Space-Time Correlation Structure of Hypersonic Boundary Layers

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As at low speeds, the study of turbulence space-time correlations in hypersonic boundary layers affords a much better description of the flow structure than do single point measurements, from which time autocorrelations are the only means of deducing the turbulence parameters. The geographic features of eddies and their method of convection at low speeds is well understood from the work of Favre.[1] The only high-speed counterpart of Favre's work can be found in preliminary data reported by Horstman and Owen in transitional boundary layers at Mach 7.[2] The rate of decay and the overall convection speed of turbulence were found unexpectedly low in these tests, especially in view of Favre's earlier results. Since the convection speed is central to the time-space transformation by which turbulence structure is deduced from Eulerian data, a closer second look at the space-time correlations of the hypersonic boundary layer was felt justified.

The present experiment was carried out on the test section wall of the 21-in. Hypersonic Wind Tunnel of the Jet Propulsion Laboratory. Edge Mach number M_e was 9.37, momentum Reynolds number R_θ was 36,800, and the temperature ratio T_w/T_o in the steady state was 0.38. The 10-cm-thick boundary layer was free of longitudinal and lateral pressure gradients, and had a maximum turbulence Reynolds number of 5,000 and sublayer thickness δ_s equal to 3% of the rms boundary-layer thickness. The present space-time correlation measurements were preceded by detailed surveys of the mean, intermittent, and turbulent flow.[3,4]

Correlation measurements were done by two hot-wire anemometers held by an actuator immersed in the flow. While one of the two wires was held fixed, the other could be traversed along the coordinates x (the stream direction), y (normal to the wall), or z. The entire arrangement could be positioned at will at any distance y above the wall. With an adjustable delay electronic correlator, space-time correlations could thus be obtained along the three principal directions x, y, z for any arbitrarily large number of inter-probe separations x', y', and z' and time delays. The use of electronically compensated 0.00001 in. diam wires ensured adequate frequency response.

Aerodynamic interference seriously hampered the measurement of the longitudinal correlations, along x, which require two probes to lie on the same mean streamline. Care to design minimum drag support fixtures was successful in decreasing, but not alleviating, spurious signals from the "downstream" probe caused by the wake of its "upstream" companion. Fortunately, the interference effect was evident only in the outer half of the boundary layer ($y \geq 0.5\delta$). The central problem of this type of measurement lies, instead, in deducing the correlation tensor of the velocity fluctuations separately from that of the pressure or temperature fluctuations. This hot-wire "signal splitting" is impossible to do formally when all turbulence modes are active.[3] A formal technique is available[5] for separating the velocity from the temperature correlations when the pressure fluctuations p' are insignificant ($p' << u', T'$) but was not applied in this work. However, sufficient results were obtained using the unresolved hot-wire signal alone (as in Ref. 2) to warrant the brief report which follows.

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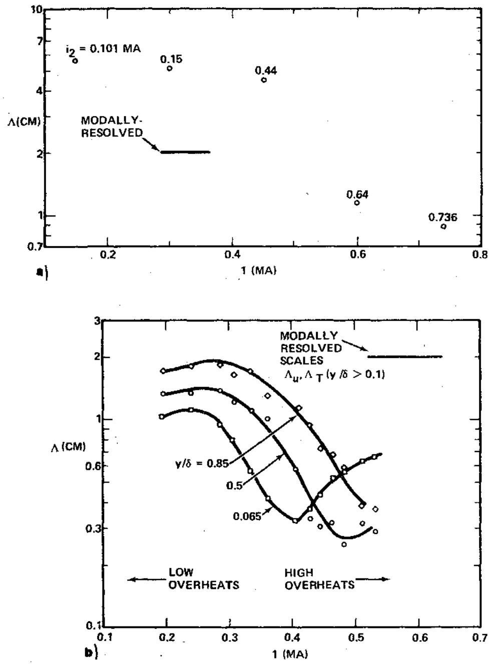

Fig. 1 Longitudinal integral scales at various distances y/δ from the wall as deduced from the unresolved hot-wire signal. a) Deduced from the two-wire space correlations (present work). Note the two hot-wire currents i_1 and i_2. b)From autocorrelation data.[3] Note size of actual scales Λ_u and Λ_T.

Longitudinal space correlations were obtained for various "overheat" settings of the two wires, which were integrated to give the longitudinal macroscale Λ of the sensor signal. Figure 1 shows that, on any fixed streamline a distance y away from the wall, Λ depends sensitively on the overheat currents i_1 and i_2 of the two wires. As Fig. 1 also shows, the same problem arises with the time scales measured from auto-correlations of the a.c. output. In these representative examples the space scales, converted from time scales using the local flow velocity, differ by a factor of 3 from the actual resolved scales of temperature and velocity Λ_t and Λ_u, respectively.[3] This behavior, explainable from the manner a hot-wire responds in compressible flow,[6] clearly shows that resolved scales cannot be routinely found by setting the current i at a single fixed level.

No sensitivity to the heating currents was found, however, in the relative position of the maxima in the space-time correlation functions, a set of which is typically shown on Fig. 2. It was therefore possible to plot, at several y positions, the optimum auto-correlation $R_o(x')$ (the so-called moving-frame auto-correlation) from which the longitudinal turbulence decay could be observed. Such an auto-correlation function is shown on Fig. 3, compared with equivalent low-speed results.[1] Note that the decay of the total turbulence field is faster than found at low speeds. Specifically, R_0 has decreased to 0.2 over a length x'/δ of about 1.3δ along the stream direction, while at the same x'/δ, Favre's data show a decrease to about 0.5-0.7, depending on position. The resulting inference that turbulence decay is accelerated as M_e increases is upset by Horstman and Owen's data at $M_e \simeq 7$.[2] For example for $y/\delta \geq 0.3$, the latter data show negligible decay ($R_0 \geq 0.8$) for x'/δ as high as 14, whereas the present data would seem to show very complete obliteration of the eddy structure ($R_0 \simeq 0$) at such distances.

Since the location, as well as the height, of the maxima in the space-time correlations was found insensitive to the sensor transfer function, the convection velocities were also calculated from the data. In Fig. 4 these "eddy speeds" are

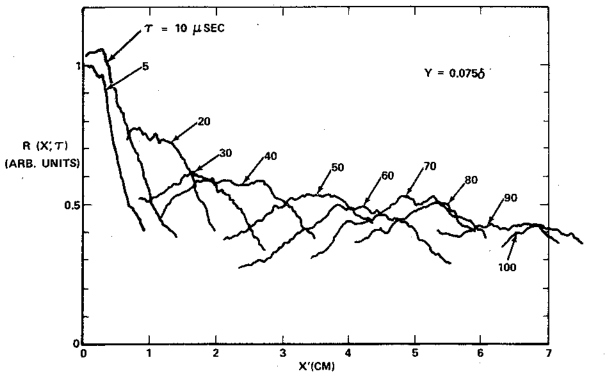

Fig. 2 Typical space-time correlation functions at fixed overheat currents.

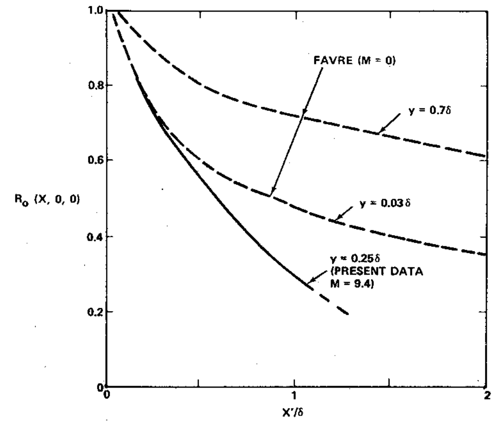

Fig. 3 Optimum longitudinal autocorrelation functions.

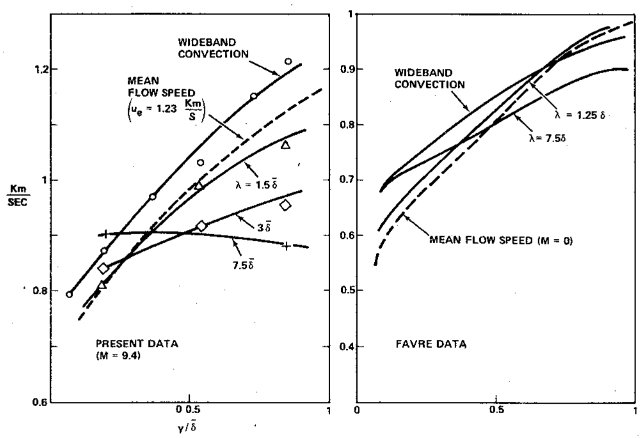

Fig. 4 Eddy convection velocities.

shown for the total (or wideband) turbulence as well as for turbulence filtered to follow eddies of size $\lambda = 1.5\delta$, 3δ, and 7.5δ. The wideband convection speed is slightly higher than the mean flow speed. The filtered correlations have given eddy speeds higher than the mean speed and lower than the mean speed near and away from the wall respectively, the more so as the eddy size increases. Such behavior is qualitatively similar to the lower Mach number case, as shown on Fig. 4; note that for eddy sizes $\lambda \sim 7.5\delta$ the speed is nearly constant at about 900 m/sec or $0.75u_e$. This latter result is in agreement with data from Ref. 2, which, however, also assigns a nearly equal speed to the total (unfiltered) turbulence, in contrast to our findings as stated above.

In summary, certain features of the correlation tensor of the hypersonic turbulent boundary layer seem to depart from the corresponding features of the low-speed boundary layer; in particular, the Mach 9.4 layer studied here decayed faster than expected from low-speed data. The dependence of convection speed on eddy size follows the trend observed in, but is more pronounced than, the low-speed data. What is of concern is the disagreement found between the present data and the hypersonic data of Horstman and Owen,[2] in which the turbulence decay is extremely slow and in which the convection speed of the total, unfiltered turbulence is almost equal to the speed of the large eddies. This may be due to the "transitional" state of the boundary layer of Ref. 2, or even to the small differences in geometry and Mach number between it and the present work. Further experiments at high Mach numbers would therefore seen necessary to shed some light on this issue.

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Slip Model for Hypersonic Viscous Flow

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Introduction

SEVERAL studies[1-3] in the recent past have indicated that a continuum flow analysis to estimate the surface properties of hypersonic vehicles with prolonged exposure at high altitudes is sufficient provided that slip effects are accounted for properly. Many authors[4-6] have studied the phenomenological expressions for slip velocity and slip temperature on such a surface. More recent studies[7] have been conducted where these expressions were determined by comparing the results of numerical integration of the Navier-Stokes equations with experimental data. No rigorous theoretical conclusion is possible, but, insofar as agreement with experiment goes, the use of continuum flow analysis with proper slip effects has been found time and again to be quite

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