SHOCK WAVE REFLECTION IN A NON-CIRCULAR INLET.

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Summary The flow between two finite wedges placed symmetrically in a supersonic flow with one or both sides capped with a semi-cone is studied. Imaging with laser vapour screen and shadowgraph techniques give images that can be difficult to interpret and result in flows which appear aphysical. Further experimentation and CFD techniques are used to resolve the confusion.

INTRODUCTION

It has been established that the shock wave reflection pattern on a plane surface below a supersonic body can comprise of regular reflection immediately below the body, which then transits to Mach reflection in the lateral direction [1]. The initial interest in the current work was to examine the nature of the three-dimensional flow in the vicinity of the point of transition from the one type of reflection to the other. This arose from the examination of three-dimensional effects in studies of wave reflection between two finite width wedges placed symmetrically in a supersonic wind tunnel [2]. The study used shadowgraph visualisation but with the light beam passing through the test section yawed so that the 3d wave profiles could be established. Figure 1a is a conventional shadowgraph showing regular reflection, which could be interpreted as a two dimensional flow. The exact same flow but with 45^o optical yaw is shown in Fig 1b. Here the reflection is clearly of Mach type as the optical beam is now grazing the peripheral Mach surface. This surface then wraps forward until it transitions to regular reflection. This is imaged as a dark protuberance immediately behind the visible Mach stem changing to a white line that is the line of regular reflection. Towards the right of the image this again splits into the Mach reflection on the near-side of the wedge. It is these transition points that are of interest. The third image of Fig. 1 is a more detailed view taken at 55^o optical yaw, which shows slight fluctuations in stem height before it settles to regular reflection raising concern about its suitability for transition studies. Against the background of previous studies which show significant sensitivity to upstream perturbations it was decided to explore a different geometry for this work. This is the subject of this paper.

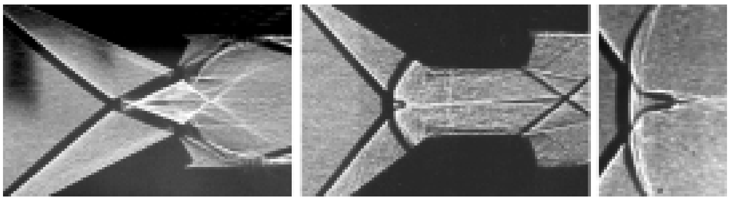

Fig. 1. Shock reflection pattern off finite width wedges [2]

GEOMETRY INVESTIGATED AND EXPERIMENTAL ARRANGEMENT

Since it is known that an internal conical shock wave cannot reflect regularly from the axis of symmetry even for small wall angles that will result in regular reflection for a double wedge, a geometry consisting of a double wedge with the open ends closed off with two semi-cones should result in a transition from Mach to regular reflection. A schematic of this arrangement with one semi-cone cut away is shown in Fig. 2. The line of reflection should change from that around a Mach disk to a line as indicated in the schematic. A number of wind tunnel models were built, a so-called cut-model of the shape shown in Fig. 2 with a 15^o wall angle and a full model with both semi-cones. The cut-model was made to facilitate the starting shock in the tunnel to be swallowed and to enable visualisation using laser vapour screen techniques (LVS) since the interactions of interest occur within the length of the model and are thus not visible using conventional shadowgraph techniques. The full model was made with a 10^o wall angle resulting in the reflection occurring downstream of the trailing edge, enabling conventional shadowgraphy to be employed. All tests were conducted at a nominal Mach number of 3.

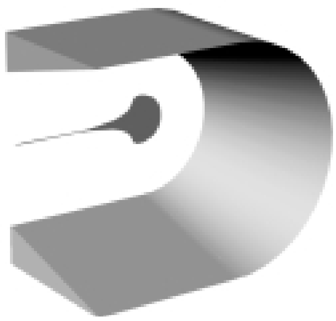

Fig. 2. Cut-model geometry.

RESULTS AND DISCUSSION

The initial experimental work showed the flow to be complex and, in particular, three features of particular interest are identified for discussion. Understanding them necessitated subsequent CFD evaluation. Fig. 3 shows three LVS images with the sheet normal to the free-stream direction, taken at successive positions in the downstream direction. The first image, approximately halfway down the model shows an expected incident wave pattern consisting of a semi-circular wave on the right arising from the semi-cone, through plane in the centre, arising from the wedge, to curved on the left as the wave diffracts around the edge of the model. Note, however, a slight unevenness developing in the conical wave profile. The second image shows a slice of the flow just 4 mm further downstream. A Mach stem of significant size, reflected shocks, and slipstreams have appeared. The transition is apparently very rapid. The third image, beyond the trailing edge, shows that the Mach stem has reduced in size and transition to regular reflection has occurred. The dark patch behind the reflection point is the area encompassed by the shear layers arising from the Mach stem surface.

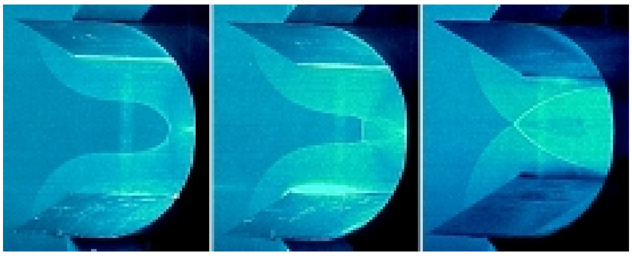

Fig. 3. LVS images of shock wave profiles

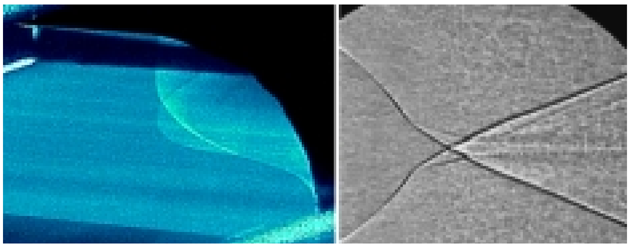

Fig.4. Views in and through the symmetry plane

Figure 4 shows an LVS image taken with the laser sheet near the plane of symmetry of the cut-model (flow from lower left to upper right), and a shadowgraph behind the full model (flow from left to right) and taken perpendicular to the wedge leading edge. Both of these show very interesting features. In the LVS image the incident shock starts at the cone leading edge (lower right) curves significantly into the flow as it increases in strength due to convergence on the cone axis, and then appears to bifurcate. Two waves then propagate in this symmetry plane and appear to cross giving an overall impression that is problematical when viewed in a two-dimensional sense. An equally inexplicable flow appears in the shadowgraph. The two incident conical waves curve inwards towards the model axis, suddenly develop a kink, which sheds a slipstream, and then reflect regularly with each other. It should be noted that the shadowgraph records all features within the full depth of the flow field, and in this case does not show any other features resulting from the three-dimensional flow.

These flows can be elucidated with the help of CFD (Fluent©). The full complexity of the flow requires considerable explanation but the selected images below allow the main features to be identified.

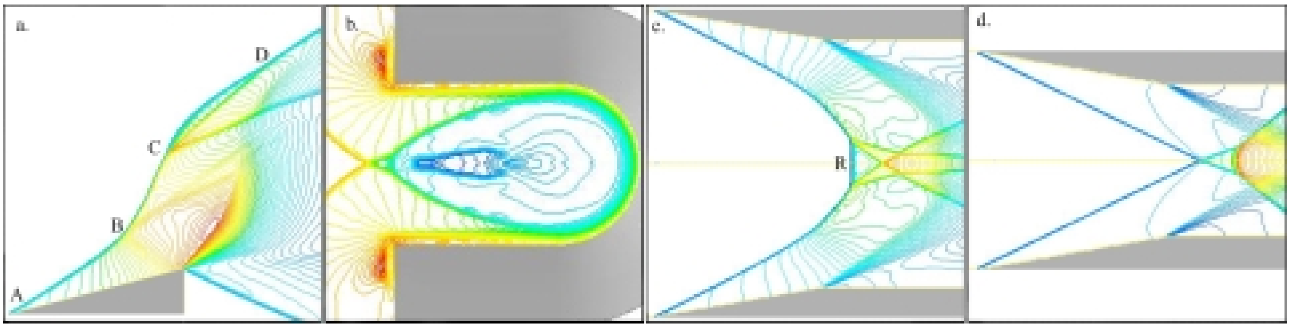

Fig. 5 Flow contours. a,b) Cut model, c,d) Full model

Figure 5a is a symmetry plane density contour plot for the cut model. The conical shock starts at the lip A, curves inwards and then rapidly transitions to a Mach reflection of significant size over a short distance at B. A contact surface and weak reflected wave emanate from this region. The height of the Mach disk then steadily decreases until it transitions to regular reflection at C. A strong contact surface is shed and the shock appears to bifurcate and then rejoin at D. The reason for this is evident from the transverse contours in a plane just downstream of the bifurcation, Fig. 5b. The green egg shape is the reflected wave coming off the Mach disk. The waves diffracting around the model edges now reflect in a regular fashion, which outstrips this contour, and thus two waves are evident in Fig. 1a. At later times the diffracting wave weakens and is overtaken again by the Mach disk reflected wave. A weak shear layer results from this merging, and although not clear in the contour plot appears in the LVS image. Similar phenomena occur for the full model: Fig. 5 b&c are for the mutually perpendicular symmetry planes. Bifurcation still occurs but the shock arising from the regular reflection is now perpendicular to the oncoming flow. What is interesting is that this shock marked R is not visible in the shadowgraph, presumably because the light beam simply passes through the two oblique waves and the line of intersection is too narrow to resolve, coupled with refraction effects.

CONCLUSION

It is shown that complex shock interactions occur in internal 3d flows. The study graphically demonstrates the possibility of mis-interpreting three-dimensional flow results, from both experiment and simulation, in terms of familiar two-dimensional patterns. Three interesting features are identified and clarified, and are the subject of further investigation.

References

[1] Marconi, F. *AIAA J.* **21:**707-713, 1983
[2] Skews, B.W. *J. Fluid Mech.* **407**:85-104, 2000