer entering the interaction. No allowance has been made for this in the data reduction. Although the data is already sufficiently well defined to allow evaluation of relevant theories, it is believed that further slight improvement may be possible by compensating for varying boundary layer thickness.

Results

Figure 3(a) and (b) show streamwise pressure distributions at two transverse locations for the Mach 3.14 case. A sharp rise of pressure closer to the wedge is apparent. Figure 3(c) to (e) are streamwise pressure distributions for the other three Mach numbers examined, taken at the same transverse location as in Figure 3(a). These plots show not only the influence of the shock but also the influence of the expansion emanating from the tip of wedge. (Tunnel blockage problems prevented the use of a taller wedge.) It is believed that, even for the lowest mach number, this expansion did not influence the pressure field upstream of the inviscid shock location.

There is evidence that, for the higher Mach numbers, the flow near the wedge may be close to separation. This is indicated by a 'plateau' in the rising pressure distribution (Figure 3(b)).

DISCUSSION

The pressure contour plots in Figure 4 validate Stalker's theory only at the lowest Mach number (1.95). All measured upstream influence is then behind the leading characteristic. At the next highest Mach number (2.56) there is a tendency for the upstream influence to move ahead of the predicted leading characteristic, but this may be due in part to the simple Mach number profiles chosen by Stalker.

At the two higher Mach numbers (3.14 and 3.74) the isobars do tend to coalesce close to the wedge, indicating a leading interaction characteristic, but not that predicted by Stalker. In these highly swept flows, boundary layer growth is significant and could have an influence on the upstream growth of the interaction. However, this does not explain the isobars crossing the interaction line. A more likely explanation is incipient separation, even though the wedge angle is small. Stalker's theory is based strictly on small perturbation analysis and cannot be expected to describe separated flows well.

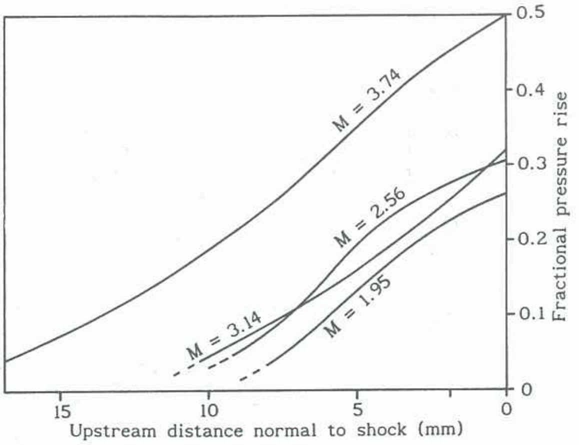


Figure 5 Upstream pressure perturbation distributions taken normal to the shock frem measurements near the spanwise limit of the data region.

Figure 5 shows the extent of upstream influence normal to the shock. It contains further evidence of separation. The decay of upstream influence is not exponential and the large increase in pressure at the interaction line for Mach 3.74 is likely to be due to separation.

CONCLUSION

In its present form, Stalker's theory is not able to account for the measured growth of upstream influence in glancing shock wave/boundary layer interaction at high Mach numbers. There are indications that, even at small wedge angles, some separation occurs at higher Mach numbers. This has important implications for designers of hypersonic inlets.

ACKNOWLEDGEMENT

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