Interaction of a Laminar Hypersonic Boundary Layer with a Corner Expansion Wave

W. W. KOZIAK* AND P. A. SULLIVAN†
Institute for Aerospace Studies, University of Toronto, Toronto, Canada

Theme

THIS paper describes the application of a quantitative space and time resolved schlieren system to measure density gradients in the region of interaction of a hypersonic laminar boundary layer with a corner expansion wave. Flowfield properties are inferred and compared with up-to-date theoretical results.

In spite of many published attempts, the problem of calculating the flow of a supersonic or hypersonic boundary layer over an expansion corner has not really been satisfactorily solved. These analyses have invariably used simplifying assumptions which have resulted in omission of important physical parts of the problem, which is complex as it includes upstream influence and centrifugal effects, transverse pressure gradients in the boundary layer, and boundary-layer expansion wave interaction.

As part of a theoretical and experimental program on this problem at the Institute for Aerospace Studies (UTIAS) Lo and Sullivan[1,2] reported an analysis which attempted to give a complete picture. The calculations, which used an integral technique, are related to the classical von Kârmân-Polhausen method. By using the viscous-inviscid equations throughout the entire regime of interest, significant centrifugal effects were shown to occur in a region which could extend far downstream of the corner. Details of the skin-friction and heat-transfer peaks were obtained, and the calculations also indicated the presence of a weak shock wave immediately downstream of the corner.

Comparatively little experimental work has been done on the laminar hypersonic boundary-layer and corner expansion flow problem. This is mainly due to the difficulty encountered when relevant data is sought, particularly since only flowfield information can verify the presence of some of the more important physical effects.

Contents

In the present experiment a quantitative laser schlieren system[3] is used to obtain measurements of density change relative to the reference conditions in the region just upstream of the expansion corner. These values are established by computation from basic tunnel parameters. Density changes are measured across the expansion wave to the edge of the boundary layer and across the boundary layer to the wall. Density traverses upstream of the corner have shown that the inviscid flow is isentropic, so that pressure at the edge of the layer can be inferred through the isentrope law $p/\rho^{\gamma} = \text{constant}$ and pressure at the wall can be calculated since the "cold" wall model is at room temperature.

The basic facility being used for the experiment is the UTIAS 11-in. hypersonic shock tunnel. The measured reflected shock reservoir pressure is nominally 940 psia, and the theoretical temperature based on reflected shock calculations in nitrogen is 1440°K. The facility is equipped with a 20° apex angle conical nozzle having an exit plane diameter of 11 in. and an open jet test section in which the freestream flow Mach number, $M\infty = 10.5$, is calculated from pitot pressure surveys. The test model comprises a 10° wedge 8 in. long followed by a 5° expansion corner. This configuration is used to avoid separation downstream. The basic model width is $7\frac{1}{2}$ in., but side bodies are included to change the width to $4\frac{1}{2}$ in. in 1-in. steps, to determine edge effects.

A series of 11 runs of the shock tunnel was performed giving four density gradient profiles through the interaction region at each of the 6 stations upstream and 16 stations downstream of the corner. These stations were equally spaced at intervals of 5 mm or $1.6\delta_1$.

Lo and Sullivan[1,2] predicted that for cold walls and the values of M_e and α_w used in the present experiments, the amplitude and extent of the upstream influence should be less than that detectable by the present technique. No effects were observed at any of the upstream stations including that located immediately prior to the corner.

The same calculations, which circumvented the computational difficulties associated with a discontinuous corner by including a small transition section rounded off to a corner radius $r_b = \delta_1$ approximately, showed a rapid decrease in wall pressure p_w and increase in δ in the corner zone. Since for $\alpha_w = 5°$ this corner zone occurs in a distance of only $0.1\delta_1$, these changes appear almost as discontinuities in the theoretical curves for the behavior downstream of the corner shown in Figs. 1–3. Certainly this region is too small to be observed in the present experiment.

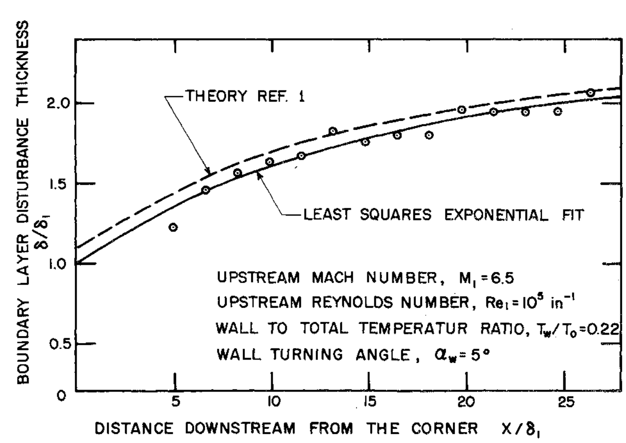

Fig. 1 Boundary-layer growth downstream of the corner.

Presented as Paper 72-75 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted February 28, 1972; synoptic received May 5, 1972; revision received April 2, 1973. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $1.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Supersonic and Hypersonic Flow; Jet Wakes and Viscous-Inviscid Interactions.

* Research Assistant. Associate Member AIAA.

† Associate Professor. Associate Fellow AIAA.

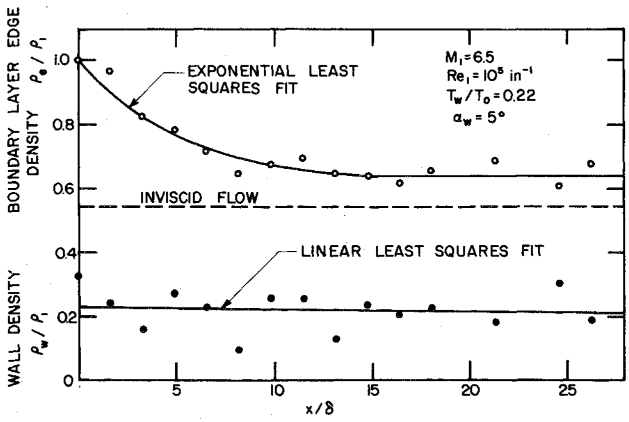

Fig. 2 Experimental density distributions downstream of the expansion corner.

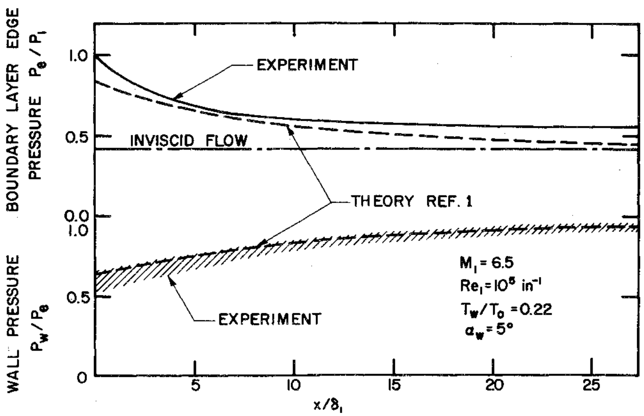

Fig. 3 Experimental and theoretical pressure distributions in the interaction region downstream of the corner.

Figure 1 compares the theoretical and experimentally measured boundary-layer growth downstream of the corner. Figure 2 gives the experimental values of density at the boundary-layer edge and at the wall. The inviscid value, calculated from the classic Prandtl-Meyer theory is included; the experimental value of ρ_e/ρ_1 was expected to approach this value in the limit $x/\delta_1 \to \infty$. It should be noted that, in the fitting of the exponential curves to δ/δ_1 and ρ_e/ρ_1, no special preference was given to the data at $x = 0$. Hence the fact that these curves happen to pass very near to $\delta/\delta_1 = \rho_e/\rho_1 = 1$ appears to provide independent confirmation of negligible upstream influence effects.

Curves of p_e/p_1 and $p_w/p_e = 1 - Ae^{-bx}$ were fitted to the data. For the p_w/p_e results a simple measure of the confidence that could be placed in this curve fit was obtained by generating 15 curves, each obtained by omitting one of the computed values of p_w/p_e in succession. The envelope of these curves is given in Fig. 3.

The experimental results agree reasonably well with the theory of Lo and Sullivan.[1] They show clearly the strong interaction between the downstream boundary-layer flow and the expansion wave which manifests itself in a very slow edge pressure decay to a limiting value. Although this value overestimates the expected inviscid limit in the present experiment, most probably as a result of conical flow effects in the test facility, this does not detract from the basic finding. More important, the rapid growth of the boundary-layer immediately downstream of the corner and the wall-to-edge pressure ratio, which is a measure of the transverse pressure gradient in the boundary layer, indicate unmistakably that the expected centrifugal effects influence the boundary-layer flow considerably and that they extend well outside of the immediate vicinity of the corner.

References

[1] Lo, A. K. and Sullivan, P. A., "A Complete Solution to the Viscous-Inviscid Equations for the Interaction of a Laminar Hypersonic Boundary Layer With a Corner Expansion Wave," AIAA Paper 70-807, Los Angeles, Calif., 1970.

[2] Lo, A. K., "A Study of the Interaction of a Laminar Hypersonic Boundary-Layer With a Corner Expansion Wave," Rept. 157, Sept. 1970, Institute for Aerospace Studies, University of Toronto, Canada.

[3] Koziak, W. W., "Quantitative Space and Time Resolved Laser Schlieren System for the Study of Hypersonic Flow," *The Review of Scientific Instruments,* Vol. 41, No. 12, Dec. 1970, pp. 1770–1773.