Coherent Structure of the Turbulent Boundary Layer at Low and High Velocities

An attempt to obtain a description of the coherent, or quasi-ordered structure of the turbulent boundary layer in the lateral direction at low and high velocity is presented in this paper. Simultaneous measurements of velocity, wall pressure and wall shear fluctuations at \( U_\infty = 10, 22.4 \) and 206 m/sec have been analyzed to obtain a description of the so-called "turbulent burst." A conditional sampling scheme has been applied to the digitized fluctuations to identify the occurrence of bursts, and their spread thereof in the lateral direction. The results for the lateral spread of the "bursts" indicate that the events can be separated into two groups with opposite phase relationship across the lateral measurements and is thought to be an indication of "arrow-head" or "horseshoe" type shape. The angular spread of the "horseshoe" may be estimated and therefore the angle of each "leg" which makes the x axis may be determined. These results lead to the conclusions that the flow structures at high velocities tend to be very narrow and swept back at, or near the wall and are much wider and flatter away from the wall.

NOMENCLATURE

- \( d \): diameter
- \( E_p(\omega) \): pressure energy spectra
- \( E_u(\omega) \): velocity energy spectra
- \( L_e \): effective length of sensor
- \( p \): pressure fluctuation
- \( q_m \): dynamic pressure
- \( \text{Re}_e \): Reynolds number based on the momentum thickness \( \rho \frac{u_e}{\nu} \)
- \( t, T \): time in seconds
- \( U_c \): convection velocity
- \( U_m \): free stream velocity
- \( U_T \): frictional velocity \( \sqrt{\frac{\tau_w}{\rho}} \)
- \( u' \): velocity fluctuation in the x direction
- \( w \): width of sensor
- \( x \): axial distance
- \( y \): coordinate perpendicular to surface
- \( y^+ \): non-dimensional viscous layer length \( y u_f/\nu \)
- \( Z \): lateral distance
- \( Z^+ \): non-dimensional viscous layer length in the lateral direction
- \( \theta \): angle defined in Fig. 1
- \( \nu \): kinematic viscosity
- \( \rho \): density

INTRODUCTION

The discovery, by means of visual observations of an organized structure in turbulent shear flows has lead to a proliferation of new measurement and data analysis procedures for the investigation of the fluctuating properties of such flows. Questions have been raised concerning the adequacy of measurements which utilize instrumentation and analyses not suited to the coherent, quasi-periodic nature of the flow structures. It has been found that the size of the transducers used in the measurements and the frequency response of the associated electronics is an important consideration in terms of the varied scales of the flow structures; and that single point measurements and conventional time-averaged analyses cannot reveal much useful information about coherence of intermittency both of which are important aspects of the flow processes involved.

To overcome these problems, modern research efforts have turned to miniaturized instrumentation and multiple measurements to obtain spatial resolution of coherent flow structures, and to digitization of the measurements so as to allow various time-series analyses to be performed on high-speed computers. With respect to the latter, it has become increasingly popular to apply various conditional sampling procedures to digitized fluctuations in order to isolate temporal sequences associated with the coherent structures. This type of analysis has revealed, among other things, that significant contributions to the long time average Reynolds stress occur during intervals when coherent structures are present in the flow, thus indicating that the modelling of turbulence and the development of drag and noise reduction mechanism might benefit greatly from a better understanding of these structures.
Visual observations of turbulent boundary layer flows seeded with various tracers have indicated the presence of several different processes involving repetitive flow structures. The wall region \((y^* = yu_*/v < 100)\) is characterized by streamwise streaks of low-speed fluid which lift up from the wall resulting in locally inflexional velocity profiles. The lift-up is followed by some sort of oscillatory motion and then a sudden breakup 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" (Refs. 1 and 2). On a larger scale, the boundary layer is dominated by vortical structures which extend to the viscous-inviscid region (Refs. 3, 4, 5). 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 (Refs. 6-7).

The primary goal of this paper is to present information concerning these phenomena at a high subsonic speed, and to specifically determine the possible role or influence of pressure fluctuations on the processes involved. Whereas most studies in this area tend to be at relatively low free stream velocities (typically, \(U_0 = 30.5\) m/sec) and Reynolds numbers \((Re_0 < 10^4)\), the present results are for a turbulent boundary layer with \(U_0 = 206\) m/sec and \(Re_0 = 108,000\). In addition, simultaneous measurements of three properties of the turbulent flow, namely, the streamwise velocity, the wall shear, and the wall pressure were made. Preliminary results from measurements at \(U_0 = 206\) m/sec led to lower velocities. Therefore, measurements for boundary layers with \(U_0 = 22.4\) m/sec and \(U_0 = 10\) m/sec have also been made. These first sets of measurements were made with sensors aligned so as to resolve the structure of the turbulence normal to the wall and in the streamwise direction along the wall. More recently, efforts have been directed toward obtaining information about the flow structures in the lateral direction. This has required modification of the instrumentation package so as to allow a greater number of measurements to be made. A stage has been reached where up to 18 simultaneous measurements can be made and analyzed digitally using programs incorporating various combinations of analyses developed by other investigators to study these phenomena in low speed flows (Refs. 4, 6, 9, 10, and 11).

**INSTRUMENTATION AND DATA RECORDING**

Thorough descriptions of the experimental facilities have been provided in Refs. 12, 13, and 14. The measurements are made on or near the wall of a .305m diameter cylindrical test section which is part of an induction wind tunnel. The wind tunnel is capable of velocities from 9.2 to 2.5 m/sec. The measurements have been made by utilizing a total of 15 sensors aligned in the lateral direction. This includes a row of 5 wall-pressure transducers directly downstream by a row of 5 wall-shear sensors. At a fixed height above each of the shear sensors is a subminiature probe for measuring the streamwise velocity. The height of the velocity probes from the wall can be varied from test to test from approximately .63 to 38 mm. In this case all the sensors are mounted directly into or through one of the test section windows. Most of the recent efforts of this investigation have been directed toward analyzing measurements along the lateral array.

The recorded data is analyzed with the system shown schematically in Fig. 3. Conventional spectra and correlation analyses of the analog data are performed using a General Radio 1900 wave analyzer and a Saicor 42 correlation and probability analyzer. The bulk of the data analysis, however, is performed on digitized sections of the recordings obtained with the use of a PDP-11/34 Mini Computer system.

The analyses that can now be performed on a production run basis on the 11/34 include the following:

- Power spectra using a Fast Fourier Transform (FFT) algorithm.
- Long-time average auto and cross correlations.
- Conditional sampling of the data using the variable interval time-average (VITA) variance to isolate temporal sequences associated with coherent events in the flow (see Kaplan and Laufer (Ref. 10) or Blackwelder and Kaplan (Ref. 8)). Ensemble averages can be formed from a set of events.
- Pattern recognition analysis to compensate for random phase "jitter" in conditional samples (see Blackwelder (Ref. 11)).
- Short time conditional samples of auto and cross correlations (see Brown and Thomas (Ref. 4)).

These analyses can be applied to the original data or to the data after it has been filtered using the FFT algorithm to include only fluctuation components in a chosen frequency range. In addition, an attempt has been made to see what benefits could be gained by incorporating certain aspects of one type of analysis into another.

**MEASUREMENTS AND DISCUSSIONS**

The mean flow parameters at several stations in the tunnel for the three flow conditions for which measurements have been made are summarized in Table 1. Details on the measurement of the mean velocity and turbulent intensity profiles can be found in Refs. 12 and 15. It should be noted that the boundary layer thickness is on the order of 10.3 cm in all cases, while the Reynolds number based on momentum thickness ranges from approximately 5,000 to 100,000.

Measurements of the velocity, wall-shear and wall-pressure fluctuations aimed at resolving coherent flow structures in the turbulent boundary layer for this paper have been made with two basic arrays, the geometries of which are shown in Figs. 1 and 2. In the first case, the measurements were repeated for three
freestream velocities (i.e., \( U_0 = 206 \), 22.4 and 10 m/sec) whereas in the case of the array shown in Fig. 2, measurements were made only at \( U_0 = 206 \) m/sec. The results obtained with the array of sensors shown in Fig. 1 have been extensively discussed in previous papers (Refs. 12, 13, 14, and 15). An attempt will be made here to restate some of the general conclusions arrived at from these previous measurements and to discuss any new results obtained with the array of Fig. 2.

One of the first analyses performed in almost every case was to obtain the spectral distributions of the various fluctuations. This was originally done directly from the recorded analog data using a Fast Fourier Transform algorithm. An early conclusion reached from the spectral analyses was that the levels of the wall pressure fluctuations for the two low-speed cases were much higher than expected. As a result of many previous measurements, it is to be expected that the rms level of the wall pressure fluctuations will fall somewhere between 0.5% and 1% of the dynamic pressure, \( q_0 \). In the case of \( U_0 = 206 \) m/sec we measured a reasonable level of 0.008 \( q_0 \); but at \( U_0 = 22.4 \) m/sec and 10 m/sec the measured levels were equivalent to approximately 0.23 \( q_0 \), and 0.55, respectively. The explanation for this is that for the low-speed tests, the wall pressure fluctuations due to the turbulent boundary layer become so weak that they drop below the noise "floor" of the measuring devices. The noise "floor" is made up primarily of tunnel noise, although other sources such as transducer vibration response and misalignment with the tunnel wall may also contribute to it.

In the high subsonic regime, where primary interest lies, the wall pressure fluctuations due to the turbulent boundary layer are thought to be sufficiently above the noise "floor" to allow for accurate measurements. In the low-speed cases the main interest was in looking at the wall-shear and fluctuation velocity profiles (for comparison to those obtained at high speed), the measurement of which should be significantly affected by tunnel noise.

Typical power spectra obtained for the wall pressure fluctuations are shown in Fig. 4. Those measured by Serafini (Ref. 16), and Wooldridge and Willmarth (17) are also shown for comparison. It can clearly be seen that for the two low-speed flows the noise "floor" is anywhere from 20 to 40 dB above the expected wall pressure fluctuations over the entire range of pertinent frequencies. In the high-speed case the measured fluctuations have a spectral distribution which agrees more favorably with previous measurements. The lower levels obtained above \( \omega_0 / U_0 \approx 0.3 \) could be due to the size of the transducer not allowing accurate resolution of small-scale fluctuations.

A comparison of previous 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 \( \omega_0 / U_0 \approx 1 \). Emmerling (Ref. 18) has summarized the available results in terms of the non-dimensional parameter \( d U_0 / \omega_0 \), 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 0.005\( q_0 \). Below this value, the measured rms level increases linearly as \( d U_0 / \omega_0 \) 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 (see Ref. 19)). For the transducer used here, \( d U_0 / \omega_0 \approx 300 \) (for \( U_0 = 206 \) m/sec) thus indicating that some loss of resolution probably exists in the present measurements. The reasons for the slightly high overall level of 0.008 \( q_0 \) have not been determined.

An additional question concerning sensor size arises for the flush mounted hot-film sensor. It has been found (see Thomas (Ref. 20)) that the bridge output voltage wall-shear relationship given previously holds only if

\[
7.8 < \frac{L_e U_0}{\nu} < 46
\]

where \( L_e \) is the effective length of the sensor in the streamwise direction. For a sensor width, \( W_0 \), of about twice the length, Thomas finds that \( L_e / L_0 = 2.6 \). Using this ratio in the present case (\( L_0 = 0.127 \) mm) would yield an \( L_0 U_0 / \nu \) of about 100, 20, and 12 for \( U_0 = 206 \) m/sec, 22.4 m/sec, and 10 m/sec, respectively. However, since \( W_0 / L_0 \) is larger than 2 (i.e., 8), the ratio \( L_e / L_0 \) will also be smaller than 2.6, thereby giving a more acceptable value of \( L_e U_0 / \nu \) for \( U_0 = 206 \) m/sec.

Power spectra for the velocity fluctuations at two points in the boundary layer are presented, together with similar data obtained by Wooldridge and Willmarth (Ref. 17), in Figs. 5, 6, and 7 for the free-stream velocities. In all three cases there is reasonable agreement in the overall shape and level of spectral distributions. This confirms the assumption that unlike the wall pressure fluctuations, the velocity fluctuation measurements are not significantly affected by tunnel noise in the lower speed flows. The differences in the spectra at the two measurement positions, particularly for \( U_0 = 206 \) m/sec (Fig. 5), is most likely due to the difficulty in matching the frequency response characteristics of the different anemometers used for the measurements. It should be noted that for the velocity fluctuation spectra, the local mean velocity and not the free-stream velocity has been used to nondimensionalize frequency.

**Lateral Array**

The bulk of the new results to be presented here are for the lateral array of Fig. 2. Although recordings have been made with the velocity probes at four distances from the wall, only two have been analyzed extensively, that is, those for \( y^* = 0.044 \) and \( y^* = 0.31 \).

Long time average normalized auto and cross correlations calculated for this array are shown in Figs. 8a-c for the case where \( y^* = 0.044 \), and Figs. 9a-c for \( y^* = 0.31 \). In each case the first figure contains the correlations between the wall shear at \( D(t') \) (see Fig. 2) and all the other measurements in the array; the second between \( u'(D) \) and the other velocity measurements; and the third between \( p'(B) \) and the other pressure measurements. (Due to sensor failure the measurement \( u'(C) \) is missing from the array in the first case, and \( t'(B) \) in the second.) It can be seen from these results that the most significant and obvious correlation exists between the wall-shear and the streamwise velocity (Figs. 8a and 9a),

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particularly as would be expected for the case where
the velocity is measured very close to the wall
(Fig. 8a). Previous measurements have indicated that
a strong correlation should also exist in the stream-
wise direction. However, due to the quite different
eature (e.g., in spectral content) of the two types
of measurements aligned in the streamwise direction,
that is, pressure and shear, it is difficult to inter-
pret their correlation. Correlation of the pres-
sure measurements and the two shear measurements
aligned in the streamwise direction in Fig. 1 have
indicated an overall convection velocity along the
wall of about 122 m/sec of $U_c/U_w \approx 0.66$ (Ref. 13).

The time delay to the maximum correlation between
the wall-shear and velocity is approximately -75 usec
for $y/\delta^* = 0.044$ (Fig. 8a) and -160 usec for
$y/\delta^* = 0.31$ (Fig. 9a). These delays can be inter-
preted in two ways. Using the distance between the
measurements, they yield an overall downward convec-
tion velocity of about 10 m/sec in the first case
and 27.5 m/sec in the second. Together with the
streamwise convection velocity noted above, they
could be taken to indicate the average orientation
in the normal direction of disturbances or wavefronts
in the flow. This interpretation leads to the con-
clusion that on the average the wavefronts lean
forward in the flow and make an angle with the wall
of 4° when $y/\delta^* = 0.044$ and 13° when $y/\delta^* = 0.31$. It
is clear that in earlier interpretation the better
estimate of what is happening very near the wall is
given by the results for $y/\delta^* = 0.044$.

The correlations in the lateral direction show
that there is much less coherence in this direction
than has been found in either the streamwise or
normal directions. In all cases a significant
correlation exists only, for the measurements adjacent
to the reference. The exception to this seems
to be the set of correlations between the velocity
measurements at $y/\delta^* = 0.31$ (Fig. 9b). In this case
a relatively high coherence can be seen across all
five measurements, perhaps indicating that this height
from the wall flow structures have a much wider lateral
extent (i.e., on the order of $\Delta z^+ \approx 5,000$).
These tendencies were to be expected since other investiga-
tions, particularly those involving flow visualiza-
tions, have shown that the wall region contains flow
structures ("bursts") having lateral dimensions on
the order of $\Delta z^+ \approx 50$ and separations of $\Delta z^+ \approx 100$,
whereas the outer region is dominated by large-scale
structures with dimensions on the order of boundary
layer thickness. The fact that we see any coherence at all in the wall measurements which are separated by a distance $\Delta z^+ \approx 1200$ is surprising. It may be an
indication, together with the very high correla-
tion between the wall-shear and velocity (Figs. 8a
and 9b), that the large-scale outer structure has a
strong and direct influence on the wall.

One would expect from symmetry arguments that the
correlations in the lateral direction should
not show any significant asymmetry about zero time de-
lay. This is generally true for the velocity (Figs. 8b
and 9b) and pressure (Figs. 8c and 9c) correlations,
but not for the correlations between the shear
measurements. This is particularly true in Fig. 8a
where a definite asymmetry can be seen in the $\tau' / \tau'(C)$
and $\tau'(D) - \tau'(E)$ correlations. (The unique charac-
ter of the $\tau'(D) - \tau'(E)$ correlation is due to
the lack of an adequate bandwidth in the $\tau'(E)$ mea-
surements of Fig. 9a.) The cause of this asymmetry has
not been determined. Any possible explanation, such
as mean cross-flow in the tunnel or a preponderance
of flow structures with a preferred orientation in
the sample of data being analyzed, would require that
the asymmetry also appear in the velocity and pressure
correlations.

The most important aspect of the processing per-
formed on any of the measurements involved using
the VITA variance analysis referred to earlier to
conditionally sample the long data records and isolate
temporal sequences believed to be associated with
coherent flow structures. Ensemble averages formed
from these conditional samples will depict average
or typical characteristics of the flow structures,
and the mean period between the samples or events
can be used to estimate the frequency of occurrence
of the structures.

It has been found that the VITA variance analysis
has a weakness in terms of this latter estimate since
the number of events detected is strongly dependent
on the threshold level chosen in the scheme (see
Ref. 12 for a definition of the terms used here). A
plot of the mean period between detected events (non-
dimensionalized by $\delta^* / U_w$) versus threshold level
is shown in Fig. 10 using various measurements as the
trigger or trigger to which the VITA variance analy-
is is applied. For reference, a line is drawn at $U / \delta^* = 5$ for the "bursting" period. It can be seen that there is, indeed, a large variation in the number
of events detected with different threshold levels.
The variation with the measurement used as the trigger
is partly to be expected since it has been found pre-
viously that the measured period does not vary with
distance from the wall. However, a certain amount
of this variation, particularly between the wall
measurements $\tau'$ and $p'$, may be attributable to an
improper choice of the averaging interval used in
the scheme which is chosen on the basis of the frequency
content of the signal being analyzed. In Fig. 10,
the averaging interval was 150 usec ($U / \delta^* \approx 1$)
for the shear and velocity, and 80 usec ($U / \delta^* \approx 1$)
for the pressure. For the ensemble averages discussed
below, the threshold level was chosen so as to give
a total number of events corresponding to approxi-
mately $U / \delta^* = 35$.

Ensemble averages of the fluctuations using $u'(D),
p'(D)$ and $\tau'(D)$ as the trigger have also been per-
formed for the case where the velocity probes are at
$y/\delta^* = 0.044$. (The fluctuation amplitude was normal-
ized by the local long-time rms. The value of 1.0
was chosen as the trigger measurement hold for all the
averages.) These were obtained by locating the
center of each event detected by applying the
VITA variance analysis to the measurement chosen as
the trigger, and then by ensemble averaging 512 data
points ($dt = 2.5$ sec) centered about these event
centers for each measurement in the array of Fig. 2.
In all three cases, the ensemble averages showed that
a definite coherence exists in the normal and stream-
wise directions, but very little, if any, exists in the
lateral direction. This agreed with the conclu-
sions reached from the overall correlations of Figs. 8
and 9. For brevity these results are presented in Ref. 20.

An attempt has been made to determine if the
absence of any coherence in the lateral direction is
due to noise which enters the ensemble averages
because of random variations in the phase between
the events at the trigger and at the measurement being
averaged (see Ref. 11). A pattern recognition
analysis is applied to determine this phase relationship for each of the samples in the ensemble averages. The samples are shifted so that the phase differences are made zero and then ensemble averaged. This has been done for the case where \( r'(D) \) is used as the trigger with the addition of an intermediate step. This involves separating the set of events detected with this trigger into two groups depending on the phase relationship of each event with the corresponding event in \( r'(C) \) as determined by the pattern recognition analysis. The corrected ensemble averages obtained for the set of events where a match is found at an earlier time (negative delay) in \( r'(C) \) are presented in Fig. 11a, and at a latter time (positive delay) in Fig. 11b. The average delay by which the samples in a given ensemble have been shifted is shown for several of the averages in these figures. The marked improvement in the ensemble averages across the shear measurements in both cases shows that a coherence exists in the lateral direction which was previously obscured by considerable random phase "jitter". The fact that this coherence extends well beyond the \( \Delta x^+ \approx 50 \) of wall region "bursts" makes it further interesting that it is due to a direct response of the wall measurements to the passage of the large scale outer structures. The fact that the events can be separated into two groups with opposite phase relationships across the lateral measurements is thought to be an indication of the "arrowhead" or "horsehoe" type shape (see Fig. 1) that has been hypothesized for the large scale outer structures when looked at from above the wall boundary layer. It is clear that the phase relationship one would obtain among a set of lateral measurements would depend on which "leg" of the structure crosses the measurements. From the results of Figs. 11a and b, it is possible to estimate the angles \( \theta^+ \) and \( \theta^- \) in Fig. 1 that each "leg" makes with the X-axis. To do this it is necessary to know the average streamwise convection velocity of the coherent structures along the wall. This has been estimated from previous measurements to be \( U_c/U_\infty \approx 0.68 \) (compared \( U_c/U_\infty \approx 0.6 \) found for the overall convection velocity from the long-time average correlations). Using this convection velocity and the average time delay between \( r'(D) \) and \( r'(C) \) in Fig. 11a, the angle \( \theta^+ \) is estimated (locally and on the average) to be 80°. The average delay in Fig. 11b also yields a \( \theta^- \) of about 80°. These results compare favorably with an estimated angle of 60° found from the measurements of Fig. 1 at \( U_c = 206 \text{ m/sec} \) (Ref. 13). For low-speed measurements (Refs. 13 and 20) this angle has been estimated to be anywhere from 18° - 22°. The significantly smaller angle obtained for the high-speed flow may imply that the flow structures become more confined in the lateral direction as the free stream velocity is increased. It can be seen from Figs. 11a and b, that for both sets of events the phase relationship between \( r'(D) \) and \( u'(D) \) is such that the events are always seen earlier in the velocity measurement. As discussed previously with regard to the long time average correlations, this can be interpreted either as downward convection of the flow structures or as forward leaning wavefronts. The average time delay between \( r'(D) \) and \( u'(D) \) for all the events of both Figs. 11a and b yields a downward convection velocity of about 10 m/sec or wavefronts making an angle of approximately 40° with the wall. The fact that these results match those obtained from the long time averaged correlation implies that the coherent events, although taking up less than 1/5 of the total time, strongly control the overall characteristics of the flow in the normal direction. This is to be contrasted with the difference found between the streamwise convection velocity of the coherent events (\( U_c/U_\infty \approx 0.68 \)) and of the overall flow (\( U_c/U_\infty \approx 0.60 \)), which implies that the faster moving coherent flow structures do not completely dominate the average flow in the streamwise direction. The analysis performed between \( r'(D) \) and \( r'(C) \) to separate the events detected with \( r'(D) \) into two groups, was also carried out between \( p'(D) \) and \( p'(C) \) for events detected with \( p'(D) \) and between \( u'(D) \) and \( u'(E) \) for those detected with \( u'(D) \). In terms of the angles \( \theta^+ \) and \( \theta^- \) of Fig. 1, the analysis of the lateral pressure measurements led to angles of about 70°. This agrees with the estimate made above from the shear. (In addition, however, the lateral pressure measurements show a great many events (%1/3) having approximately zero time delay between adjacent measurements. This is not surprising in itself since the flow structure in Fig. 1 would show this sort of phase relationship near the centerline. What is puzzling is that the analysis of the lateral shear measurements does not show an equivalent large group of events with zero time delay). The \( u'(D) - u'(E) \) analysis yielded a \( \theta^- \) angle of about 10° which seems to indicate a spreading of the flow structures as one moves away from the wall. As can be seen from the above, an analysis of these results has led to a collaboration of many of the conclusions reached concerning the nature of the coherent structures in the lateral and normal directions. Other analysis following the lines of the one discussed by Brown and Thomas (Ref. 4), was also performed in Ref. 20. The results show the same correlations for the positive delay events described with reference to Figs. 11a and b. CONCLUSIONS An investigation of the coherent or quasi-ordered structure of the turbulent boundary layer in the lateral direction at high velocity is made. Simultaneous measurements of velocity, wall-pressure and wall-shear fluctuations at \( U_\infty = 10, 22.4, \) and \( 206 \text{ m/sec} \) have been analyzed to obtain a description of the so-called "turbulent bursts". A conditional sampling analysis which searches for periods when the fluctuating quantities have larger and rapidly changing values was used to identify the occurrence of a burst in the data. The results for the lateral spread of the "bursts" indicate that the events can be separated into two groups with opposite phase relationship across the lateral measurements, and is thought to be an indication of "arrowhead" or "horsehoe" type shape. The angular spread of the "horsehoe" may be estimated and therefore the angle of each "leg" which makes with the X axis may be determined. Using a convection velocity of \( U_c/U_\infty \approx 0.6 \) the average delay as estimated from the lateral measurements (locally and on the average) the angle is estimated to be 80°. These results lead to the conclusions that the flow structures at high velocities tend to be very narrow and swept back at or near the wall, and much wider and flatter away from the wall. ACKNOWLEDGMENT The work reported herein was supported by the...
REFERENCES


### TABLE I

**MEAN FLOW PARAMETERS AT SEVERAL STATIONS FOR THREE TEST CONDITIONS**

<table>
<thead>
<tr>
<th>X/D</th>
<th>15.5</th>
<th>20.5</th>
<th>9</th>
<th>15.5</th>
<th>31</th>
<th>31</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta ) (m)</td>
<td>0.0263</td>
<td>0.0296</td>
<td>0.063</td>
<td>0.067</td>
<td>0.072</td>
<td>.64</td>
</tr>
<tr>
<td>( U_{m} ) (m/sec)</td>
<td>9</td>
<td>10</td>
<td>21.2</td>
<td>22.4</td>
<td>24</td>
<td>206</td>
</tr>
<tr>
<td>( q ) (kilo pascals)</td>
<td>0.047</td>
<td>0.06</td>
<td>0.27</td>
<td>0.32</td>
<td>0.475</td>
<td>20</td>
</tr>
<tr>
<td>( \delta ) (cm)</td>
<td>6.83</td>
<td>8.9</td>
<td>5.5</td>
<td>7.6</td>
<td>%</td>
<td>14</td>
</tr>
<tr>
<td>( \delta' ) (cm)</td>
<td>0.99</td>
<td>0.497</td>
<td>0.672</td>
<td>.94</td>
<td>%</td>
<td>2.04</td>
</tr>
<tr>
<td>( \delta ) (cm)</td>
<td>0.79</td>
<td>0.976</td>
<td>0.525</td>
<td>0.74</td>
<td>%</td>
<td>1.52</td>
</tr>
<tr>
<td>( \delta ) (cm)</td>
<td>0.99</td>
<td>0.497</td>
<td>0.672</td>
<td>.94</td>
<td>%</td>
<td>2.04</td>
</tr>
<tr>
<td>( \delta ) (cm)</td>
<td>0.79</td>
<td>0.976</td>
<td>0.525</td>
<td>0.74</td>
<td>%</td>
<td>1.52</td>
</tr>
<tr>
<td>( Re_{\delta} )</td>
<td>( 4.62 \times 10^3 )</td>
<td>( 6.56 \times 10^3 )</td>
<td>( 8.45 \times 10^3 )</td>
<td>( 1.25 \times 10^4 )</td>
<td>( 2.82 \times 10^4 )</td>
<td>( 1.08 \times 10^5 )</td>
</tr>
<tr>
<td>( v/u_{*,c} ) (cm)</td>
<td>( 4.21 \times 10^{-3} )</td>
<td>( 2.76 \times 10^{-3} )</td>
<td>( 1.75 \times 10^{-3} )</td>
<td>( 1.7 \times 10^{-3} )</td>
<td>( 1.74 \times 10^{-3} )</td>
<td>( 3.34 \times 10^{-4} )</td>
</tr>
<tr>
<td>( v/u_{*,c} ) (usec)</td>
<td>120</td>
<td>51.6</td>
<td>24.0</td>
<td>22.5</td>
<td>23.0</td>
<td>0.62</td>
</tr>
<tr>
<td>( (v'/u)_{m} )</td>
<td>0.005</td>
<td>-</td>
<td>-</td>
<td>0.005</td>
<td>0.021</td>
<td>0.008</td>
</tr>
</tbody>
</table>

**FIG. 1** LATERAL ARRAY OF FLUSH HOT-FILM SHEAR SENSORS

**PROPOSED PLAN VIEW OF LARGE-SCALE OUTER STRUCTURE FROM THOMAS, REF. 20**
FIG. 2 FULL LATERAL ARRAY OF SENSORS

<table>
<thead>
<tr>
<th>y</th>
<th>z/δ</th>
<th>δ+</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.60</td>
<td>230</td>
</tr>
<tr>
<td>0.50</td>
<td>0.66</td>
<td>160</td>
</tr>
<tr>
<td>0.30</td>
<td>0.038</td>
<td>380</td>
</tr>
<tr>
<td>1.00</td>
<td>0.13</td>
<td>570</td>
</tr>
<tr>
<td>4.05</td>
<td>0.31</td>
<td>1350</td>
</tr>
</tbody>
</table>

FIG. 3 DATA ANALYSIS SYSTEMS
FIG. 4 TYPICAL SPECTRA OF THE WALL-PRESSURE FLUCTUATIONS FOR THREE FREE STREAM VELOCITIES
FIG. 6  TYPICAL SPECTRA OF THE VELOCITY FLUCTUATIONS FOR $U_m = 22.4$ m/sec

FIG. 7  TYPICAL SPECTRA OF THE VELOCITY FLUCTUATIONS FOR $U_m = 10$ m/sec
FIG. 8A LONG TIME AVERAGE CORRELATIONS FOR THE FULL LATERAL ARRAY WITH VELOCITY PROBES AT Y/6 = 0.044
(Um = 206 M/SEC) (REFERENCE: v'(D))

B) REFERENCE: u'(D)

C) REFERENCE: a'(D)

FIGS. 8B & C LONG TIME AVERAGE CORRELATIONS FOR THE FULL LATERAL ARRAY WITH THE VELOCITY PROBES AT
Y/6 = 0.044 (Um = 206 M/SEC)
FIG. 9A. LONG TIME AVERAGE CORRELATIONS FOR THE FULL LATERAL ARRAY WITH VELOCITY PROBES AT $v/\delta = 0.31$
($U_\infty = 206 \text{ MSEC}$, REFERENCE: $\tau' (D)$)

B) REFERENCE: $U' (D)$

FIGS. 9B & C. LONG TIME AVERAGE CORRELATIONS FOR THE FULL LATERAL ARRAY WITH THE VELOCITY PROBES AT
$v/\delta = 0.31$ ($U_\infty = 206 \text{ MSEC}$)
FIG. 10 VARIATION OF THE MEAN PERIOD BETWEEN DETECTED EVENTS WITH THRESHOLD LEVEL IN THE VITA VARIANCE ANALYSIS USING VARIOUS MEASUREMENTS AS THE DETECTOR OR TRIGGER.

FIG. 11A ENSEMBLE AVERAGED VELOCITY, SHEAR AND PRESSURE FLUCTUATIONS FOR THE FULL LATERAL ARRAY AFTER CORRECTION FOR PHASE "JITTER" ($\tau_L = 206$ MSEC, $u' (v/\delta) = 0.044$, TRIGGER +C/EVENTS WITH NEGATIVE DELAYS BETWEEN +C (D) AND +C (E))
Fig. 13b: Ensemble averaged velocity, shear and pressure fluctuations for the full lateral array after correction for phase
errors. (UL = 2.0, MSEC, U* = 0.14U, TURB: + (D) CONV: With positive delays between + (D) and - (C)