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Organized Structures in a Supersonic, Turbulent Boundary Layer

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1. INTRODUCTION

To improve the understanding of compressible turbulent boundary layers, turbulence measurements were taken in a high Reynolds-number zero pressure-gradient layer with a freestream Mach number of 2.87. The measurements were designed to investigate the structure of the large scale motions in the layer. Morkovin (1962) hypothesized that the essential dynamics of equilibrium compressible turbulent boundary layers followed the incompressible pattern closely, as long as the fluctuating Mach number remained small. While this hypothesis has been widely accepted in describing the time-averaged behavior, the effect of compressiblity on boundary layer structure has not been extensively investigated.

In subsonic flows, many studies have investigated the near-wall behavior, especially the bursting cycle. Kline et al. (1967) conjectured that the bursting phenomenon plays a leading role in the production of turbulent energy and that it controls the diffusion of this energy from the inner layer to the outer layer. Later research by Corino & Brodkey (1969), Kim et al. (1971) and Willmarth and Lu (1971) supported Kline's hypothesis.

The burst-sweep cycle is modelled by many researchers using hairpin vortices (see, for example, Smith 1984). These vortices take on many forms, but are basically Λ -shaped loops. In these models, the mechanism of vortex stretching produces the locally intense shear layers which then cause the oscillation and breakup of the low-speed streaks. The vortex stretching, caused by the interaction of larger eddies from the outer-lauer with the lifted low-speed streaks, manifests itself as a region of concentrated vorticity just outside the sublayer. The stretched vortex elements undergo a rapid breakup due to their high instability. Some of the models view the formation of the low-speed streaks as being due to the concentration of low-speed fluid between the counter-rotating legs of the vortex loop.

Recent research has indicated that hairpin vortices similar to those connected with the bursting process may extend throughout the boundary layer. Head and Bandyopadhyay (1981) used flow visualization to study a zero pressure gradient boundary layer and discovered the presence of hairpin vortices throughout the entire layer, as if the layer consisted exclusively of hairpins "attached" to the wall region. Individually, the hairpins are inclined to the wall at the characteristic "eddy angle" of 40-50° - similar to the typical angle found in many near wall studies.

In the current work, we investigated the structure of the outer layer motions in a compressible turbulent boundary layer, and the data presented here are the first of their kind.

2. APPARATUS AND EXPERIMENTAL TECHNIQUES

The tunnel was operated at a stagnation pressure of 6.9×10^5 Nt/m², and the unit Reynolds number was 6.5×10^7/m. The wall conditions were nearly adiabatic and the freestream turbulence intensity was approximately 1%. All measurements were taken in the boundary layer developing on the tunnel floor at a position 2.21m from the nozzle throat (as measured along the tunnel wall). Conditions at that point are given in Table 1. The test boundary layer was representative of a well-developed, two-dimensional, zero pressure gradient layer.

The data collection system consisted of a VAX 11/750 minicomputer and CAMAC (Computer Automated Measurement and Control) data acquisition system. Four fluctuating signals could be sampled simultaneously and digitized at a rate of 1MHz per channel. The CAMAC memory allowed a maximum, continuous record length of 24576 data points per channel for each of four channels.

Measurements of the wall-pressure fluctuations were made using four identical miniature differential pressure transducers manufactured by Kulite Semiconductor Products, Inc. The natural frequency, as quoted by the manufacturer, was 500 KHz. The best estimate for the usable frequency range was approximately 0-40KHz. Four pressure transducers were mounted in-line in a cylindrical plug, and the separation distance between each transducer was 5.1 mm.

DISA 55M10 constant temperature hot-wire anemometers were used to measure instantaneous mass flux. The hot-wire probes were constructed as described by Smits et al. [1983]. For multi-wire runs, a special hot-wire support was designed to hold four normal wires in pairs of two, one above the other, and the two pairs of wires could be moved relative to each other vertically (see Fig. 1).

M_∞	2.87
Re_∞/m	6.5×10^7
δ	28 mm
δ^*	6.2 mm
U_∞	565 m/s
$(\rho u)_\infty$	479 kg/m²s
P_{wall}	3.34 p.s.i.
C_f	.00114

TABLE 1. Flow conditions on the tunnel centerline at x = 2.21 m.

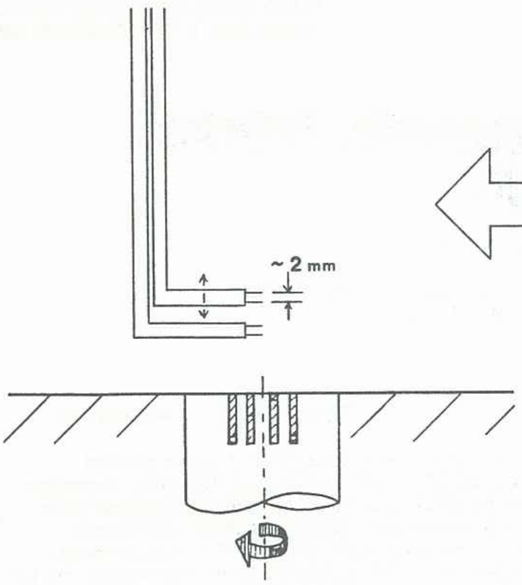

Figure 1. Arrangement of hot wire probes and wall pressure transducers.

A small Mach 3 pilot tunnel was used to calibrate the hot wires. The frequency response was adjusted by means of the square wave test, and the roll-off frequency always exceeded 100KHz. The wires were kept at an overheat ratio of unity, minimizing temperature sensitivity.

By combining the use of the wall-pressure transducers and hot wires, simultaneous measurements of the instantaneous wall pressure and instantaneous mass flow were made. The hot wires were placed at different points in the flow (relative to the wall-pressure transducers) to obtain a wide spatial resolution of the flow field. The matter of relative phase shift between the signals is an important consideration. By examining the frequency limitations of both systems, an upper limit of 40KHz was set on the measurements of correlations between wall pressure signals, and correlations between wall pressure and hot-wire signals. By matching the frequency response of the wires, phase shifts between hot wire signals were minimized, and correlations between hot-wires were accurate up to 100KHz.

3. RESULTS AND DISCUSSION

Two hot wires, one directly above the other at a fixed separation distance, were traversed through the boundary layer. The calculated space-time correlations at different distances from the wall are shown in Fig. 2. The peak values of the correlations are quite high, reaching a maximum of 0.65 near the middle of the boundary layer. More importantly, the delay time corresponding to the peak of the space-time correlation, τ_{max}, decreases from 20 microseconds at the floor to nearly zero at the edge of the boundary layer. The value of τ_{max} along with the wire separation distance Δ and the local mean velocity can be used to define an angle θ :

$$\theta = \tan^{-1}\left(\frac{\bar{U}\,\tau_{max}}{\Delta}\right)$$

The angle θ may be called a "structure angle", in that it is associated with an average large-scale motion. The results from three different traverses can be seen in Fig. 3 as a

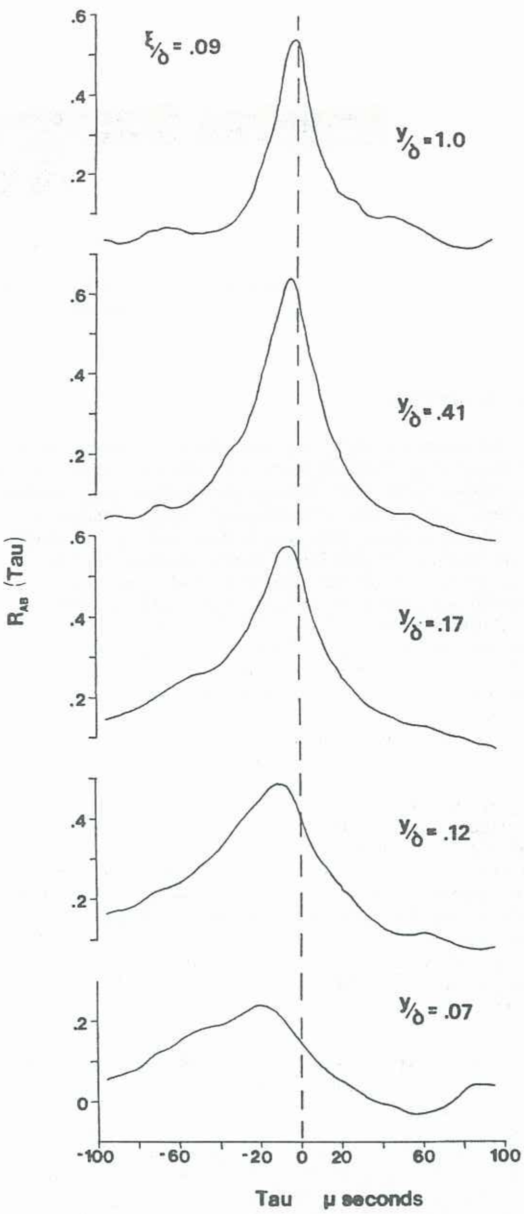

Figure 2. The space-time correlation of mass-flow fluctuations throughout the boundary layer. Hot-wire separation is 0.1δ.

function of position in the boundary layer. The angle is small near the floor, increases quickly to about 45°, and it remains constant at this value throughout 70% of the boundary layer. Note that the distribution of the structure angle seems to be independent of the two different separation distances chosen.

The distribution of θ is in accordance with Head and Bandyopadhyay's (1981) observations in a subsonic boundary layer at low Reynolds numbers, yet the results give higher angles than Robinson (1986), who measured a structure angle of 30° in a supersonic boundary layer. In contrast to the present case (where the hot wires were traversed at fixed separation distance), Robinson's structure angles were deduced with one hot wire fixed at the wall and the other wire traversed directly above it. This method is similar to that used by Brown and Thomas (1977), who measured a structure angle of 18° using a hot-wire probe traversed above a wall shear stress gauge.

If a hairpin-type structure is assumed, it is possible that both Robinson and Brown & Thomas have their lower probe buried in the elongated legs of the vortex, thereby indicating a shallower structure angle than that measured here.

Cross-correlations were computed between pressure fluctuations at the wall and mass-flow fluctuations measured at various points within the boundary layer. Figure 4a shows the correlations with the hot wire located at 0.45 δ downstream of the pressure transducer, while Figure 4b shows them for a streamwise separation of 0.91 δ.

The first point of interest is the rather low level of correlation, with a maximum peak of 0.22. This level of correlation was observed for even the smallest transducer separations and can be ascribed to the differences in the frequency content of the pressure and mass-flow signals.

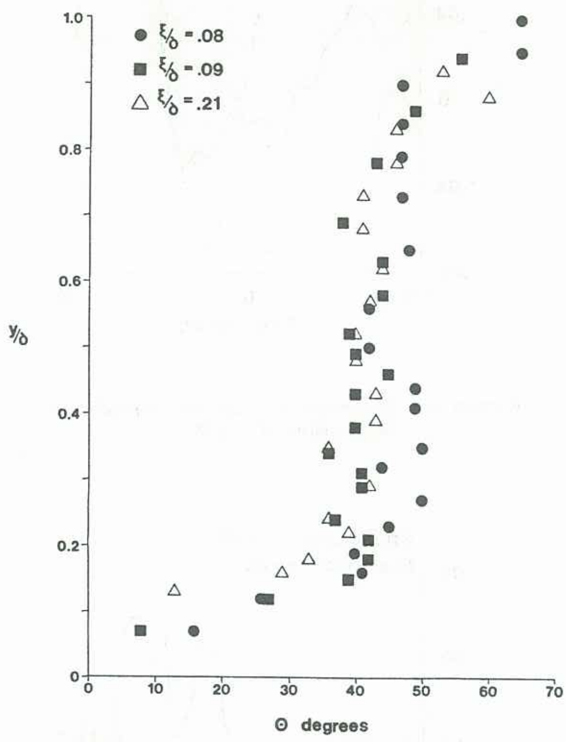

Figure 3. Computed large-scale structure angle throughout the boundary layer for two different wire separation distances.

Secondly, although the separation of the transducers doubled, the level of the correlation remained nearly the same. Furthermore, the general shape of the correlation was retained (the small peak at a negative value of τ, followed by a sharp rise to the major peak). Hence, the structures appear to retain their shape and coherence as they are convected downstream.

Figures 4c and 4d show correlations for spanwise separations between the transducers of 0.11δ and 0.45δ respectively (both also have a streamwise separation of 0.09 δ). We see that the results in Fig. 4c show a slight decrease in correlation level when compared to the previous results which had no spanwise separation. In addition, in Fig. 4d, we observe that with an increased spanwise displacement, the correlation has broken down completely, suggesting that the structures have a very limited spanwise extent.

4. CONCLUSIONS

While a much more intensive study is called for, this preliminary investigation indicates that the effect of compressibility on organized structures in a turbulent boundary layer is probably small.

For example, the deduced structure angles from this investigation are consistent with Head and Bandyopadhyay's observations in incompressible flow. The eddy angle is low near the floor, increases quickly to about 45° (where it remains throughout 70% of the boundary layer), and increases again near the edge of the boundary layer.

These "average" structures appear to retain their shape for several boundary layer thickness as they move downstream, and their spanwise extent is very limited. In all respects, the large scale motions are similar to those observed in subsonic flow.

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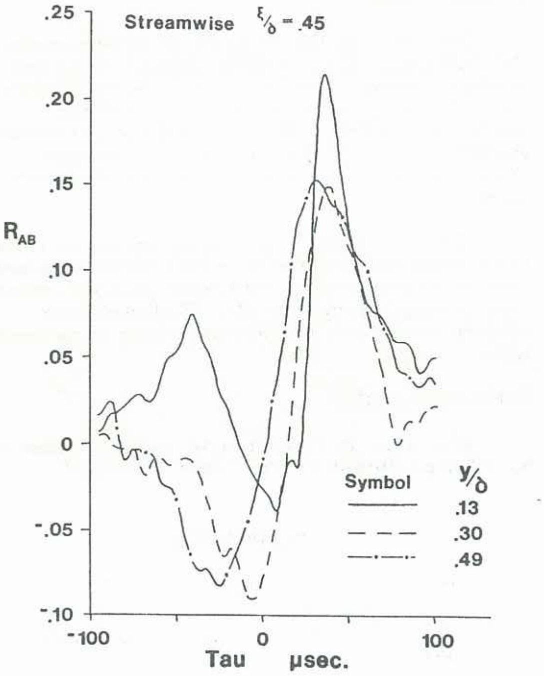

Figure 4a. Space time correlation between a wall-pressure signal and a mass-flow signal. Streamwise separation of 0.45 δ.

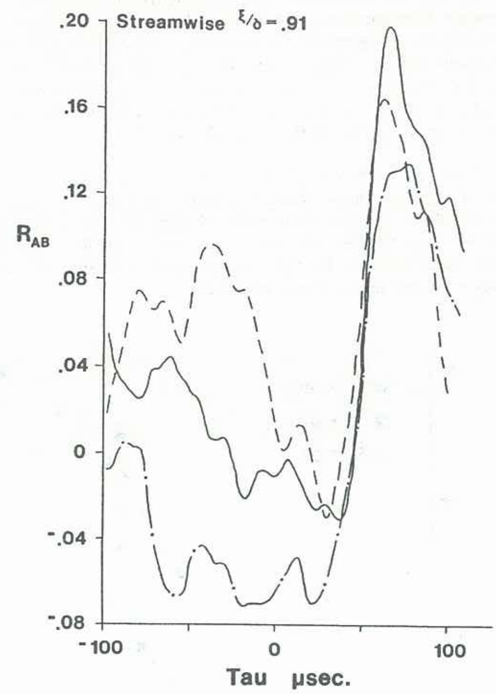

Figure 4b. The same as Fig. 4a; streamwise separation of 0.91δ .

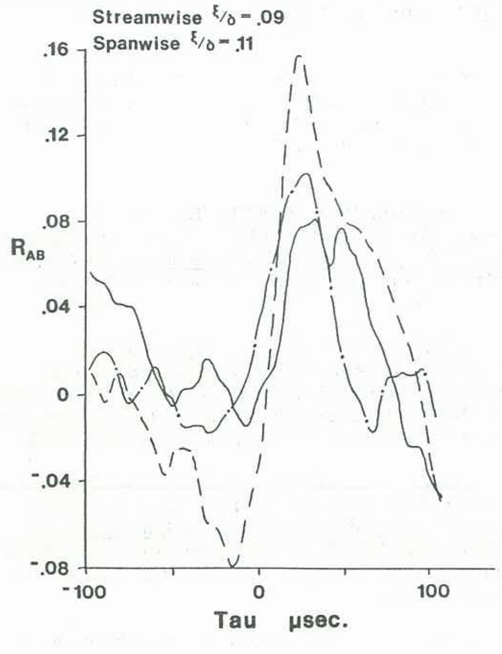

Figure 4c. The same as Fig. 4a; streamwise of 0.09 δ, spanwise separation of 0.11δ

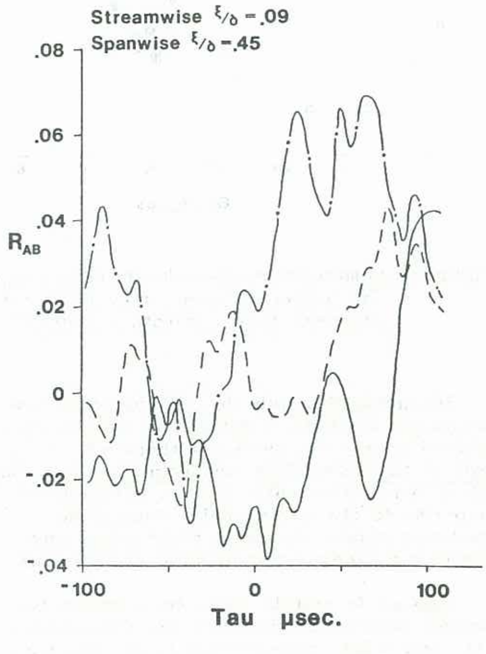

Figure 4d. The same as Fig. 4a; streamwise separation of 0.09 δ, spanwise separation of 0.45δ .