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The Nature of Boundary-Layer Turbulence at a High Subsonic Speed

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Simultaneous measurements of velocity, wall-pressure, and wall-shear fluctuations in a turbulent boundary layer at $M_\infty = 0.64$ and $Re_\theta = 108{,}000$ have been analyzed to obtain a description of coherent (or quasiordered) structures present in the flow. A conditional sampling analysis has been applied to the digitized fluctuations to identify the occurence of such events in the data, and to establish the relationship between the fluctuating quantities during individual and ensemble averaged events. It has been determined that the mean period between readily identifiable coherent structures, when scaled by flow velocity and boundary-layer thickness, falls within the range of values obtained by other investigators for the mean period between "bursts" in the wall region of low-speed flows. The development of the velocity fluctuation profile during passage of these structures also seems to show definite similarities to the development of "burst" profiles as depicted by other investigators. The vertical scale of a typical structure is on the order of δ^* and its duration is on the order of 10 δ^*/U_∞. Since our measurements are made outside the wall region of the boundary layer, this flow phenomenon is obviously some aspect of the large-scale outer structure. The correspondence in frequency of occurence and profile development to the wall region "bursts," together with the high degree of correlation between the wall shear and the outer structure, may be an indication of a possible link or interaction between the two flow processes. This is being examined further by repeating the measurements at several lower velocities so that the wall region occupies an increasingly larger fraction of the boundary layer.

I. Introduction

THERE has been considerable practical interest in turbulent boundary-layer flows for the past several decades as a result of the high drag and noise associated with such flows. The expectation has been that a better understanding of the origin and nature of boundary-layer turbulence would lead to useful criteria for the development of drag and noise reduction mechanisms.

In recent years many research efforts have been directed toward obtaining qualitative and quantitative information concerning the quasiordered structure of boundary-layer turbulence. The first evidence of the existence of randomly occurring, coherent turbulent structures came from visual observations of flows seeded with various tracers.[1-5] These studies have indicated the presence of a streamwise streaky structure in the wall region of the flow, and that eruptions of these low-speed streaks (which locally result in inflexional velocity profiles) are characterized by oscillatory motions which lead to sudden breakdowns into small-scale turbulence. The ejection of low-speed fluid from the wall is accompanied by sweeps of high-speed fluid from the outer regions toward the wall. This overall process has been referred to as a "burst."

The visual observations also indicate the existence of coherent vortical structures which extend to the outer edge of the boundary layer. The relationship or interaction between this large-scale outer structure (LSOS) and the turbulent "bursts" is still not clearly defined. In particular, how these processes and their relationship change with increasing Reynolds number has not been fully explored. On the basis of observations and measurements over a limited range of Reynolds numbers, it has become commonly accepted that the "bursting" process is strictly a sublayer phenomenon that scales with wall variables, while the large-scale outer structure is basically Reynolds number independent. A possible link between the two processes may exist in the fact that the frequency of occurrence of the turbulent "bursts" has been found to scale with outer flow variables and seems to be related to the period of passage of the outer structures.[6]

In the effort to obtain quantitative data on these phenomena, various selective sampling schemes have been developed to analyze wall pressure,[7,8] velocity,[9,10] and Reynolds shear stress[11,12] measurements in turbulent boundary-layer flows. It has become necessary to resort to this type of analysis because the intermittency of the processes would cause them to be "buried" in conventional time averaged analyses. Some of the results obtained in several of these studies are discussed in the text of this paper. More comprehensive summaries of the techniques and results contained in these and other investigations can be found in several good review articles.[13-15]

An experiment performed by Zilberman et al.[16] is of particular interest because of its unique approach to the problem. They used a spark to initiate and mark in time a turbulent spot in an initially laminar boundary layer. The structure thus created was tracked, utilizing velocity measurements along its streamwise and lateral extent, as it merged and interacted with the natural turbulent boundary layer. The structure was found to exhibit features in agreement with the bulges in the interface region of the boundary layer, and representations of the flow pattern in a coordinate system traveling with the spot showed temporal sequences similar to those seen in flow visualizations. The existence of a possible regeneration mechanism for the large eddy structures was also explored.

In a study by Brown and Thomas,[17] a conditional sampling scheme based on improved short-time correlation was applied, in conjunction with various filtering techniques, on simultaneous measurements of velocity and wall shear in a boundary layer with a relatively high freestream velocity ($U_\infty = 36$ m/s) and Reynolds number ($Re_\theta = 10{,}160$). They conclude from their results that an organized structure somewhat analogous to the turbulent spot is present in the flow. A proposed model of the structure is a horseshoe vortex

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traveling at an oblique angle to the wall and having dimensions on the order of δ normal to the wall and 2δ in the streamwise direction. They note that the wall shear has a slowly varying component which they attribute to the passage of this structure. In addition, on the basis of correlation of the high-frequency wall-shear fluctuations, they also suggest that the "burst" phenomenon is a direct response of the region near the wall to the large-scale motion of the organized structure, i.e., that "bursts" are wall signatures of the large-scale eddy structures.

The long range objective of our investigation is to determine what influence can be exerted on the characteristics of turbulent boundary layers at high subsonic speeds by externally imposed pressure fluctuations or by changes in the boundary-layer wall characteristics. Since it has been found that significant contributions to the long time average Reynolds stress occur during intervals when coherent structures (in particular, "bursts") are present in the flow, it has become apparent that the interventions of greatest practical importance will be those that affect these structures. Specifically one might attempt to influence the frequency of occurrence and lateral development of the structures.

In order to obtain information concerning the possible role of pressure fluctuations in these processes, our study includes simultaneous measurements of both velocity and wall pressure. A measurement of the shear on the wall below the velocity measurements is also included. These additional wall measurements were intended to provide some correlation between flow structures crossing the array of hot wires with processes occurring very near the wall below and upstream of the array. The results presented here were obtained for flow conditions which differ significantly from those in previous studies. The freestream velocity is in the subsonic regime [$U_\infty = 206$ m/s (675 ft/s)] and the Reynolds number is an order of magnitude higher ($Re_\theta = 108{,}000$) than that for which this phenomenon has been previously investigated. The measurements were made on the wall of an axially symmetric test section in order to insure true two dimensionality of the flow.

II. Experimental Facilities and Procedures

A. Wind Tunnel

Setup

An induction wind tunnel was constructed for the present experiment (Fig. 1). The inlet section of the tunnel, which is open to the atmosphere, has an initial diameter of 1.52 m (5 ft) and contains flow straightners and several fine mesh screens. The test section is 1.52 m (5 ft) long, has an inside diameter of 0.3 m (12 in.), and is 9.12 m (30 ft) downstream of the inlet section. Four rectangular windows are fitted into the test section for mounting instrumentation. The test section is followed by a 30-deg half-angle conical diffuser which is connected to a 1133 m^3 (40,000 ft^3) vacuum sphere. A 6-deg half-angle conical centerbody was placed inside the tunnel immediately downstream of the test section to create a variable area throat.

In order to minimize the noise level of the wind tunnel, the flow passing through it was generated by induction and in addition was choked downstream of the test section by starting with a very low pressure in the vacuum sphere. By creating a sonic throat, the propagation of noise from sources downstream of the test section was eliminated at the throat. The Mach number in the test section can be varied between 0.6 and 0.8 by moving the centerbody to change the area of the throat. The results reported here are for a freestream Mach number of 0.64.

Calibration

The flow in the test section was calibrated with a pitot probe and a hot-film probe utilizing a constant temperature anemometer. In order to determine the velocity boundary-layer thickness, the static and total pressure distributions across the boundary layer at the test section were measured. Based on these pressure distributions, the boundary-layer Mach number profile and the corresponding velocity profile were calculated and are shown in Fig. 2. The boundary-layer turbulent intensity profile measured using the hot-film probe is presented in Fig. 3. It can be seen that the boundary-layer velocity profile follows a 1/7 power law and that a very low freestream turbulence intensity of 0.8% was obtained in the test section.

Based on these measurements, the velocity boundary-layer thickness δ, displacement thickness δ^*, momentum thickness θ, and wall friction velocity u_τ were computed. The parameters of the boundary-layer flow in the test section are summarized in Table 1.

B. Instrumentation

Velocity and Shear

The mean and fluctuating components of the streamwise velocity in the flow were measured with hot-film probes and constant temperature anemometers. The probes are Thermo-Systems type 1260 miniature probes which have an alumina coated cylindrical sensor. The sensor is 0.1 cm (0.040 in.) wide and 0.005 cm (0.002 in.) in diameter. Several rakes have been constructed to hold five of these probes at various distances from the tunnel wall. The measurements reported here were made with the five probes spaced within 1.27 cm (0.5 in.) ($y/\delta = 0.125$) from the wall (see Figs. 4 and 5.) The dc components of the linearized signals from the hot-film probes were recorded on a visicorder, while the fluctuating component of each of the signals was amplified and filtered and then recorded on one of seven channels of a Phillips Ana-Log 7 magnetic tape recorder. A small calibration wind tunnel was used to obtain the voltage vs velocity relationship and to adjust the frequency response of each of the probe-anemometer systems.

The fluctuating shear on the tunnel wall was measured with a flush hot-film sensor (Thermo-Systems type TSI 1237) shown as F in Fig. 4. The instrumentation required for the flush mounted sensor is the same as that described for the hot-film probes except that a linearizer is not used. A detailed description of the use of this type of sensor for measuring wall-shear is given in Ref. 18.

Pressure

Flush mounted piezoresistive pressure transducers (Kulite type MIC-080-5) were used to measure the pressure fluctuations on the tunnel wall. The diameter of the pressure sensitive area of the transducers is 0.1 cm (0.040 in.) and they are rated for a pressure differential of 5 psi. A natural frequency of 200 kHz quoted by the manufacturer would indicate a flat frequency response from dc to 40 kHz ($\omega\delta^*/U_\infty \cong 18$). Five such transducers are available and can be placed at various spacings and patterns on a plug in the tunnel wall below the hot-film probes (see Fig. 5). (This plug is also used to mount the flush hot-film sensor.) The signal from each of the transducers was put through an amplifier/filter and then recorded on one of seven channels of a Honeywell 5600 tape recorder.

Table 1 Boundary-layer flow parameters

$M_\infty = 0.64$	$\delta = 10.2$ cm (0.334 ft)
$U_\infty = 206$ m/s (675 ft/s)	$\delta^* = 1.4$ cm (0.047 ft)
$q_\infty = 0.2$ bar (2.9 psi)	$Re_\theta = 1.08 \times 10^5$
$u'/U_\infty = 0.008$	$\nu/u_\tau^2 = 0.62 \times 10^{-6}$ s
$\theta = 0.9$ cm (0.032 ft)	$\nu/u_\tau = 3.37 \times 10^{-6}$ m (1.1×10^{-5} ft)

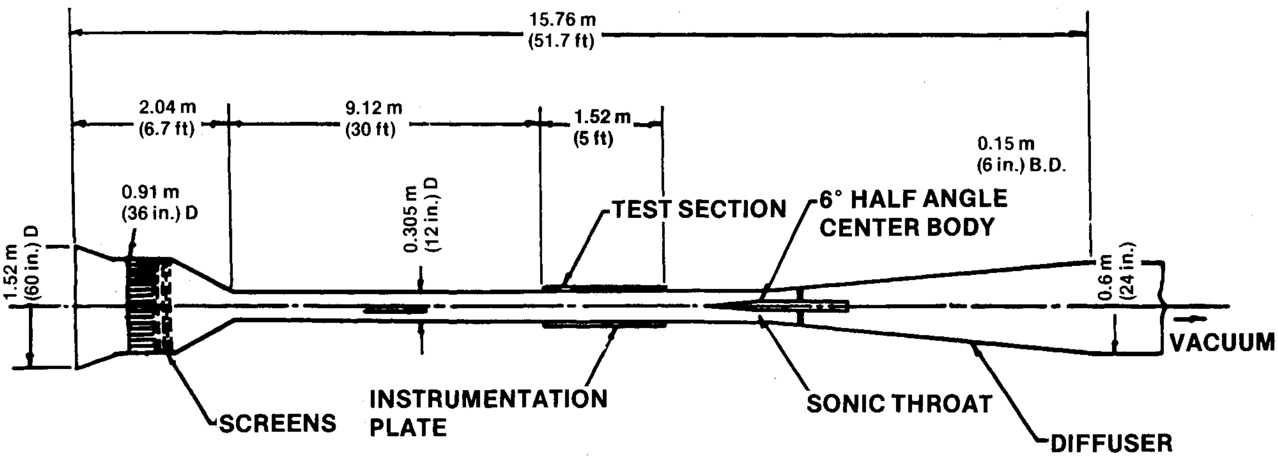

Fig. 1 Wind tunnel.

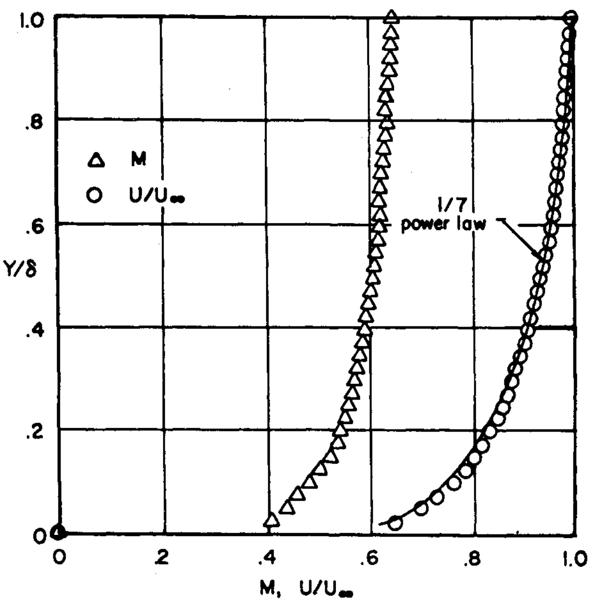

Fig. 2 Boundary-layer Mach number and velocity profiles.

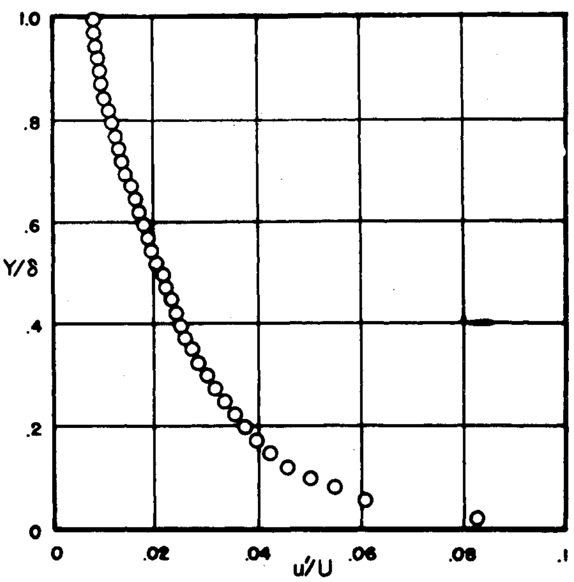

Fig. 3 Turbulent intensity profile.

The sensitivity of these transducers was checked with both a static and dynamic calibration. The output voltage was found to vary linearly with the applied pressure and the applied voltage to the transducer bridge circuit. The sensitivity was found to be on the order of 9.0 mV/bar/V(IN) [0.6 mV/psi/V(IN)]. The dynamic calibration with a 124-dB, 250-Hz pressure field yielded an equivalent sensitivity of − 142 dB re: 1V/μbar at 9-V dc input.

C. Measurement and Data Analysis Procedures

Test Configuration

The instrumentation layout for the results reported here is shown in Fig. 4. Five streamwise velocity measurements were made at positions I, J, K, L, and O; the fluctuating wall shear was measured at F, and the fluctuating wall pressure at Q, P, and S. Another wall pressure measurement was made adjacent to location P [0.38 cm (0.15 in.) away in the lateral direction], but the results of this measurement are not presented. The spacing between the velocity and pressure measurements was made as small as the dimensions of the transducers and probes would permit. The five velocity measurements span a distance of approximately 0.8δ^* from the wall, the closest to the wall being at 0.088δ^*. The distance between each of the pressure measurements is 0.26δ^*. This was deemed sufficiently small in terms of the distance over which the wall pressure fluctuations maintain a high correlation.[7,19] The shear measurement was made on the wall directly below the velocity measurements, approximately 0.5δ^* downstream of the third pressure measurement(S).

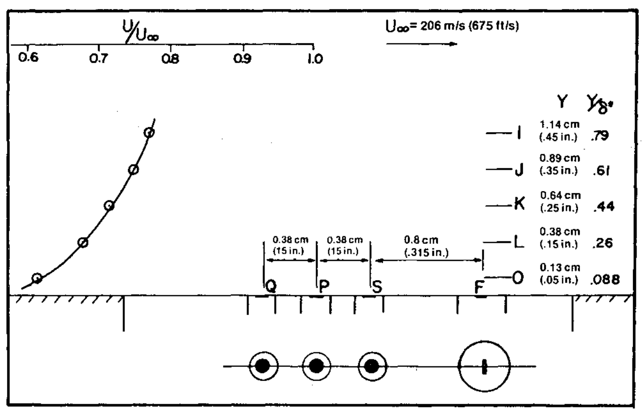

Fig. 4 Test configuration.

Recording and Digitizing Procedures

Preliminary measurements were made of the three fluctuating quantities under investigation in order to determine

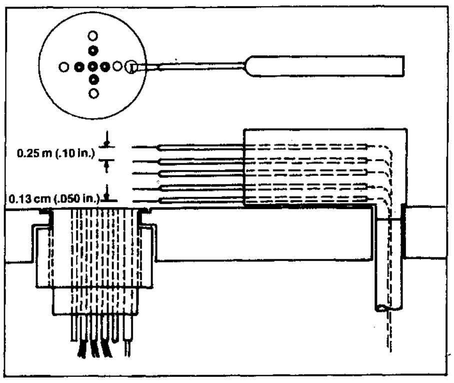

Fig. 5 Sketch of instrumentation setup.

the range of overall root-mean-square levels and spectral distributions that would be encountered. For this purpose, the fluctuating quantities were analyzed over the entire range of flat response of the probes and transducers (approximately $\omega\delta^*/U_\infty < 18$). The results of this analysis, which are presented in the next section were used to determine the conditions for recording and digitizing the data. For the time sequences presented in this report the overall data bandwidths were as follows: $0.0009 < \omega\delta^*/U_\infty < 9$ for the velocity fluctuations and $0.0045 < \omega\delta^*/U_\infty < 18$ for the shear and pressure fluctuations. The sequences were digitized at a sampling rate (f_s) of $2\pi f_s \delta^* / U_\infty = 90$. This high a rate was achieved by utilizing a large ratio of record-to-playback speeds on the recorders and through the use of a 100-kHz synchronization signal recorded along with the data on both recorders.

Analysis of Digital Data

The numerical analysis of the digitized fluctuations was performed on a CDC 6600 computer. Basically, a conditional processing scheme similar to one devised by Kaplan and Laufer[20] was utilized to infer the occurrence of deterministic flow structures from the data. This involved calculation of the variable interval time average (VITA) variance (see Ref. 10) defined as:

$$\text{VAR}_{u'}(t) = \frac{\hat{u'^2}(t) - [\hat{u}'(t)]^2}{\overline{u'^2}} \tag{1}$$

where

$$\hat{u}'(t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} u'(\tau)\,\mathrm{d}\tau \quad (T = \text{averaging time})$$

and

$$\overline{u'} = \frac{1}{T_t}\int_0^{T_t} u'(\tau)\,\mathrm{d}\tau \quad (T_t = \text{total data sample time})$$

From this a detector function was calculated according to:

$$\text{IVAR}_{u'}(t) = \begin{cases} 1 & \text{for } \text{VAR}_{u'}(t) \geq V_0 \\ 0 & \text{for } \text{VAR}_{u'}(t) < V_0 \end{cases} \tag{2}$$

It has been found that large values of VAR (t) are associated with steep changes in the fluctuating quantity, for example, strong streamwise accelerations or decelerations in the case of the velocity fluctuations. Since various studies have indicated that large and rapidly changing velocity and pressure fluctuations are associated with coherent turbulent structures, it is assumed that periods of exceptionally high levels of VAR (t) correspond to the occurrence of such events in the fluctuating quantity and that the level of VAR (t) is related to the intensity of the events. It then follows that for a given threshold level V_0, the function IVAR (t) serves to mark

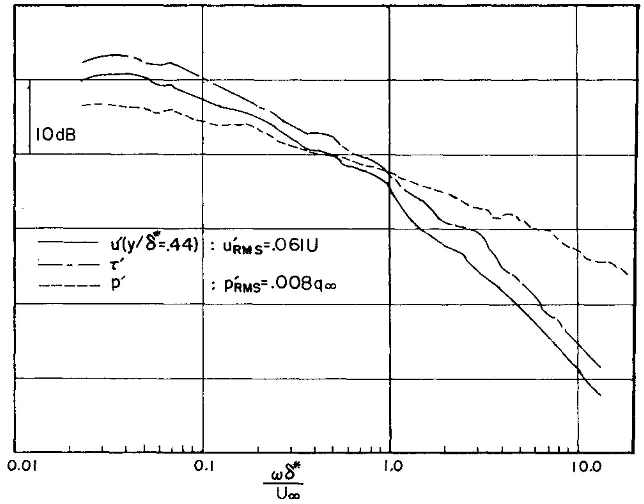

Fig. 6 Typical spectral distributions of the velocity, shear, and pressure fluctuations.

the times when events of a certain intensity or higher are detected. The average time interval between these events can thus be determined, and an ensemble average time history of the event at each measurement position can be obtained. An analysis of the instantaneous velocity, wall-shear, and wall-pressure fluctuations during periods when IVAR (t) is "on" simultaneously for all these measurements could reveal useful information on the generation and development of the coherent structure.

In addition, conventional time averaged analyses such as numerical Fourier transform and time correlation were also performed on the data. More specific details concerning the facility, instrumentation, and data analysis procedures can be found in Ref. 21.

III. Data Presentation and Discussion

A. Time Averaged Properties of the Turbulent Fluctuations

Overall Levels and Spectral Distributions

The recordings of the fluctuating pressure and shear on the tunnel wall and of the fluctuating streamwise velocity in the boundary layer were first analyzed to obtain the overall rms levels and spectral distributions of the fluctuations. For the test configuration shown in Fig. 4, the rms levels of the velocity fluctuations ranged from $0.05U$ at I to $0.09U$ at O (see Fig. 3) while the wall-shear fluctuations had an rms level of approximately $0.09\rho u_\tau^2$. The rms level of the wall-pressure fluctuations was found to be in the neighborhood of 0.008 q_∞. Typical power spectra for the velocity, shear and pressure fluctuations are shown in Fig. 6. Although frequency has been scaled for the purpose of this figure by U_∞/δ^*, it has been found that the spectra of the velocity fluctuations at different points in the boundary layer fall approximately onto the same curve when frequency is scaled by U/δ^*, where U is the local mean velocity. This behavior has also been observed by Serafini.[22] It should be noted however that some uncertainty exists in the accuracy of the u-fluctuation spectra at high frequencies due to the difficulty of optimizing and matching the frequency response characteristics of the various anemometers.

It can be seen in Fig. 6 that the wall pressure fluctuations contain significantly more energy at high frequencies than either the velocity or shear fluctuations. Although the falloff in energy is also at a rate of about 6 dB/octave, this does not occur until around $\omega\delta^* / U_\infty = 3$. It has been found by several investigators[7,13,23] that transducer size has a significant effect on the resolution of wall-pressure fluctuations. A comparison of various measurements seems to indicate that if the transducer diameter is too large, a loss of resolution of small-scale pressure fluctuations will occur. This manifests itself as consistently lower measured spectral densities at high frequencies, that is, above $\omega\delta^*/U_\infty \approx 1$. Emmerling [7] has summarized the available results in terms of the nondimensional parameter du_τ/ν, where d is the transducer diameter. For values of this parameter above approximately 100 the overall rms level of the wall pressure fluctuations is always measured to be around $0.005q_\infty$. Below this value, the measured rms level increases linearly as du_τ/ν is lowered. This increase is attributed to the increased resolution of intense small-scale fluctuations, or equivalently of high-frequency spectral components, by the smaller transducers. (More recent results seem to indicate that a good part of this increase can be attributed to errors introduced by the use of pinhole microphones.[14])

For the present investigation the condition $du_\tau/\nu \cong 50$ would require a transducer diameter on the order of 0.018 cm (0.007 in.). Since a transducer this small could not be obtained, it was decided upon consideration of other requirements to use Kulite MIC-080-5 transducers whose pressure sensitive area has a diameter of 0.1 cm (0.040 in.)($du_\tau/\nu \cong 300$). A comparison of the spectrum of wall-pressure fluctuations measured by this transducer with those obtained by other investigators (see Ref. 23) shows that some resolution of very high frequencies is being lost by our transducer. However, the high overall level of 0.008 q_∞ would indicate that our pressure measurements contain components not included in other measurements. One possibility is the inclusion of more low-frequency fluctuations due to the very low high-pass filter setting ($\omega\delta^*/U_\infty = 0.0045$). It is also possible that Mach number effects are responsible for the inconsistency, since the results quoted are for low-speed flows ($M_\infty < 0.3$). Some error might also be attributable to the transducer sensing surface not being precisely flush with the wall.

Cross Correlations

Various normalized cross correlations between the fluctuating quantities were calculated once the fluctuations were digitized. Some of the more interesting correlations are presented in Fig. 7. All of the correlations shown were calculated for time delays ranging from −2.5 ms to +2.5 ms ($-35 < tU_\infty/\delta^* < +35$). The time delay was imposed on the second of the two measurements listed in parenthesis for each correlation. The correlations of the three wall-pressure fluctuation measurements in the streamwise direction indicate that the overall streamwise convection velocity of disturbances traveling along the wall is given by $U_c/U_\infty = 0.59$. The correlation of Q and P ($\Delta x = 0.26\delta^*$) and Q and S ($\Delta x = 0.52\delta^*$) both yielded approximately the same value for the convection velocity. The value obtained here falls within the range $U_c/U_\infty = 0.5$-0.8 found in other investigations,[7,19,23] depending on the streamwise separation between

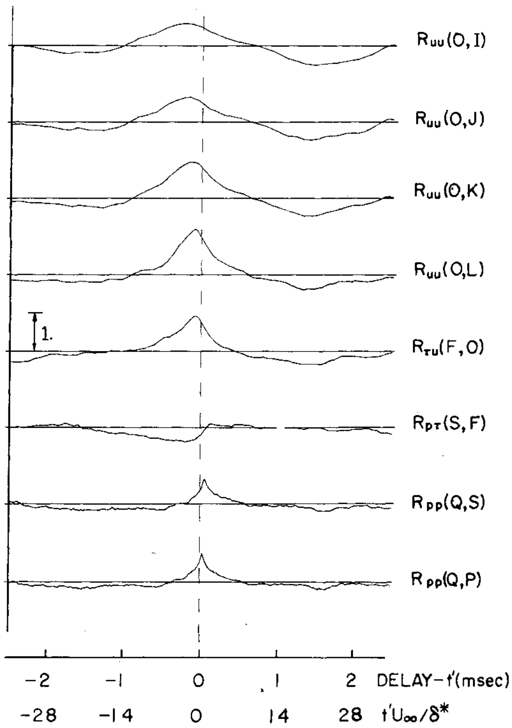

Fig. 7 Normalized cross correlations between velocity, shear and pressure fluctuations.

measurements and on the frequency characteristics of the fluctuations correlated.

The four velocity-velocity correlations and the velocity-shear correlation show that disturbances in the flow tend to arrive first at points away from the wall and at increasingly later times as the wall is approached. This can be interpreted either as a propagation of the disturbances from the outer part of the boundary layer toward the wall or as a tendency for the disturbance fronts to be leaning forward in the flow.

B. Results of the Conditional Sampling Analysis

One of the main objectives of the present study was to obtain a description of the coherent structures occurring in boundary-layer turbulence by applying a conditional sampling analysis to the digitized fluctuations. Our study differs from work done previously in this area by including simultaneous measurements of velocity, wall pressure, and wall shear and by extending the range of flow conditions for which the phenomenon has been investigated. Table 2 lists three typical investigations: one by Blackwelder and Kaplan [10] of conditionally sampled turbulent velocity profiles, another by Emmerling [7] of the instantaneous distribution of wall-pressure fluctuations under a turbulent boundary layer, and a

Table 2 Test conditions and data sampling densities for three typical investigations and the present study

Study	U_∞, m/s	δ^*, cm	Re_θ	ν/u_τ, mm	ν/u_τ^2, μs	$\Delta t^a u_\tau^2/\nu$	$\Delta t^a U_\infty/\delta^*$
Blackwelder and Kaplan [10] (velocity)	4.27	0.94	2550	0.070	392	1.0	0.18
Emmerling [7] (wall pressure)	7.62	0.46	2000	0.043	130	1.0	0.24
Brown and Thomas [17] (wall shear and velocity)	36.3	0.55	10160	0.012	9.0	...	...
Present study (velocity, wall pressure, and wall shear)	206	1.43	108000	0.0034	0.62	8.0	0.070

[a] Δt = data sampling interval.

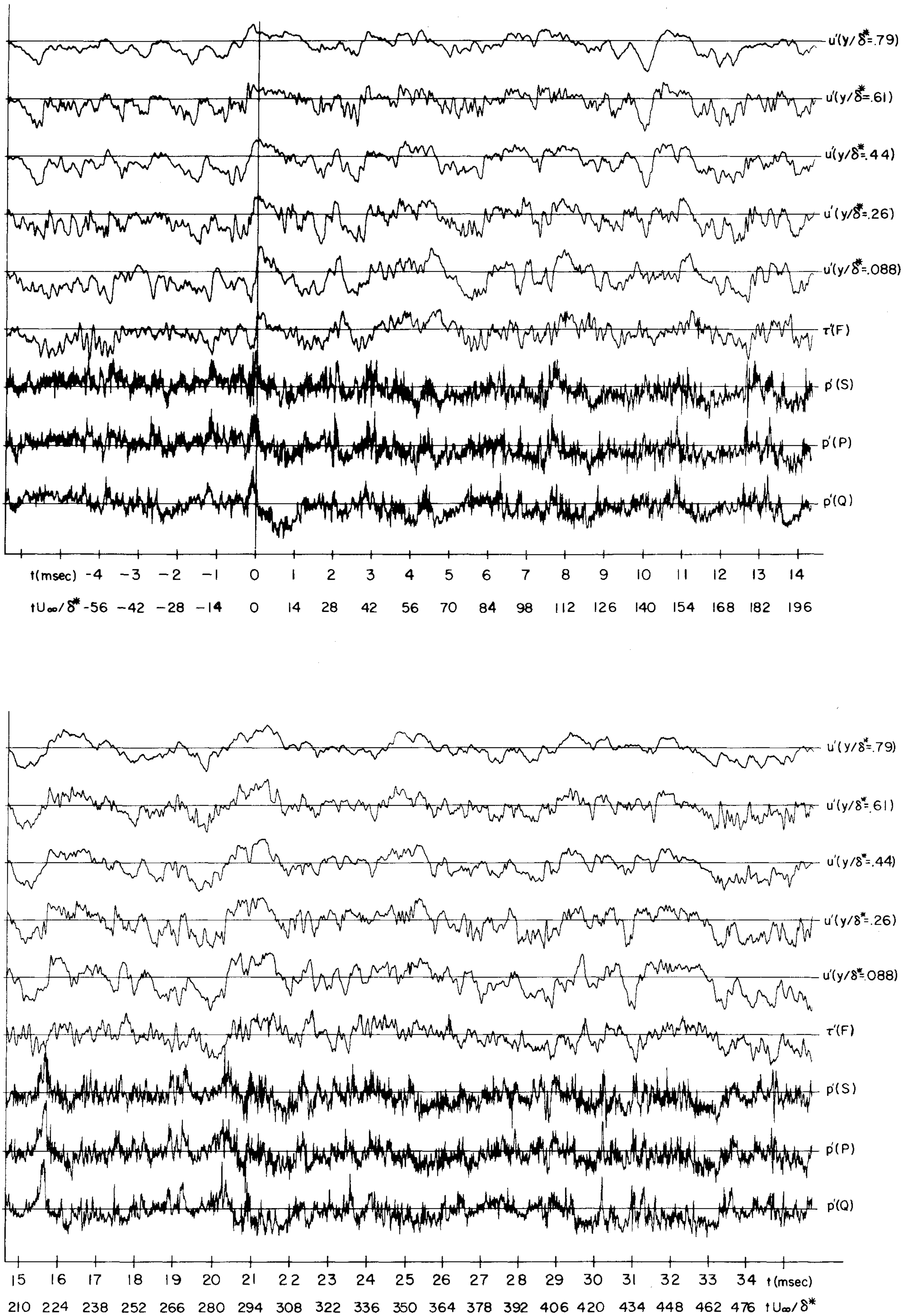

Fig. 8 Sample plot of digitized data showing fluctuating velocities, shear, and pressures.

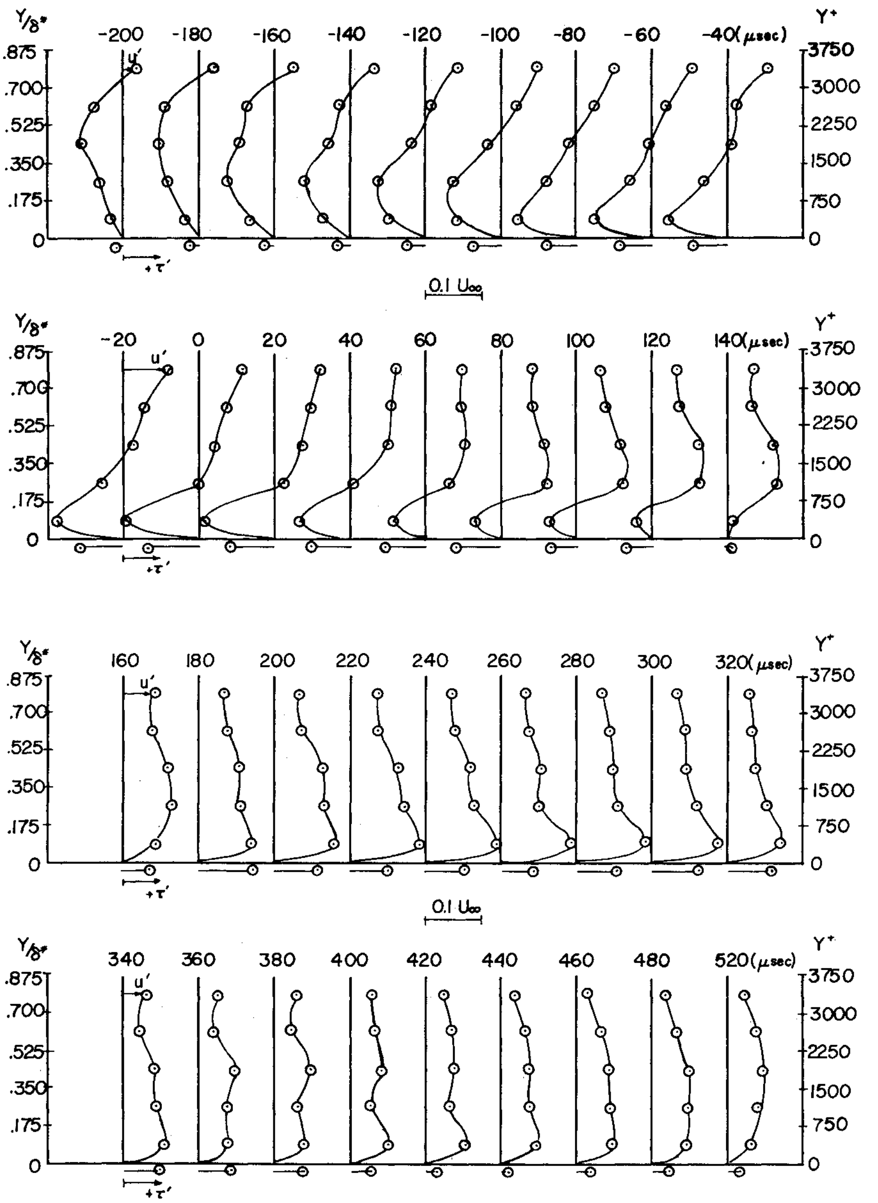

Fig. 9 Sequence of velocity fluctuation profiles and fluctuating shear during a typical event.

third by Brown and Thomas[17] of conditionally sampled and filtered measurements of wall shear and velocity. It can be seen that these studies, as well as all the others brought to the authors' attention, are performed in flows with relatively low freestream velocities [typically $U_\infty < 30.5$ m/s (100 ft/s)] and with low Reynolds numbers ($Re_\theta < 10^4$). In comparison, the present investigation is for a boundary layer with a much higher freestream velocity [$U_\infty = 206$ m/s (675 ft/s)] and Reynolds number ($Re_\theta = 1.08 \times 10^5$).

By studying the quasiordered nature of boundary-layer turbulence in this range of conditions, it should be possible to determine if the picture of the turbulent structure derived from low-speed flows extends to the high-subsonic, compressible regime. One property of interest is the frequency of occurrence of characteristic events in the flow. As a result of many experiments performed at Reynolds numbers ranging from 10^3 to 10^4, it has become widely accepted that the mean period $\bar{T}$ between occurrences of coherent flow structures throughout the boundary layer scales with outer flow variables, and that the measured value of $\bar{T}U_\infty/\delta^*$ will fall somewhere betwen 25 and 50 depending on where the measurement is made, which fluctuating quantity is measured, and what criteria are used to ascertain the occurrences. For example, Lu and Willmarth[12] have found that a consistent estimate of the characteristic mean time interval between relatively "large bursts" in their Reynolds stress measurements at $Re_\theta = 4320$ is given by $\bar{T}U_\infty/\delta^* \approx 32$ for most of the boundary layer (the value tends to be lower near the wall and higher at the edge of the boundary layer). Similarly, Emmerling[7] has found a mean period given by $\bar{T}U_\infty/\delta^* \approx 27$ for the "occurrence of characteristic wall structures" while Blackwelder and Kaplan[10] found a typical frequency $f\delta/U_\infty \approx 13$ ($\bar{T}U_\infty/\delta^* \approx 50$) for the occurrence of turbulent "bursts" in their velocity measurements below $y^+ \approx 100$.

For the results presented here, the threshold level V_0 in the detection scheme described in Sec. II B was chosen based on an analysis of the correlation between the resulting detector function and visually observable periods of coherence in various portions of the digitized fluctuations. Preliminary results indicate that with this detection criterion, the mean period between coherent events in our measurements is in the range $\bar{T}U_\infty/\delta^* \approx 30\text{-}36$.

A sample plot of digitized fluctuations is presented in Fig. 8. Approximately 42 ms ($tU_\infty/\delta^* = 588$) or 8400 data points are shown for each of the nine fluctuating quantities. Using the symbol α to represent one-half of the vertical distance between adjacent zero lines in Fig. 8, the vertical scales of the plots are as follows: for the velocity fluctuations $\alpha = 0.13\ U_\infty$, for the shear fluctuations $\alpha = 0.27\ \rho u_\tau^2$, and for the pressure fluctuations $\alpha = 0.024\ q_\infty$. A great deal of readily observable correlation can be seen at various times across parts or all of the measurement grid. The time $t=0$ marks the approximate location of one event in the data as determined by applying the VITA variance analysis described in Sec. II B to the velocity at $y/\delta^*=0.088$. For this particular event, the detection scheme also triggers on the wall shear (at $t=\approx +5$ μs) and the four other velocity measurements (at $t\approx -120$, -210, -275, and -330 μs moving away from the wall).

A sequence of velocity fluctuation profiles centered about the time $t=0$ are shown in Fig. 9. The entire sequence is for an interval of 700 μs ($tU_\infty/\delta^*=10$). Also shown at each time is the instantaneous shear fluctuation on the wall as measured by the flush mounted hot-film sensor. It may be of interest to note that the development of the velocity fluctuation profiles during this sequence shows some similarities to the "bursting" event as depicted by investigators doing both theoretical[24] and experimental[11] work. In particular, the profiles shown in Fig. 9 and those obtained by Blackwelder and Kaplan (Ref. 10, Fig. 5) in the wall region of a boundary layer with $U_\infty=$ 4.27 m/s (14 ft/s) and $Re_\theta=2550$ seem to indicate the occurrence of similar flow processes. A shear layer, with positive fluctuation velocities above and negative velocities below, first appears in the outer measurements and moves toward the wall. The region of negative fluctuation velocities undergoes a deceleration followed by a rapid acceleration which combined with the movement of the shear layer toward the wall results in positive fluctuation velocities at all the measurement positions. The rapid acceleration in the lower measurements continues to very large positive fluctuations which then slowly relax to more typical levels. The time involved for the entire process is approximately $tU_\infty/\delta^*=10$ or $tu_\tau^2/\nu=1150$ in our case and $tU_\infty/\delta^*\approx 15$ or $tu_\tau^2/\nu\approx 50$ for the Blackwelder and Kaplan results.

This comparison is not meant to suggest that our results represent the "bursting" process which, by definition, is taken to be a wall region phenomenon. However, the similarities between our results and those obtained in the wall region of low-speed flows could be an indication that some aspects of the large-scale outer structure which would be basically Reynolds number independent are present in the latter measurements; or, alternatively, that flow processes similar to "bursts" exist in the outer region. In this regard, it is of interest to note that although the Blackwelder and Kaplan measurements extend to $y^+=100$ in terms of wall variables, they alternatively span a distance of approximately δ^* or about 1/7 the boundary-layer thickness. From Fig. 9 it can be seen that our measurements also extend to approximately one displacement thickness.

The strong influence that this flow structure exerts on the wall is clearly evident in Figs. 8 and 9. It can be seen from Fig. 8 that there is more than just a casual correlation between the wall measurements, particularly the wall shear, and the velocity fluctuations during this particular event. In Fig. 9 a definite correspondence can be seen between the sign and magnitude of the wall shear fluctuation and the slope of the fluctuation velocity profile as it has been drawn at the wall for each instant in time. Brown and Thomas[17] have suggested that the wall shear does respond in a "slowly varying" mode to the passage of the large-scale outer structure, and that the "bursting" process manifests itself as a high-frequency fluctuation with a definite phase relationship to the slowly varying component. (It is possible that this high-frequency, small-scale component is missing in our shear measurement due to the size of the sensor used.) This may be an explanation for the high degree of correlation between our velocity measurements in the outer region and the shear fluctuations at the wall, but it is far from a closed question. The correlation that exists is more than qualitative or in a time average sense as in the Brown and Thomas results. The inability to compare directly results from different experiments suggests that more standardized analyses be performed on data at different flow conditions in order to define more clearly the processes involved and their dependence on, say, Reynolds number.

An interpretation of the changes occurring in the wall-pressure fluctuations during coherent events in the data has not been achieved primarily due to the insufficient number of measurements in a given direction. The recent acquisition of additional instrumentation will allow us to repeat the preceding test with five pressure measurements in the streamwise direction immediately upstream of the velocity measurements. Also being added is a sixth velocity measurement closer to the wall ($y/\delta^*=0.044$) to improve the resolution of the velocity profile.

The immediate major goal of our continuing research effort will be to modify the wind tunnel so as to allow the tests described earlier to be repeated at several lower velocities [(e.g., 9.15, 45.75, and 91.5 m/s (30, 150, and 300 ft/s)], while the boundary-layer thickness is kept approximately constant. This will allow us readily to compare the effect of Reynolds number on these processes. Tests at the lower velocities will also permit us to make direct comparisons between measurements within and outside the wall region in order to explore further the questions raised by the present measurements. Plans are also being made to set up a measurement grid to obtain information relating to the lateral development of coherent structures.

IV. Conclusions

A wind tunnel facility ($M_\infty=0.6$ to 0.8) with extremely low noise levels ($u'/U_\infty\approx 0.008$) has been constructed and is being used for the investigation of coherent structures in a turbulent boundary layer at high subsonic speeds. A successful instrumentation package has been developed for the measurement of velocity, wall-shear, and wall-pressure fluctuations in the boundary layer. Procedures have been developed to produce discrete time sequences of the fluctuations which are conditionally sampled to obtain information concerning the frequency of occurrence and nature of the coherent structures.

Simultaneous measurements of the velocity, wall-shear and wall-pressure fluctuations in a boundary layer with $U_\infty=206$ m/s (675 ft/s), $Re_\theta=1.08\times 10^5$, and $\delta^*=1.4$ cm (0.047 ft) have been analyzed. Conventional time averaged analyses of the fluctuations, such as frequency and correlation analyses, have yielded results which compare favorably with those obtained by other investigators working for the most part at low freestream velocities. Some discrepancy exists in the overall level and spectral distribution of the wall-pressure fluctuations which may be due to the size of the transducer used for the measurements. Cross correlations of the pressure fluctuation measurements has yielded a streamwise convention velocity of disturbances traveling along the wall given by $U_c/U_\infty=0.59$.

A conditional sampling analysis which searches for periods when the fluctuating quantities have large and rapidly changing values was used to identify the occurrence of deterministic flow structures in the data. The average time interval between characteristic events detected in this way was estimated to be in the range $\bar{T}U_\infty/\delta^*\approx 30$-36. This result is in agreement with the mean period found for the so-called "burst" phenomenon in the wall region of low-speed (low Reynolds number) flows. The time history of the fluctuation velocity profiles during a typical event was also found to show many similarities to the "bursting" process as depicted by velocity measurements below $y^+=100$ in one low-speed study. However, since our velocity measurements are made outside ($y^+\approx 350$-3500) the wall region of the boundary layer, the flow process we see is obviously some aspect of the large-scale outer structure. The fact that the vertical scales of the flow structures in our measurements and in the low-speed study are both close to one displacement thickness and their durations are similar when scaled by δ^*/U_∞, can be interpreted, if it is not just coincidence, in one of two ways. If the low-speed measurements are without doubt depicting the "burst" phenomenon, then the similarities imply the existence of flow processes similar to wall "bursts" in the outer region. On the other hand, the similarities could be an indication that certain aspects of the outer structure may be present in the wall region measurements, that is to say they may not be fully isolating strictly wall region processes such as "bursts."

Our measurements also indicate a strong correlation between the velocity fluctuations in the outer region and the wall shear and wall pressure. In particular, there is a definite correspondence between the wall shear fluctuations and the velocity fluctuation profiles during coherent events. This may be an indication of the possible relationship between the large-scale outer structure and wall region processes. These questions are being examined further with the help of more extensive measurements and analysis of the data, and by direct comparison of measurements at several velocities.

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