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THE EVOLUTION OF TURBULENCE IN SHOCK-WAVE/BOUNDARY LAYER INTERACTIONS

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SUMMARY Hot wires are used to measure the longitudinal mass-flow fluctuations in a series of shock-wave/turbulent boundary-layer interactions. The interactions are generated by two-dimensional compression corners, and range from a fully attached flow to one which has a small separated zone. The evolution of the turbulence intensities are traced along some representative streamlines, and the observed amplification and subsequent decay of these intensities is discussed in terms of current calculation methods.

1 INTRODUCTION

Our understanding of shock-wave/turbulent boundary-layer interactions has been hindered by the limited availability of high quality turbulence data. In particular, calculation methods have generally not performed well in these flows, and improved turbulence models cannot be developed until adequate turbulence data become available for a wide range of interactions.

To fulfill partially this need, the turbulence behaviour in a number of compression corner flows were investigated at the Gas Dynamics Laboratory of Princeton University. The mean flow data was extensively documented by Settles (1975) and Settles et al. (1979) and, using these results four corner angles were selected for detailed turbulence measurements: 8°, 16°, 20° and 24°. Constant-temperature hot-wire anemometers were used throughout.

In this paper, we present the normal wire results for the first three cases. The incoming freestream Mach number was 2.87 and the 8°, 16° and 20° cases correspond to a fully attached flow, a flow experiencing incipient separation, and a flow exhibiting a small separated region. The incoming flow was identical in all three cases, and the upstream boundary layer δ_o was approximately 26 mm thick, with a Reynolds number based on momentum thickness of 77,600.

The experimental apparatus and techniques are given in somewhat greater detail in section 2. The results are presented and discussed in section 3, and the conclusions are summarized in section 4.

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2. APPARATUS AND EXPERIMENTAL TECHNIQUES

The tunnel configuration is shown in Fig. 1. The tunnel was operated at a stagnation pressure of 6.9×10^5 N/m^2, and the unit Reynolds number was 6.3×10^7/m. The wall conditions were near-adiabatic and the freestream rms turbulence intensity was approximately 1%. The models were mounted on the tunnel floor and fitted with aerodynamic fences to avoid interference from the side-wall boundary layers. Blockage problems limited the model lengths downstream of the corner to 195 mm for the 8° model, 151 mm for the 16° model and 121 mm for the 20° model.

Constant temperature hot wire anemometers were used throughout, and details of the operating procedure were given by Smits et al. (1983). The hot wires were operated at high overheat ratios (1.0∿1.3) and it was assumed that at these overheat ratios their response to total temperature fluctuations was negligible. The frequency response was typically 200 kHz. Details of the data acquisition system have been given elsewhere (Hayakawa, et al., 1982) and will not be repeated here.

The anemometer measures fluctuations in mass-flow rate $(\rho u)'$. To determine the behaviour of the fluctuations in velocity, we invoked Morkovin's (1962) "Strong Reynolds Analogy," which assumes that the pressure fluctuations are small, and that the density fluctuations are related to the velocity fluctuations according to

$$\frac{\langle \rho' \rangle}{\overline{\rho}} = (\gamma-1)\, M_a^2\, \frac{\langle u' \rangle}{\overline{U}}$$

These assumptions appear to hold even in severely perturbed boundary layers (see, for example Dussauge and Gaviglio, 1981). In addition to the above, the value of the density-velocity correlation is required. The measurements by Dussauge and Gaviglio suggest a constant value of 0.8 across the boundary layer, and this value was adopted for all data analysis.

3. RESULTS AND DISCUSSION

Before presenting the turbulence measurements, it is useful to consider some aspects of the mean flow behaviour.

The static pressure and skin friction coefficient distributions are shown in Figs. 2 and 3, respectively. From these figures, it is clear that the flow tends towards separation as the corner angle increases. In the 20° case, the flow has actually separated, with a separated zone approximately one-half δ_o long.

The mean velocity profiles generally demonstrate a quick recovery downstream of the corner. For all three

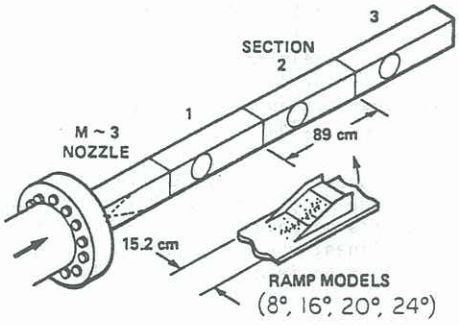

Fig. 1. Sketch of the 20 x 20 cm high Reynolds Number channel and test model installation. From Settles, et al (1979).

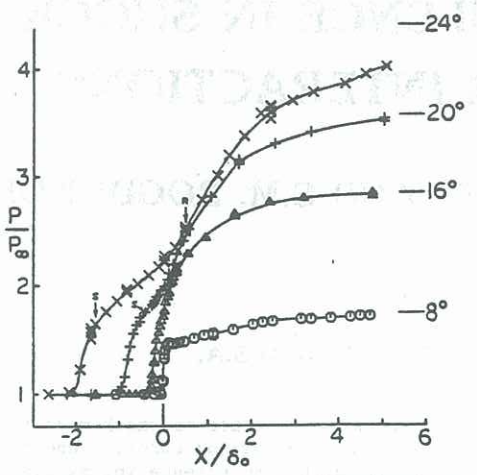

Fig. 2. Surface pressure distributions. From Settles, et al. (1979)

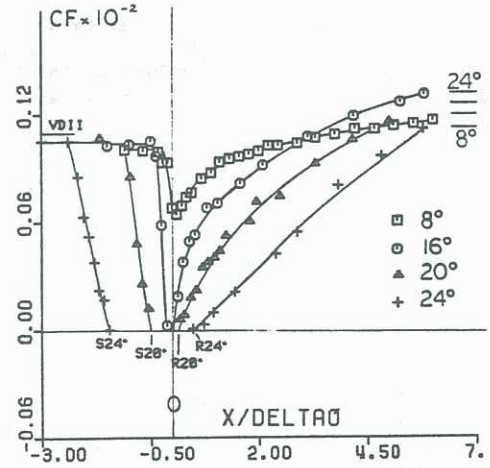

Fig. 3. Skin-friction distributions. From Settles, et al. (1979)

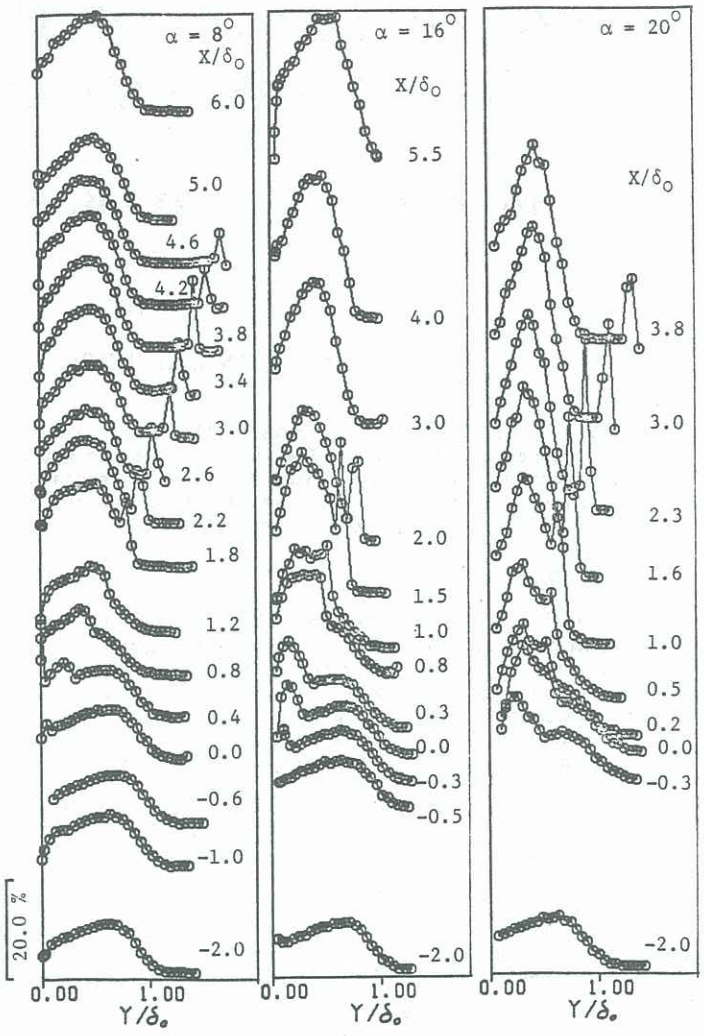

Fig. 4. Profiles of $\langle(\rho u)'\rangle / (\overline{\rho U})_{ref}$ as a function of distance normal to the wall.

cases, Settles, et al. (1979) observed that the profiles rapidly fill out and approach their equilibrium shape by the furthest downstream station.

When we consider the turbulence behaviour, however, it quickly becomes clear that the boundary layer is far from equilibrium, even at the furthest point downstream. Figures 4 and 5 show the mass-flow fluctuation intensity $\langle(\rho u)'\rangle$ and velocity fluctuation intensity $\langle u'\rangle$. Note that the intensities are non-dimensionalized by the incoming freestream values $(\overline{\rho U})_{ref}$ and $\overline{U}_{ref}$. The figures therefore show the behaviour of the absolute fluctuation levels.

The most obvious feature of the turbulence behaviour is the dramatic amplification that occurs as the boundary layer passes through the interaction region. To understand this amplification more fully, it is useful to consider the evolution of the turbulence intensities along selected streamlines. In this way, the amplification may be related to the terms which appear in the Reynolds stress transport equations (see, for example, Hayakawa, et al., 1983).

Three streamlines, corresponding to upstream boundary layer locations of y/δ_o = 0.2, 0.4 and 0.6 were selected for this purpose (see Fig.6). For each of these these streamlines, the evolution of $\overline{u'^2}$, normalized by its upstream value is given in Fig. 7.

Figure 7 shows that these flows may be conveniently divided into two regions: an "interaction zone," which loosely corresponds to the region where severe pressure gradients exist, and a "recovery zone," which is the region downstream of the interaction zone. Within the interaction zone, $\overline{u'^2}$ displays a rapid increase along each streamline. The magnitude of the increase, however, is a function of both the initial position within the boundary layer and the shock strength; the largest increase occurs for the largest corner angle. In contrast, the behaviour within the recovery zone does not display such a simple trend. Near the wall, the turbulence intensity decays quite rapidly (Fig. 7a), whereas further away the intensities are still increasing at the furthest downstream station (Fig. 7b). This behaviour clearly reflects the time dependent response of the turbulent motions. As expected, the larger eddies in the outer part of the boundary layer obviously respond more slowly than the motions near the wall.

In terms of a calculation method, it appears possible to predict some features of the initial rise in turbulence intensity using a rapid distortion approach, as suggested by Debieve, et al. (1980). The behaviour within the recovery region, however, obviously requires a more detailed consideration of the terms in the Reynolds stress transport equation. In particular, a lagged response model appears to be required, combined with a careful balance between "generation" terms such as div $\underset{\sim}{U}$ and "destruction" terms such as the dissipation.

In developing appropriate turbulence models for these interactions, information regarding the length scale behaviour is generally required. The integral length scales were deduced from the time scales using Taylor's

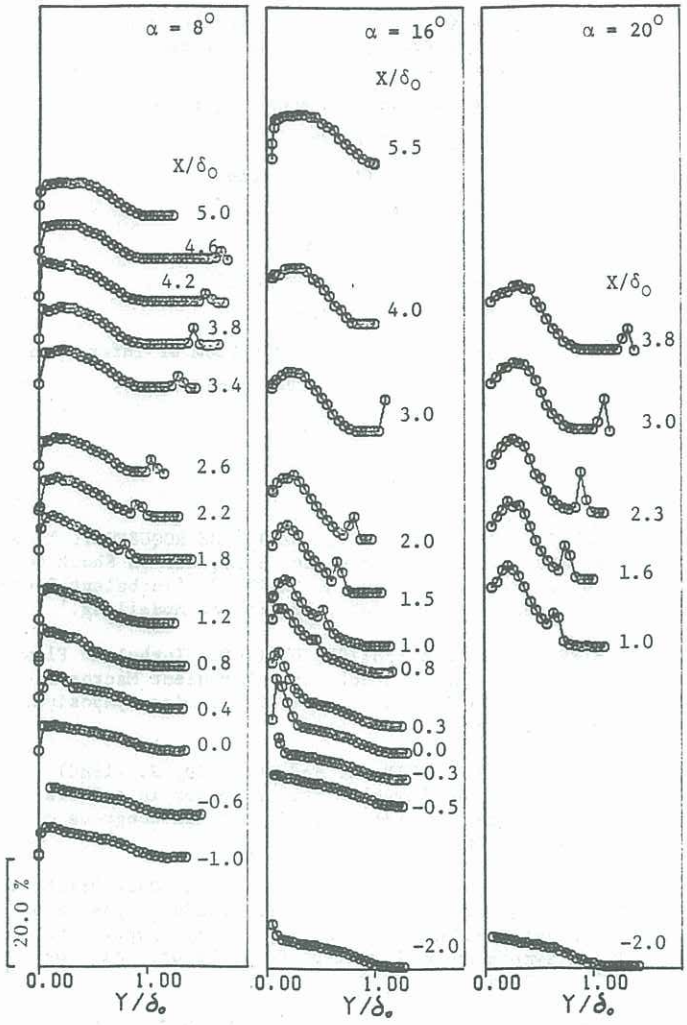

Fig. 5. Profiles of $\langle u' \rangle / \overline{U}_{ref}$ as a function of distance normal to the wall/

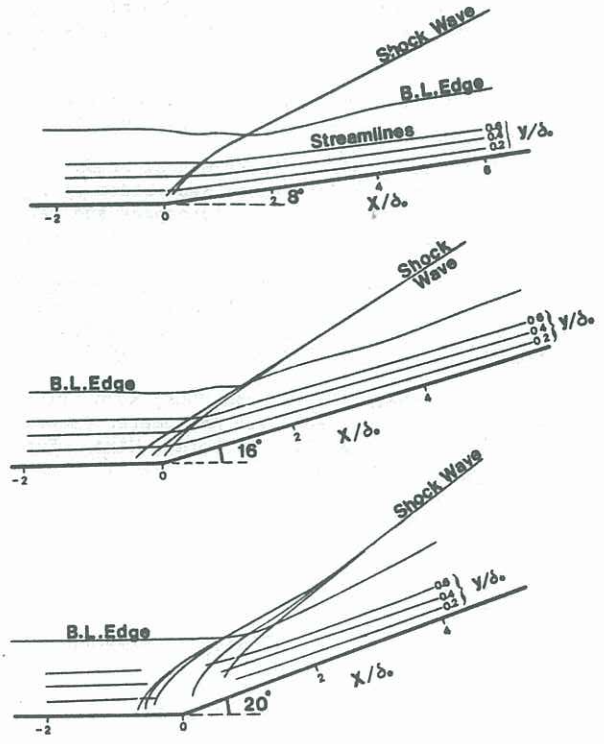

Fig. 6. Flowfield map, showing selected streamlines.

hypothesis, and the time scales were found by extrapolating the spectral density distribution to zero frequency. The results are shown in Fig. 8.* The accuracy of these results is rather limited, partly because of the questionable applicability of Taylor's hypothesis, and partly because of the subjectivity of the extrapolation procedure. Nevertheless, Fig. 8 shows that the integral length scale definitely increases through the interaction, and that this increase tends to become greater as the corner angle increases. A similar increase in length scale was observed by Ardonceau, et al. (1979) and Debieve and Bestion (1981).

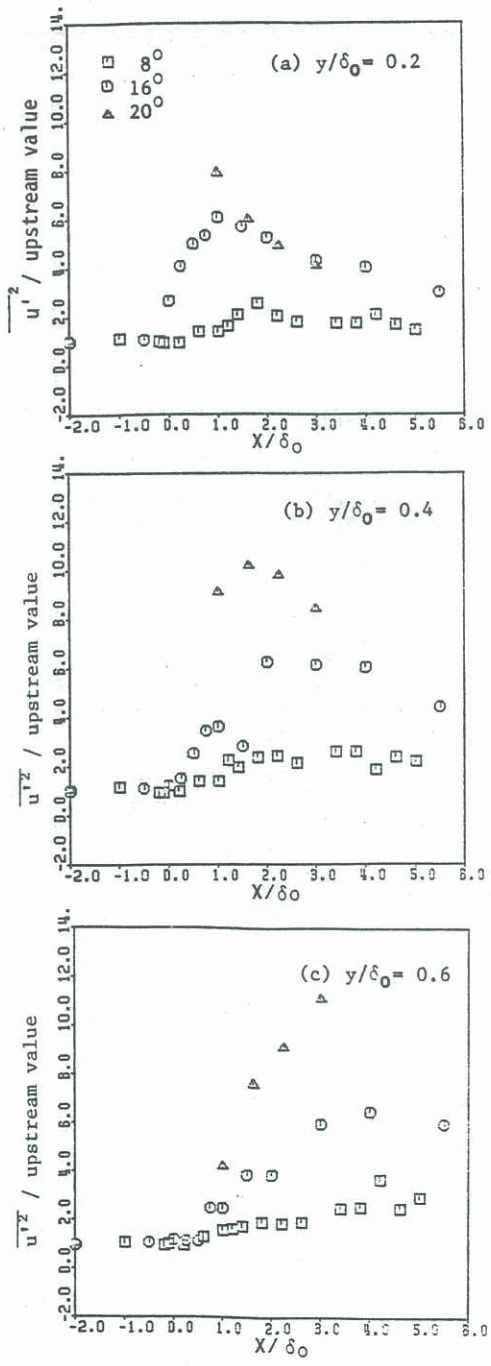

Fig. 7. Evolution of normalised $\overline{u'^2}$ along selected streamlines.

*The incoming boundary thickness δ_o was used to non-dimensionalize the results, and it must be noted that the results would look somewhat different if the local boundary layer thickness δ was used instead. In rapidly changing flows such as those considered here, however, it is not clear that δ is a meaningful length scale.

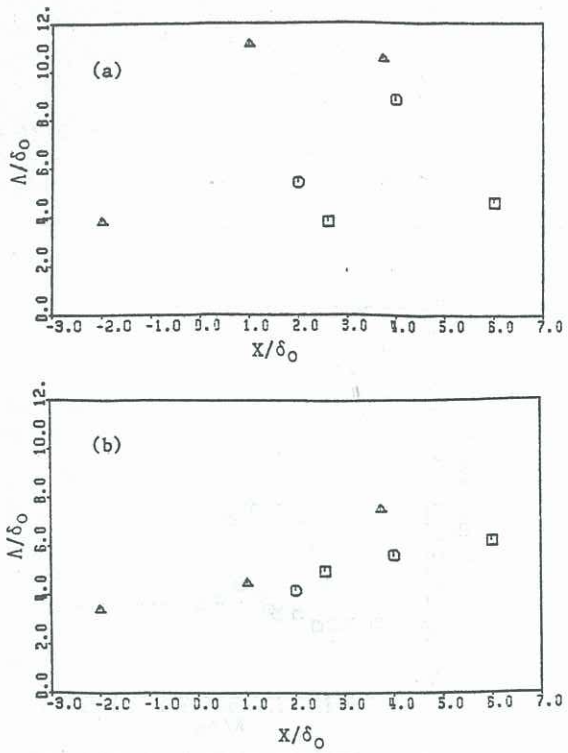

Fig. 8. Integral length scales. a) $y/\delta_o = 0.4$, b) $y/\delta_o = 0.6$ (Notation as in Fig.8)

4. CONCLUSIONS

Hot wires were used to measure longitudinal mass-flow fluctuations in a series of two-dimensional compression corners. The interactions ranged from a fully-attached flow to a flow with a small separated zone. Morkovin's "Strong Reynolds Analogy" was used to derive the behaviour of the velocity fluctuation intensity.

The results indicate that the turbulence intensity increases as soon as the flow experiences compression, and the amplification becomes larger with increasing shock strength. In the recovery zone downstream of the interaction, the behaviour along a streamline is a strong function of wall distance. Clearly, the outer part of the boundary layer appears to respond much slower than the inner part to the effect of the shock-wave induced perturbation.

The integral length scale also increases through the interaction zone, and appears to be a strong function of shock strength.

All three interactions considered here behave in a similar fashion, and no specific influence due to separation was observed.

NOTATION

M_a	Mach number
U,u'	velocity in x-direction, mean and fluctuating
x	distance along model surface measured from corner, taken as positive in the downstream direction
y	distance normal to model surface
γ	specific heat ratio
δ	99% boundary layer thicknes
ρ	density
$\overline{\rho U}$	mean mass-flow rate
$(\rho u)'$	fluctuating mass-flow rate

Subscripts and other notation

ref	freestream condition upstream of interaction
o	incoming or undisturbed condition
< >	root mean square value

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