AN EXPERIMENTAL STUDY OF COHERENT STRUCTURES
IN A THREE-DIMENSIONAL TURBULENT BOUNDARY LAYER

by

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(ABSTRACT)

In order to improve the state of turbulence modeling for three-dimensional flows, more
detailed information on the fundamental physics of the flow is required. It has been recognized
for some time now that organized motions or coherent structures in the flow play a large part in
determining the flow characteristics, and there is now a large body of literature dealing with
various aspects of coherent structures. However, almost all of the existing literature deal with
mean two-dimensional flows with very little reported for mean three-dimensional flows.

In the present study, measurements were performed in a three-dimensional, pressure-driven
turbulent boundary layer ($Re_a = 5936$) in the flow around a wing-body junction with a variety of
multiple-sensor probes, to examine the features of the coherent structures in the flow. This test
flow has a number of practical applications and was selected because of its strong three-
dimensional nature and the availability of an extensive set of mean-flow measurements from
previous investigations. The measurements were carried out with a hot-wire rake with sixteen
sensors spaced approximately logarithmically over 25.4 mm (1 inch), a parallel-sensor probe with
two parallel sensors spaced approximately 4.8 mm apart, a rotatable wall-sensor probe with two
wall-mounted hot-film sensors spaced 6.93 mm apart and a traversable wall-sensor probe with two
variable-spacing wall-mounted hot-film sensors. The hot-wire rake was used to examine the
structure of the flow in both the Y (normal to the wall) and Z (spanwise) directions. The parallel
and rotatable wall-sensor probes were used to look at the angular characteristics of the coherent structures in the flow and at the wall, respectively, and the spanwise structure of the flow at the wall was examined through the traversable wall-sensor probe.

The results of the measurements show that the spectral characteristics of the flow are affected by three-dimensional effects. The direction of motion of the coherent structures lags behind the local mean-velocity vectors in the X-Z plane (parallel to the wall) with very little variation with frequency (structure size). Unlike two-dimensional boundary layers, the spectral variation of the convective wave speed does not collapse when normalized with the local mean velocity and friction velocity in the outer and inner regions, respectively. In the outer region of the boundary layer, the distribution of the intermittency with Y appears to agree quite closely with previously reported results for two-dimensional boundary layers. The mean ejection frequency in the near-wall flow and the frequency at the peak of the first moment of the wall shear-stress power spectrum show fairly close agreement, consistent with previously reported results for a two-dimensional boundary layer. The measurements with the traversable wall-sensor probe indicate the presence of an organized structure, probably low-speed streaks in the near-wall region, with a preferred spanwise spacing. This spanwise spacing was found to be $\Delta z^* = 85$ and 135 at two different measurement stations, somewhat different from the well accepted value of $\Delta z^* = 100$ for two-dimensional boundary layers. Time-delayed correlations of the velocity signal over a range of Y locations reveal an inclined linear wavefront similar to previously reported results for a two-dimensional boundary layer.
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# SYMBOLS AND NOTATION

**Roman**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, B</td>
<td>hot-wire/hot-film calibration constants</td>
</tr>
<tr>
<td>c(t)</td>
<td>criterion function</td>
</tr>
<tr>
<td>d(t)</td>
<td>detector function</td>
</tr>
<tr>
<td>$C_p$</td>
<td>pressure coefficient</td>
</tr>
<tr>
<td>E</td>
<td>hot-wire/hot-film output voltage</td>
</tr>
<tr>
<td>$e_x$</td>
<td>rms voltage of function generator in frequency-response test</td>
</tr>
<tr>
<td>$e_o$</td>
<td>rms output voltage of hot-wire anemometer in frequency-response test</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
</tr>
<tr>
<td>$f_e$</td>
<td>mean frequency of near-wall ejections</td>
</tr>
<tr>
<td>$f_i$</td>
<td>mean passage frequency of turbulent/non-turbulent interface in the outer region of the boundary layer</td>
</tr>
<tr>
<td>$f_r$</td>
<td>mean frequency of first moment of fluctuating wall shear-stress power spectrum</td>
</tr>
<tr>
<td>G</td>
<td>flow-gradient angle in the X-Z plane</td>
</tr>
<tr>
<td>$G_{uu}$</td>
<td>power spectrum of u</td>
</tr>
<tr>
<td>$G_{xx}$, $G_{yy}$</td>
<td>power spectra of x(t), y(t)</td>
</tr>
<tr>
<td>$G_{xy}$</td>
<td>cross spectrum between x(t), y(t)</td>
</tr>
<tr>
<td>i</td>
<td>$\sqrt{-1}$</td>
</tr>
</tbody>
</table>
k : wave number (= 2πf/\bar{U})

k_i : decay constant in the exponential-decay model for the spatial variation of coherency between a point in the inner region of the boundary layer and the rest of the boundary layer

k_o : decay constant in the exponential-decay model for the spatial variation of coherency between a point in the outer region of the boundary layer and the rest of the boundary layer

k_x : decay constant in the exponential-decay model for the streamwise variation of coherency

k_z : decay constant in the exponential-decay model for the spanwise variation of coherency

L : threshold level in the modified u-level burst-detection algorithm

L_x(f) : coherence length scale

L_{qi} : "inner" coherence length scale measured by rake sensor #1

L_{qo} : "outer" coherence length scale measured by rake sensor #16

L_{wu} : "upper" coherence length scale measured by an interior rake sensor

L_{\gamma z} : spanwise coherence length scale in local free-stream coordinates

m : N - 1

N : sample size
   total number of occurrences over all frequency bands in the histogram of the first moment of the \tau'_u power spectrum

N_e : number of ensemble realizations

n : hot-wire/hot-film calibration constant
   number of occurrences in a particular frequency band in the histogram of the first moment of the \tau'_u power spectrum

n_u : hot-wire rake sensor number that is at the same Y location as the upstream sensor

P : pressure

p : 1/n
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_u$</td>
<td>time-delayed cross-correlation coefficient of fluctuating $u$ velocity component</td>
</tr>
<tr>
<td>$R_{xy}$</td>
<td>long-time averaged cross-correlation coefficient between $x(t)$ and $y(t)$</td>
</tr>
<tr>
<td>$R_{rr}$</td>
<td>long-time averaged cross-correlation coefficient between fluctuating wall shear-stress components</td>
</tr>
<tr>
<td>$R_s$</td>
<td>short-time averaged autocorrelation coefficient for fluctuating wall shear stress</td>
</tr>
<tr>
<td>$Re_0$</td>
<td>Reynolds number based on momentum thickness</td>
</tr>
<tr>
<td>$r_r$</td>
<td>regression coefficient in least-squares fit of straight line to time-delayed correlation structure front</td>
</tr>
<tr>
<td>$r_i$</td>
<td>regression coefficient in the exponential-decay model for the spatial variation of coherency in the $Y$ direction in the inner region of the boundary layer</td>
</tr>
<tr>
<td>$r_o$</td>
<td>regression coefficient in the exponential-decay model for the spatial variation of coherency in the $Y$ direction in the outer region of the boundary layer</td>
</tr>
<tr>
<td>$r_x$</td>
<td>regression coefficient in the exponential-decay model for the coherency between the upstream sensor and the hot-wire rake with $\Delta X$ spacing only.</td>
</tr>
<tr>
<td>$r_z$</td>
<td>regression coefficient in the exponential-decay model for the spatial variation of coherency in the $Z$ direction</td>
</tr>
<tr>
<td>$S$</td>
<td>turbulent shear-stress angle in the $X-Z$ plane</td>
</tr>
<tr>
<td>$S_L$</td>
<td>Schmitt trigger level</td>
</tr>
<tr>
<td>$S_u$</td>
<td>variance of calibration data in linearized calibration equation</td>
</tr>
<tr>
<td>$s$</td>
<td>$\sqrt{(-\overline{uv})^2 + (-\overline{vw})^2}$</td>
</tr>
<tr>
<td>$s(t)$</td>
<td>indicator function</td>
</tr>
<tr>
<td>$T$</td>
<td>total time record length of data</td>
</tr>
<tr>
<td>$T_w$</td>
<td>maximum thickness of wing = 71.7 mm</td>
</tr>
<tr>
<td>$t$</td>
<td>temperature</td>
</tr>
<tr>
<td>$U$</td>
<td>mean-flow angle in the $X-Z$ plane shown in Figs 38 - 44 and Figs 48</td>
</tr>
<tr>
<td>$U,V,W$</td>
<td>instantaneous-velocity components in local free-stream coordinates</td>
</tr>
</tbody>
</table>
\( \mathcal{U}, \nabla, \mathcal{W} \) : mean values of \( U, V, W \)

\( \mathcal{U}_i \) : mean streamwise-velocity component in local free-stream coordinates at the \( \mathcal{Y} \) location of sensor \( i \) of the hot-wire rake

\( U_c(f) \) : convective wave speed

\( U_e \) : local free-stream velocity outside the edge of the boundary layer

\( U_{ref} \) : reference free-stream velocity at 10.9T upstream of the leading edge of the wing

\( U_{turb} \) : \( \sqrt{s} \)

\( U_\tau \) : friction velocity

\( u, v, w \) : fluctuating-velocity components in local free-stream coordinates

\( u_{rms} \) : local rms velocity

\( X(f), Y(f) \) : complex Fourier Transforms of \( x(t), y(t) \)

\( X, Y, Z \) : coordinates of a structure front in the \( X-Y \) plane

\( X_T, Y_T, Z_T \) : wind-tunnel coordinates (Fig 4)

\( X_w, Y_w, Z_w \) : local wall shear-stress direction coordinates (Fig 4)

\( x(t), y(t) \) : general time-dependent signals

\( X^*, x^* \) : streamwise distance normalized on \( U_\tau \) and \( \nu \)

\( Y \) : mean \( \mathcal{Y} \) location of boundary-layer edge defined by \( \beta = 0.5 \)

\( Y^*, y^* \) : \( \mathcal{Y} \) location normalized on \( U_\tau \) and \( \nu \)

\( Z_{a2} \) : standardized normal random variable for \( 100(1-\alpha)\% \) confidence interval
Greek

\( \alpha_f \)  : angle of inclination of time-delayed structure front

\( \beta \)  : angular position of probe in wind-tunnel coordinates

\( \beta_{FS} \)  : local free-stream direction in wind-tunnel coordinates

\( \beta_m \)  : angle of maximum coherency in the X-Z plane measured relative to the X_\tau axis

\( \beta_w \)  : angle of mean skin-friction vector at the wall measured relative to the X_\tau axis

\( \Delta f \)  : Fourier Transform bandwidth

\( \Delta L_\gamma \)  : 95% confidence interval in the coherence length scale

\( \Delta s \)  : spacing between the sensors of the parallel-sensor probe = 4.81 mm

\( \Delta t \)  : time delay

\( \Delta U_c \)  : 95% confidence interval in the convective wave speed

\( \Delta \mathcal{U} \)  : total 95% confidence interval in \( \mathcal{U} \)

\( \Delta \bar{u}^2 \)  : total 95% confidence interval in \( \bar{u}^2 \)

\( \Delta U_{\varepsilon} \)  : 95% confidence interval in \( \mathcal{U} \) due to random-calibration error

\( \Delta U_r \)  : 95% confidence interval in \( \mathcal{U} \) due to finite-sample size

\( \Delta u_{\varepsilon}^2 \)  : 95% confidence interval in \( \bar{u}^2 \) due to random-calibration error

\( \Delta u_r^2 \)  : 95% confidence interval in \( \bar{u}^2 \) due to finite-sample size

\( \Delta \gamma_{1027}^2 \)  : 95% confidence interval in \( \gamma^2 \) at \( \gamma^2 = 0.27 \)

\( \Delta X' \)  : streamwise spacing normalized on \( U_\tau \) and \( \nu \)

\( \Delta Y_R \)  : \( Y \) location of the lowest sensor of the rake (#1) in free-stream coordinates
\( \Delta X_U, \Delta Y_U \): position of slant-wire sensor relative to hot-wire rake sensor # 1 in free-stream coordinates

\( \Delta Z_U \): spanwise spacing in local free-stream coordinates

\( \Delta Z_w \): spanwise spacing between traversable wall-sensors in local wall shear-stress coordinates

\( \Delta Z_w^* \): \( \Delta Z_w \) normalized on \( U_t \) and \( v \)

\( \delta_i \): boundary-layer displacement thickness

\( \gamma^2(f) \): coherence function

\( \delta \): boundary-layer thickness defined by \( U = 0.995U_e \)

\( v \): kinematic viscosity

\(-\rho \overline{uv}, -\rho \overline{vw}\): turbulent (Reynolds) shear stresses

\( \sigma \): standard deviation of boundary-layer edge distribution

\( \tau_w \): instantaneous wall shear stress

\( \overline{\tau_w} \): mean wall shear stress

\( \tau'_w \): fluctuating wall shear stress

\( \Phi_{uu}(f) \): power spectrum of \( u \)

\( \Phi_{uv}(f) \): cross spectrum between \( u \) measured by two different sensors

\( \Phi(f) \): phase shift

\( \Phi_{\tau'_w}(f) \): power spectrum of \( \tau'_w \)

\( \phi(kY) \): power spectrum of \( u \) as a function of \( kY \)

\( \phi(k\delta) \): power spectrum of \( u \) as a function of \( k\delta \)

\( \chi^2_{n,1-\alpha} \): \( \chi^2 \) distribution random variable with \( n \) degrees of freedom at \( 100(1-\alpha) \% \) point
1 INTRODUCTION

1.1 COHERENT STRUCTURES IN BOUNDARY LAYERS

In spite of the application of considerable effort and resources, the state of turbulence modeling for three-dimensional boundary layer flows cannot be said to be well advanced. Many three-dimensional models are the result of attempts to extend existing two-dimensional models to three dimensions without proper consideration of the underlying physics of the flow. Consequently, these models lack robustness and generality in their application (Devenport and Simpson, 1992; Ölgemöller, 1993a; Abid, 1988; Abid and Schmidt, 1984). In order to improve on existing three-dimensional turbulence models, future models must incorporate the fundamental physics of the flow instead of simply being extensions of two-dimensional models. In recent years, it has been recognized that the behavior of turbulent boundary layers are to a large extent affected, if not dominated, by the underlying organized motion or coherent structures in the flow, which consequently have become the focus of much research. There is no single, widely accepted definition of a "coherent structure"; but it is generally regarded as a mass of fluid within which there exists significant correlation between a flow variable (velocity component, vorticity, pressure etc.) with itself or another flow variable. The concept of coherent structures is implicit in any turbulent flow with non-zero turbulent shear stresses. If the flow field consisted of purely random velocity fluctuations in time and space, then $-\rho \overline{uv}$ and $-\rho \overline{vw}$ would be zero everywhere as $u$, $v$ and $w$ would be uncorrelated. In order for non-zero turbulent shear stresses to exist, there must
be a biasing of the velocity fluctuations which implies the existence of an underlying coherent flow structure.

A variety of coherent structures in turbulent boundary layers have been observed by numerous researchers through flow visualization (Kline et al., 1967; Praturi and Brodkey, 1978) in the past and by direct numerical simulation (Kim, 1985; Robinson et al., 1989a) more recently. In the near-wall region of the boundary layer, quasi-streamwise vortices and low-speed streaks have been observed, and the bursting phenomenon involving the breakup of the low-speed streaks is thought to be responsible for most of the production of the turbulent shear stresses (Kline et al., 1967; Corino and Brodkey, 1969). The formation mechanism, frequency of occurrence, spatial distribution and temporal lifetime of the various structures have all been widely investigated. The larger structures which dominate the outer-region flow have been invoked by many authors to explain the various interactions between the outer and inner regions of the boundary layer, such as momentum and turbulent kinetic energy (TKE) transfer. Extensive reviews of the history, issues and current state of coherent-structures research may be found in Cantwell (1981) and Robinson (1989b, 1991).

1.2 BACKGROUND

A comprehensive summary of the current state of knowledge of boundary-layer structure may be found in Kline (1992). He listed nine different types of coherent structures which occur in the boundary layer, including near-wall, low-speed streaks, high-speed flow at the wall, bulges and backs in the outer region and vortical structures of several kinds. Two types of vortices, namely quasi-streamwise (leg) and transverse (head) vortices, are considered to be the central
structures of the boundary layer in the sense that all the other motions can be explained in terms of these structures.

Transverse vortices have been observed through flow visualization by a number of researchers, including Clark and Markland (1971), Nychas et al. (1973) and Praturi and Brodkey (1978). Clark and Markland (1971) found them to be the predominant form of vortex element for \( y^* > 70 \). They also observed that the lifetimes of the vortices increased with distance from the wall, and the diameters of the vortices increased over their lifetimes. Nychas et al. (1973) observed large-scale transverse vortices which occurred for \( y^* > 70 \) and suggested that these vortices were the cause of the bulges in the outer interface of the boundary layer. They also found a close spatial association between the passage of transverse vortices and the occurrence of bursts in the near-wall region, which implicated transverse vortices as the key structural element connecting the near-wall activity with the outer-region flow. These results were subsequently supported by the work of Praturi and Brodkey (1978) which also showed entrainment of free-stream fluid occurring in the vicinity of the large, outer-region transverse vortices. The formation mechanism of transverse vortices has been described by Robinson et al. (1989b) as the rollup of near-wall shear layers with locally concentrated spanwise vorticity. Once formed, transverse vortices are relatively long lived and often persist for streamwise distances up to \( x^* = 1000 \) (Kline, 1992).

Quasi-streamwise vortices occur primarily in the inner region of the boundary layer, as opposed to transverse vortices which are predominant in the outer region. However, both are also found in the log region (Robinson, 1991; see Fig 1). Robinson (1989b) examined a flat-plate, direct numerical simulation (DNS) boundary layer with \( Re_\theta = 670 \) and found that both types of vortices have wide distributions of size, strength and Y location. Quasi-streamwise vortices were found to occur most frequently at \( 45 < y^* < 50 \) and transverse vortices at \( 110 < y^* < 170 \). Both types of vortices can also occur joined together as a single structure forming a "horseshoe" vortex.
In such cases, the legs of the horseshoe vortex which are tilted towards the wall are rapidly stretched by the velocity gradient normal to the wall producing a region of high dissipation (Kline, 1992).

Quasi-streamwise vortices have also been observed experimentally by Kim et al. (1971) and Grass (1971). In both cases, the vortices were found to occur in the near-wall region in close connection with the burst/ejection process. Clark and Markland (1971) observed frequent occurrences of quasi-streamwise vortices in counter-rotating pairs with a 3° to 7° upward tilt in the wall region of a turbulent water channel.

Kline (1992) and Robinson (1990) have cited quasi-streamwise vortices as the probable cause of the low-speed streaks in the near-wall region. According to this scenario, the streaks are formed from the near-wall, low-speed fluid "pumped" up by the upward-rotating side of a quasi-streamwise vortex as it moves downstream. High-speed fluid is brought in by the downward-rotating side of the vortex forming alternating high and low-speed structures in the near-wall region. Once formed, the low-speed streaks persist for streamwise distances up to \( x^+ = 1000 \) (Kline, 1992).

Because of their central role in the production of turbulence, the low-speed streaks in the near-wall region have been extensively studied. The existence of the streaks in the near-wall region were first observed by Kline et al. (1967). They performed hydrogen bubble flow visualization in a low Reynolds number turbulent boundary layer with a bubble-generating wire placed parallel to the wall at various \( Y \) locations. It was observed that the bubbles produced from within the viscous sublayer (\( y^+ = 2.7 \) ) accumulated into low-speed streaks which drifted slowly away from the wall. The mean spanwise spacing of the streaks was approximately \( \Delta Z^+ = 100 \). It was found that these streaks subsequently experienced oscillations followed by a sudden lift up away from the wall and finally rapid disintegration. The sequence of events from oscillation to disintegration was termed a "burst". The oscillation phase of the burst was observed to occur in
the $8 < y^* < 12$ region and the breakup phase at $10 < y^* < 30$. It was also found that the rate of bursting was increased by an unfavorable pressure gradient and decreased by a favorable pressure gradient.

Corino and Brodkey (1969) observed a similar sequence of events in a fully-developed high Reynolds number pipe flow which they termed "ejections". They found that the frequency and intensity of the ejections increased with the Reynolds number based on the pipe diameter over the range $2300 < Re < 50000$. They also estimated that the ejections were responsible for the production of approximately 70% of the turbulent stresses. These results were subsequently supported by the work of Kim et al. (1971) who found that the bursts in the $6 < y^* < 100$ region accounted for almost all the net production of turbulent kinetic energy.

Blackwelder and Eckelmann (1979) studied the near-wall flow structure using heated wall elements and concluded that the low-speed streaks observed by Kline et al. (1967) were the accumulation of fluid between the near-wall quasi-streamwise vortices where the vertical velocity component was away from the wall.

The mean spanwise spacing of the streaks ($\Delta Z^* = 100$) and their role in turbulence and turbulent shear stress production are now well accepted features of turbulent boundary layer flows (Kline, 1992), but the scaling of the burst statistics is still controversial. Because of their occurrence in the near-wall region, it was generally assumed that the burst statistics would scale on the wall variables $u_*$ and $v_*$. However, Rao et al. (1971) reported that the mean burst period and time between bursts scaled on the outer variables $U_*$ and $\delta$ instead of the inner variables for data in the range $600 < Re_\delta < 9000$. On the other hand, Luchik and Tiederman (1987) used their data from a channel flow to test inner and outer scaling as well as the mixed scaling recommended by Alfredsson and Johansson (1984) and concluded that inner scaling was the correct choice.

As a result of the focus of attention on the bursting process, much effort has been
expended on the detection of bursts from point velocity measurements and also estimating the burst frequency. A number of burst detection algorithms using one and two-component velocity measurements have been proposed by various authors. Among the most popular are the uv quadrant (Lu and Willmarth, 1973), u-level (Lu and Willmarth, 1973), variable-interval time average (VITA) (Blackwelder and Kaplan, 1976) and VITA with slope (Johansson and Alfredsson, 1984) algorithms. Strickland and Simpson (1975) used a short-time autocorrelation technique to determine the average period between bursts and proposed a method of relating the bursting frequency to the first moment of the wall shear-stress power spectrum without using a specific burst-detection algorithm.

Some of the proposed burst-detection algorithms were evaluated by Bogard and Tiederman (1986) and Luchik and Tiederman (1987) by comparing the results obtained with each algorithm with flow visualization in a low Reynolds number channel flow. It was found that the short-time autocorrelation method of Strickland and Simpson gave the best agreement with the flow-visualization results in determining the period between bursts. However, the autocorrelation technique is not a true burst-detection algorithm as it is only able to detect the frequency of the bursts and not the bursts themselves. Among the actual burst-detection algorithms, the uv quadrant algorithm was found to be the best, followed by a modification of the u-level algorithm with separate detector on-off thresholds.

In much of the early work following Kline et al. (1967), the terms "bursts" and "ejections" were used interchangeably. However, the former term is no longer widely used and "ejections" will be used for the rest of this report.
1.3 OUTLINE AND OBJECTIVES OF PRESENT STUDY

In the present study, measurements were performed in a three-dimensional turbulent boundary layer with a number of custom-made hot-wire/hot-film probes which were designed to reveal features of the coherent structure of the flow. The test flow was a pressure-driven, three-dimensional turbulent boundary layer formed at a wing-body junction (Fig 2). This flow was selected because its turbulence structure is strongly three-dimensional, and an extensive set of mean-flow measurements and flow-visualization results is available from previous studies. Also, this flow is encountered in many practical engineering situations such as the appendage-body junctions on aircraft, ships and submarines as well the support columns of structures standing on river and ocean beds.

The overall features of the test flow are well known from previous studies (Ölçmen, 1990; Devenport and Simpson, 1989, 1990; Flemming et al. 1991, 1993; Ailinger, 1990). In the plane of symmetry of the wing, the approach flow is strongly affected by the adverse pressure gradient produced by the wing and eventually separates from the test floor at 0.47T (T = maximum wing thickness = 71.7 mm) upstream of the nose. This forms a recirculating region near the nose of the wing with intense backflow and pressure fluctuations. In the vicinity of this region, the turbulent stresses are much larger than those normally observed in turbulent boundary layers (Devenport and Simpson, 1990). Histograms of velocity fluctuations in this region are double-peaked, indicating that the flow has a bimodal structure (Devenport and Simpson, 1990). This bimodal structure extends to the pressure fluctuations on the wall which also exhibit double-peaked histograms (Rife et al. 1992). Outside the plane of symmetry, the flow is deflected away from the wing in the spanwise direction by the pressure gradient imposed on it by the presence of the wing. The flow in the inner region of the boundary layer, being less energetic, is deflected at a greater
angle than the flow in the outer region, resulting in a varying flow direction through the boundary layer. The spanwise vorticity in the approach boundary layer wraps around the wing and forms a "horseshoe" vortex with trailing legs stretching downstream in the streamwise direction. The boundary layer on the surface of the wing separates near the trailing edge and forms a characteristic "fish tail" wake behind the wing (Fig 3). The entire flow field is dominated by the pressure field imposed by the presence of the wing and the velocity field induced by the horseshoe vortex around the wing.

Unlike two-dimensional boundary layers, the mean-velocity profiles in three-dimensional boundary layers do not collapse onto a single profile under the familiar Coles (1956) "Law of the Wake". Ölçmen (1990, 1992) tested a number of "Law of the Wall" models with a selected experimental database of three-dimensional flows, including the wing-body junction flow, and concluded that the mean-velocity profiles were best described by Johnston's (1960) model. Ölçmen (1990, 1993b) also examined the anisotropy constant and Townsend structural parameter, and tested a number of algebraic eddy viscosity models. The anisotropy "constant" was found to be variable and generally less than its normally assumed value of 1, indicating that the eddy viscosities in the X-Y and Y-Z planes were not equal. Consistent with this result, Ölçmen observed that the shear-stress angle in the flow lagged behind the flow-gradient angle in general. The Townsend structural parameter was also found to be variable and generally less than its normally assumed value of 0.15, indicating a non-linear relationship between the turbulent kinetic energy (TKE) and the turbulent shear stresses in the flow.

The overall objective of the present study was to obtain quantitative information on the existence, behavior and role of coherent structures in the three-dimensional turbulent boundary layer formed around the wing-body junction. The specific objectives were:

1. to examine the length scales of the flow structure in the vertical and spanwise directions
through multiple-point velocity measurements with a 16-sensor hot-wire rake.

2. to examine the convective wave speed and direction of motion of the coherent structures in the boundary layer through the use of a parallel-sensor hot-wire probe.

3. to examine the near-wall flow structure with regards to the spanwise spacing of the low-speed streaks and the direction of motion of the near-wall coherent structures.

4. to examine the spectral characteristics of the flow in terms of power spectra and coherence functions.
2 EXPERIMENTAL APPARATUS AND TECHNIQUE

2.1 INTRODUCTION

The experimental investigation of a three-dimensional turbulent boundary layer in the present study involved measurements with a variety of multiple-sensor hot-wire/hot-film probes in a wing-body junction flow. The flow was generated by mounting a wing in the test section at a zero angle of attack and zero sweep on the test floor. All the measurements were conducted at a nominal test speed of 27 m/s. At 0.75 chord lengths upstream of the model, the momentum-thickness Reynolds number was approximately $Re_\theta = 5936$ (Ölçmen, 1990).

Two distinct coordinate systems were used in the definition of measurement locations and the presentation of results. All measurement locations are specified by the wind-tunnel coordinate system which is defined as having the X axis parallel to the wind-tunnel axis and positive in the downstream direction, the Y axis normal to the test wall and positive in the direction away from the wall, and the Z direction in the transverse direction such that it completes a right-handed system. The origin of the wind-tunnel coordinate system is located at the junction between the leading edge of the wing and the test-section floor. The free-stream coordinate system which is used to define velocity components has its Y axis coincident with the wind-tunnel coordinate system but is rotated about the Y axis such that its X axis is parallel to the local free-stream velocity vector. The Z axis then completes a right-handed system. The relationship between the two coordinate systems is shown in Fig 4. Henceforth, the wind-tunnel coordinate system will be
identified as (X_r, Y_r, Z_r) and the free-stream coordinate system will be identified as (X, Y, Z). Velocity components will be identified as (U, V, W) and are defined in the free-stream coordinate system unless otherwise stated.

In addition, the cross-correlation and coherency results for the traversable wall-sensor measurements will be presented in terms of the spanwise coordinate of the wall shear-stress coordinate system, which is defined as having its X coordinate parallel to the local wall shear-stress vector in the X-Z plane, its Y coordinate normal to the wall and its Z coordinate completing a right-handed system. The wall shear-stress coordinate system is identified as (X_w, Y_w, Z_w) in Fig 4. The spacing of the sensors in the Z direction of this coordinate system will be denoted as ΔZ_w.

The coherency results for the parallel-sensor probe measurements are presented in terms of the angle β - β_{fs}, where β is the angle measured from the X axis of the wind-tunnel coordinates positive in the anti-clockwise direction when viewed from a plan view. β_{fs} (Fig 4) is the angle of the X axis relative to the X_r axis of the wind-tunnel coordinate system.

For the present study, the measurement locations were chosen to correspond to the LDV locations #0 - #6 on the right-hand side of the wing in Ölçmen's (1990) data set (Fig 5). Henceforth, these locations will be referred to as stations #0 - #6 starting from the most upstream location. The positions of the measurement stations in the X-Z plane are given in Table 1a. As was explained by Ölçmen (1990), these stations are located along a line which is tangent to the velocity vector in the X-Z plane at the Y location where \( \overline{u'^2} \) is maximum. These positions were chosen to study the effect of the turbulent kinetic energy on the flow characteristics since most of the turbulent kinetic energy in the flow is contained in the \( \overline{u'^2} \) fluctuations. The important flow parameters at the measurement stations obtained by Ölçmen (1990) and Atlinger (1990) are given in Table 1b.
2.2 TEST FACILITY AND EQUIPMENT

2.2.1 THE WIND TUNNEL

All the measurements were carried out in the Virginia Tech boundary-layer tunnel (Fig 6). The wind tunnel is an open-circuit design with a centrifugal blower that is driven by an 18.64 kW (25 horsepower) constant-speed a.c. motor. The air from the blower enters the test section after passing through a fixed-setting damper, a plenum, a honeycomb, seven screens and a 4:1 contraction ratio. The test section is 8 m long and has a rectangular cross section of 0.91 m x 0.27 m. The roof of the test section is adjustable to vary the streamwise pressure gradient within the test section. A two-axis ($Y_T-Z_T$) motorized traverse located above the roof of the test section was used to position the probes in the $Y_T-Z_T$ plane for some of the measurements.

At the nominal test speed of 27 m/s, the potential core of the test-section flow is uniform to within 0.5% in the spanwise direction and 1% in the vertical direction with a turbulence intensity of 0.1% (Devenport & Simpson, 1990). The flow entering the test section was tripped by a 6.3 mm high step at the leading edge. The test-section roof was adjusted such that a nearly zero-pressure gradient, two-dimensional equilibrium boundary layer was produced on the test-section floor in the absence of the wing. This two-dimensional boundary layer has been investigated by Ahn (1986) who found its mean structure and spectral characteristics to be closely similar to two-dimensional equilibrium, boundary layers studied by other researchers.

The wing was mounted at zero angle of attack and zero sweep on the test-section floor 3.02 m downstream of the leading edge. A gap of 37 mm was left between the top of the wing and the test-section roof to prevent the formation of a second junction vortex which might have interfered with the primary flow of interest on the test-section floor. The blockage effect of the wing was minimized by using inserts attached to the test-section side walls that simulated the
inviscid streamlines produced by the wing in an infinite stream.

2.2.2 THE WING

The wing is cylindrical and has an airfoil section which consists of a 3:2 semi-elliptic nose joined to a NACA 0020 tail at their respective maximum widths with the major axis of the ellipse aligned with the centerline of the tail section. It was constructed from aluminum and has a chord, span and maximum thickness of 300 mm, 229 mm and 71.7 mm, respectively. A 6.35 mm wide strip of sandpaper was attached to both surfaces of the wing 38.1 mm downstream of the leading edge to trip the boundary layer and ensure transition to turbulent flow.

2.3 SENSORS AND INSTRUMENTATION

2.3.1 HOT-WIRE RAKE

A custom made hot-wire rake with 16 hot-wire sensors spaced approximately logarithmically over 25.4 mm (1 inch) (Fig 7) was used to obtain simultaneous streamwise velocity measurements over approximately 0.7 boundary-layer thicknesses at each station. The sensors of the rake were constructed from platinum-iridium wire with lengths and diameters of approximately 2.78 mm and 5 μm, respectively. The ends of the sensors were gold-plated to minimize prong interference, leaving an effective sensing length of approximately 1.2 mm. The sensors were numbered 1 to 16 starting with the sensor at the bottom of the rake (i.e. nearest to the wall). The position of each sensor relative to sensor #1 is given in Table 2. The measurement plane of the hot-wire rake is defined as the plane passing through the center of each sensor and normal to all the sensors.
2.3.2 SLANT-WIRE PROBE

A TSI model 1273-T1.5 slant-wire probe was used to obtain data at a location upstream of the rake. The slant-wire probe was chosen because it could be mounted with the probe body angled to direct its wake away from the rake (Fig 13) thereby avoiding the problem of flow interference. The slant-wire probe has an unplated platinum-tungsten sensor mounted at an angle of 45° to the probe axis with a sensing length of 1.54 mm.

2.3.3 PARALLEL-SENSOR PROBE

A TSI model 1244BS-T1.5 parallel-sensor probe was used to measure the angular variation of the coherence function and convective wave speed in the boundary layer. The probe has two parallel unplated platinum-tungsten sensors with a spacing of 4.81 mm between them (Fig 8). The sensing length of each sensor is 1.25 mm. The sensors are each normal to the probe axis and are offset on opposite sides of the probe axis such that the probe axis passes through the midpoint of the measurement axis. The measurement axis of the probe is defined by the line that passes through the centers of the two sensors.

2.3.4 ROTATABLE WALL-SENSOR PROBE

The directional characteristics of the near-wall flow were investigated using a custom-made probe to position two hot-film sensors with a fixed spacing flush with the wall. The design of the probe is shown in Fig 9. The sensors are located on the ends of two quartz rods which serve as the substrate and contain the leads. Each sensor has a diameter of approximately 1.5 mm. The rods are fitted onto a cylindrical plexiglass plug such that the sensors are equally offset on opposite sides of the centerline of the plug with a spacing of 6.93 mm between them. The plug in turn rotates within an aluminum sleeve, allowing the orientation of the measurement axis
(defined as the line passing through the centers of the two sensors) to be varied. A vernier mechanism was designed to allow the angular position of the measurement axis to be adjusted in steps of 5°. The adjustment is carried out in discrete steps by matching a set of holes drilled at 45° intervals on the edge of the plexiglass plug with another set of holes drilled at 40° intervals on the aluminum sleeve. The sensors were constructed by depositing a drop of type A3788 platinum paint from ENGELHARD INDUSTRIES onto the leads and subsequently curing the paint by passing a 50 mA current through the leads till there was no further change in the resistance of the paint. The sensors were designed for a nominal resistance of approximately 5 ohms and the final resistance was adjusted by depositing additional layers of platinum if the initial resistance was too high and removing some platinum with a razor blade if the initial resistance was too low.

2.3.5 TRAVERSABLE WALL-SENSOR PROBE

A custom-made probe (Simpson et al., 1977) designed to position two hot-film sensors flush with the wall was used to examine the spanwise structure of the near-wall flow. The design of the probe is shown in Fig 10. The body of the probe consists of two parallel rectangular quartz plates with a quartz slider between them. The slider and one of the plates serve as the substrate for two platinum hot-film sensors, each with a sensing diameter of approximately 0.5 mm. The position of the sensor on the slider relative to the one on the plate may be varied by moving the slider which is driven by a lead screw with a pitch of 1.27 mm (0.05 inches). The lead screw in turn is adjusted by a knob with 25 circumferential divisions giving a final linear resolution of 0.051 mm (0.002 inches) for the slider. The construction of the sensors was performed in an identical manner to those of the rotatable wall-sensor probe.
2.3.6 HOT-WIRE ANEMOMETERS AND ELECTRONICS

Overheat for the hot-wire/hot-film sensors was provided by a ten-channel AA LAB SYSTEMS AN-1003 constant-temperature anemometer unit and six constant-temperature anemometers of the type designed by Miller (1976) and modified by Simpson et al. (1979). The modified Miller-type anemometers have a simple, low-noise, low thermal-drift design with a stable output even at low flow velocities. The frequency responses of all the anemometers were tested using the method described by Simpson et al. (1979). The AA LAB SYSTEM anemometers were flat up to 14 kHz while the modified Miller type anemometers were flat up to 10 kHz. A typical frequency-response curve is shown in Fig 11.

A schematic diagram of the electronic connections is shown in Fig 12. The AA-LAB SYSTEMS anemometers were equipped with built-in signal-conditioning amplifiers which enabled the output signals to be matched to the input range of the data-acquisition system in order to maximize the voltage resolution. The Miller-type anemometers were operated together with a set of custom-built buck and gain amplifiers which performed the same function. Each buck and gain amplifier had a flat frequency response (±3 dB) up to 20 kHz and was capable of a maximum gain of 100.

2.3.7 DATA ACQUISITION AND REDUCTION

Two microcomputer-based analog-to-digital (A/D) boards were used to acquire the data for the measurements. For the vertical and horizontal hot-wire rake measurements, an RC ELECTRONICS ISC-16 A/D board was used. The ISC-16 board has 16 channels with a 12-bit (4096 step) digitization resolution over a fixed input range of ±10 V giving a voltage resolution of 4.883 mV. The maximum sampling rate per channel is 62.5 kHz. An ANALOGIC A/D board was used for all measurements other than the vertical and horizontal hot-wire rake measurements.
The ANALOGIC board has 16 channels with a 16-bit (65536 step) digitization resolution over an adjustable input-voltage range. The input-voltage range was set to ±10 V which provided a voltage resolution of 0.305 mV.

Both data-acquisition boards were operated with a 6 MHz IBM AT microcomputer. A 940 MB PANASONIC WORM (Write Once, Read Many) optical disk drive was connected to the computer for mass storage of the data. The hardware was controlled by data-acquisition programs written in C which were designed to transfer the data from the computer's buffer memory to the optical disk in the shortest possible time. All the data were acquired in real-time at a sampling rate of 25 kHz in segments of 4096 points for each channel. For each measurement, 125 data segments were acquired for each channel producing a total record length of 20.475 s with 512000 samples.

Reduction of the raw data was subsequently performed off-line on an IBM RT workstation and a 33 MHz 80486 based microcomputer using data-reduction programs written in FORTRAN. Spectral results were calculated utilizing the Fast Fourier Transform (FFT) subroutines given in Newland (1984) and Press et al. (1990).

2.4 EXPERIMENTAL TECHNIQUE

2.4.1 VERTICAL HOT-WIRE RAKE MEASUREMENTS

Measurements were performed at each station with the hot-wire rake positioned with its measurement plane vertical (Fig 13). The rake was aligned such that its sensors were normal to the local free-stream velocity as measured by Ölçimen (1990). In this position, each sensor was sensitive mainly to the U and V components of velocity with a negligibly small degree of sensitivity to the W component (Jorgensen, 1971). Based on Ölçimen's data, W is never more than
0.4\(U\) for the stations examined here; \(W\) is less than 0.177\(U\) for all but the sensor nearest to the wall. Since \(V\) is much smaller than \(U\) in boundary-layer flows, it was assumed that the output of the sensors represented only the local \(U\) component of velocity.

All the hot-wire sensors were operated at an overheat ratio of 0.7. The \(Y\) location of the rake was adjusted such that the bottom sensor (#1) was approximately 0.5 mm above the wall. The slant-wire probe was positioned approximately 6 mm upstream of the rake and data were acquired from both the rake and the slant-wire probe simultaneously. Four sets of data were acquired at each station with the \(Y\) location of the slant-wire sensor adjusted to match sensors #2, #3, #4 and #5 of the rake. The \(Y\) locations of sensor #1 of the rake (\(\Delta Y_r\)) and the positions of the slant-wire sensor relative to sensor #1 of the rake (\(\Delta X_u, \Delta Y_u, \Delta Z_u\)) are summarized in Tables 3a and 3b, respectively, and the test conditions are given in Table 4.

Prior to each measurement, the rake and slant-wire probe were calibrated against a pitot-static tube in the potential core of the test section with the model removed. The dynamic pressure sensed by the pitot-static tube was measured by an inclined manometer with a resolution of 0.01 inches of water. The value of the constants \(A\), \(B\) and \(n\) for each sensor in the hot-wire transfer function \(E^2 = A + BU^n\), where \(E\) and \(U\) are the output voltage and flow velocity, respectively, were determined by performing a least-squares regression on the calibration data. Any set of calibration constants which had a regression coefficient of less than 0.999 for any of the sensors was discarded and the calibration was repeated until a regression coefficient greater than 0.999 for all the sensors was achieved.

### 2.4.2 HORIZONTAL HOT-WIRE RAKE MEASUREMENTS

Measurements were performed with the measurement plane of the hot-wire rake positioned parallel to the wall and the sensors of the rake normal to the local \(X\) axis (Fig 14). This position
of the rake was chosen to provide simultaneous velocity measurements over a span of 25.4 mm in the local Z direction. Sensor #10 of the rake was centered on each station in the $X_T-Z_T$ plane and a profile of ten measurements over the thickness of the boundary layer was taken. The Y locations of the rake in the profile and the test conditions are given in Tables 5 and 6, respectively. All sensors were operated at an overheat ratio of 0.7 and calibration of the rake was performed in an identical manner to the vertical hot-wire rake measurements.

2.4.3 PARALLEL-SENSOR PROBE MEASUREMENTS

Parallel-sensor probe measurements were made at each station in order to investigate the directional characteristics of the coherent motion in the flow (Fig 15). The probe was inserted vertically through the roof of the test section in order to position its measurement axis horizontally. Twelve sets of data were acquired at each location corresponding to 12 angular positions of the probe measurement axis at each of ten Y locations. A worm-gear driven angular traverse with a 0.15° resolution was used to vary the angular position of the measurement axis between $\beta_{fs} - 10°$ to $\beta_{fs} + 45°$ in steps of 5°. The Y locations of the sensors in the profile at each station and the test conditions are given in Tables 7 and 8, respectively.

Both sensors of the probe were operated at an overheat ratio of 0.7. The probe was calibrated in the potential core of the test section prior to each measurement using the same procedure that was used to calibrate the rake. The sensors were calibrated one at a time in order to prevent the thermal wake of the upstream sensor from interfering with the calibration of the downstream sensor.
2.4.4 ROTATABLE WALL-SENSOR MEASUREMENTS

Measurements were conducted at stations #1, #4 and #6 with the rotatable wall-sensor probe (Fig. 16) in order to investigate the directional characteristics of the near-wall flow in the same way that the parallel-sensor probe was used in the rest of the boundary layer. The test conditions for these measurements are given in Table 9. The probe was mounted through a circular hole in the wall to position the sensors flush with the wall. Twelve sets of data were acquired at each location with the angular position of the probe measurement axis varied between $\beta_{PS} - 10^\circ$ and $\beta_{PS} + 45^\circ$ in steps of $5^\circ$. Both sensors were operated at an overheat ratio of 0.05.

The calibration of the wall-mounted hot-film sensors required a different procedure from the hot-wire rake. The transfer function of a wall-mounted sensor is:

$$E^2 = A + B \tau_{w}^{1/3}$$  \hspace{1cm} (2.1)

and a conventional calibration would have required a flow with a known and controllable value of $\tau_{w}$ which is difficult to achieve. Instead, the sensors were calibrated over the range of the turbulent $\tau_{w}^{i}$ fluctuations by using a histogram-matching algorithm. A reference histogram of $(\tau_{w}^{i})^{1/3}$ at each measurement location was first constructed using Ölçmen’s (1990) LDV data of the $u$ velocity component fluctuations in the near-wall region of the flow and assuming a linear velocity profile in the viscous sublayer. A histogram of $E^2$ was also constructed for each sensor from the measured output voltage. For any given values of the constants A and B, eqn (2.1) could then be used to construct a measured $(\tau_{w}^{i})^{1/3}$ histogram. Obviously, the mean and standard deviation of such a measured $(\tau_{w}^{i})^{1/3}$ histogram would be functions of A and B. The constants A and B for each sensor were then determined by forcing the mean and standard deviation of the measured $(\tau_{w}^{i})^{1/3}$ histogram to match their respective values in the reference $(\tau_{w}^{i})^{1/3}$ histogram. A typical set of calibration histograms is shown in Fig. 17.
2.4.5 TRAVERSABLE WALL-SENSOR MEASUREMENTS

Measurements were made at stations #1, #4 and #6 with the traversable wall-sensor probe (Fig 18) in order to examine the spanwise structure of the near-wall flow. The test conditions are given in Table 10. The probe was inserted through a rectangular hole in the test floor at each station such that the sensors were flush with the wall. The fixed sensor was centered on the chosen measurement station and the probe was oriented such that the movable sensor traversed away from the wing normal to the direction of the local wall shear stress measured by Ailinger (1990). Data were acquired with the movable sensor traversed between $\Delta Z_w = 0$ mm and $\Delta Z_w = -5.08$ mm in steps of 0.051 mm, where $\Delta Z_w$ is the distance between the sensors. Both sensors were operated at an overheat of 0.05.

The traversable wall sensors were calibrated using the same histogram-matching method that was used to calibrate the rotatable wall sensors.
3 SIGNAL PROCESSING AND DATA REDUCTION

3.1 REVIEW OF SIGNAL-PROCESSING CONCEPTS

Some time and frequency-domain signal-processing concepts used in the present study will be briefly reviewed here. A more extensive discussion can be found in Bendat and Piersol (1986).

The complex Fourier Transform of a time-dependent signal \( x(t) \) of finite record length \( T \) is defined as:

\[
X(f) = \int_{0}^{T} x(t) e^{-2\pi j f t} dt
\]  

(3.1)

The power spectrum of \( x(t) \) is then given by:

\[
G_x(f) = \frac{1}{T} XX^* 
\]  

(3.2)

where \( X^* \) is the complex conjugate of \( X \). The power spectrum represents the frequency distribution of \( \overline{x(t)^2} \) and satisfies:

\[
\overline{x(t)^2} = \int_{-\infty}^{\infty} G_x(f) df
\]  

(3.3)

The cross spectrum between two time-dependent signals \( x(t) \) and \( y(t) \) is defined as:

\[
G_{xy}(f) = \frac{1}{T} XY^* 
\]  

(3.4)

\( G_{xy}(f) \) is complex in general. Its magnitude at each frequency is the product of the amplitudes of
the harmonics of \( x(t) \) and \( y(t) \) at that frequency and its argument represents the phase shift of the harmonic of \( x(t) \) relative to that of \( y(t) \).

The coherence function between \( x(t) \) and \( y(t) \) is defined as:

\[
\gamma^2(f) = \frac{\frac{1}{N_e} \sum G_{xy} \frac{1}{N_e} \sum G_{xx}}{\frac{1}{N_e} \sum G_{xx} \frac{1}{N_e} \sum G_{yy}}
\]

(3.5)

where the summation is taken over \( N_e \) ensemble realizations of the signals. The coherence function represents a normalized measure of the correlation between the spectral components of \( x(t) \) and \( y(t) \) at each frequency with the biasing effect of phase removed and it can be shown that \( \gamma^2(f) \) represents the square of the correlation coefficient between the two signals at frequency \( f \) (Rood, 1984). The value of \( \gamma^2(f) \) ranges from 0 (no correlation) to 1 (perfect positive or negative correlation). However, a critical value of \( \gamma^2(f) \) for two spectral components to be considered statistically correlated is 0.27 (Bendat and Piersol, 1986). At this value of \( \gamma^2(f) \), an ensemble average of 125 data records (as is the case with the present set of measurements) would have a finite sample size error of \( \Delta \gamma^2 = 0.094 \). \( \gamma^2(f) \) is a more useful measure of the relationship between two signals than the conventional long time-averaged cross-correlation coefficient defined as:

\[
R_{xy} = \frac{x(t) y(t)}{\sqrt{x(t)^2 y(t)^2}}
\]

(3.6)

as it reveals the spectral characteristics of the relationship as opposed to being an integrated result over all frequencies as is the case with \( R_{xy} \).

If \( x(t) \) and \( y(t) \) represent the velocities at two locations in a turbulent flow, then \( \gamma^2 \) will be a function of the spacing \( s \) between the two locations, i.e. \( \gamma^2 = \gamma^2(f,s) \). This leads to the
definition of a coherence length scale \( L_\alpha(f) \) as follows:

\[
\gamma^2(f, L_\alpha(f)) = 0.27
\]

(3.7)
i.e. \( L_\alpha \) is the spacing at which the coherence function between the velocity components at frequency \( f \) is equal to the critical value. \( L_\alpha(f) \) is thus a measure of the size of the various frequency motions in the flow.

### 3.2 HOT-WIRE RAKE DATA REDUCTION

The vertical hot-wire rake data were first processed to extract the mean and mean-squared velocity profiles so that a check could be made against the LDV profiles measured by Ölçmen (1990) at the same stations. The mean and mean-squared velocity at each sensor location was calculated by averaging over 512000 data samples. The power spectrum of the \( u \) velocity fluctuations measured by each sensor was calculated for each data segment of 4096 points and then ensemble averaged over the 125 segments to produce the final results. Paired sample results such as cross-spectra and phase shifts were calculated for every possible combination of two sensors out of the 16 in a similar manner. The coherency results were calculated by applying eqn (3.5) to the harmonic at each frequency over the 125 data segments. At the sampling frequency used to acquire the data (25 kHz), a frequency resolution of 6.1 Hz was obtained for all the spectral results.

For the hot-wire rake measurements, the coherence length scale "measured" by a particular sensor is defined as the length scale calculated from the spatial variation of the coherency between the \( u \) velocity fluctuations measured by that particular sensor and the other sensors of the rake. Figure 19a illustrates the "inner" coherence length scale \( (L_{\alpha u}) \) "measured" by sensor #1 in the inner
region of the boundary layer looking up towards the boundary layer edge. Similarly, an "outer" coherence length scale is "measured" by sensor #16 in the outer region of the boundary layer looking down towards the wall. For sensors in the interior of the rake, the coherence length scale obtained from the spatial variation of coherency upwards towards the edge of the boundary layer is termed the "upper" coherence length scale ($L_{u\omega}$).

The horizontal hot-wire rake data were processed in an similar manner to the vertical hot-wire rake data. However, the spanwise coherence length scale was defined differently from the length scales in the vertical rake measurements. Only the length scale "measured" by sensor #10 was calculated since that was the sensor that was centered on each measurement station. The spanwise coherence length scale ($L_{u\varphi}$) was defined as the sum of the length scales obtained from the spatial variation of coherency on both sides of the sensor (Fig 19b).

3.3 PARALLEL-SENSOR PROBE DATA REDUCTION

At each angular position of the probe measurement axis, the power spectrum of each channel and cross spectrum and phase shift between the two channels were calculated for each data segment and then ensemble averaged over 125 segments to produce the final results. The coherency between the $u$ fluctuations measured at each sensor location was calculated by applying eqn (3.5) to the cross and power spectra calculated for each of the data segments. The convective wave speed at each frequency was calculated using the method of Stegen and Van Atta (1970) where:

$$U_c(f) = \frac{2\pi f \Delta s}{\Phi(f)}$$  \hspace{1cm} (3.8)
The data from the upstream sensor was also processed to determine the intermittency at the three outermost Y locations at each station corresponding approximately to $Y/\delta = 0.5, 0.7, 1.1$. The intermittency was calculated using the algorithm described by Hedley and Keffer (1974a) which uses the high-frequency content of the turbulent fluid to distinguish it from the non-turbulent fluid. The signal is first differentiated with respect to time to amplify its high-frequency component and squared to rectify it. A moving-average smoothing window is then applied to separate the turbulent/non-turbulent switching component of the signal from the turbulent fluctuations. Finally, the signal is passed through a Schmitt trigger to produce an indicator function which indicates the turbulent/non-turbulent state of the fluid. The intermittency is then calculated by time-averaging the indicator function.

The intermittency detection algorithm contained two adjustable parameters (smoothing-window width and Schmitt-trigger level) which were determined by comparing the intermittency profile at station 0 (where the flow is nearly two-dimensional) with the results of Klebanoff (1955) and Corrsin and Kistler (1954) for two-dimensional boundary layers. Once determined, the same parameter values were used at all Y locations.

### 3.4 WALL-SENSOR DATA REDUCTION

For the traversable wall-sensor probe measurements, the long time-averaged cross-correlation coefficient and the coherence function between the fixed sensor and the movable sensor were obtained as a function of the sensor spacing by calculating the values for each data segment and then ensemble averaging over 125 segments to get the final result.

The modified u-level burst-detection algorithm described by Luchik and Tiederman (1987)
was applied to the signals from both the sensors to detect the ejections in the near-wall region and measure the mean ejection frequency. This algorithm was found by Luchik and Tiederman to give good agreement with flow-visualization results. For the modified u-level burst-detection algorithm, the detector function is turned on (i.e. an ejection is occurring) when

$$u < -L\sqrt{u^2}$$  \hspace{1cm} (3.9)

and turned off when

$$u \geq -0.25L\sqrt{u^2}$$  \hspace{1cm} (3.10)

Luchik and Tiederman recommended $0.5 < L < 1.25$ and $L = 0.75$ was used for the present study.

### 3.5 UNCERTAINTY ANALYSIS

In the following analysis, the uncertainty of a function of many variables is estimated using the method described by Kline and McClintock (1953) which is as follows: If $Q$ is a function of $n$ variables of the form:

$$Q = Q(x_1, x_2, ... x_n)$$  \hspace{1cm} (3.11)

and the uncertainties in $x_1, x_2, ... x_n$ are $\Delta x_1, \Delta x_2, ... \Delta x_n$, respectively, at the same odds, then the uncertainty in $Q$ is given by:

$$\Delta Q = \sqrt{\left(\frac{\partial Q}{\partial x_1}\right)^2\Delta x_1^2 + \left(\frac{\partial Q}{\partial x_2}\right)^2\Delta x_2^2 + ... + \left(\frac{\partial Q}{\partial x_n}\right)^2\Delta x_n^2}$$  \hspace{1cm} (3.12)

In estimating the uncertainties in the mean and mean-squared velocities, two distinct contributions had to be accounted for. The first contribution to the uncertainty was the finite
sample size of data which was used to compute the results and the second contribution was the random error in the calibration of the hot-wire/hot-film anemometers. The uncertainty due to the finite sample size was estimated using the standard formulas for the sampling distribution of a normally distributed random variable given in Bendat and Piersol (1986). In order to estimate the uncertainty due to the random error in the calibration, the uncertainty in each individual sample of the instantaneous velocity was first estimated from the calibration data using the method described in Doeblin (1990). The uncertainty in the mean and mean-squared velocities were then obtained by applying eqn (3.12).

The total uncertainty in the mean velocity was finally obtained as:

$$\Delta U = \frac{Z_{\alpha/2} \sqrt{\mu^2}}{\sqrt{N}} + \frac{Z_{\alpha/2} S_{U} p U^{(p-1)p}}{\sqrt{N}}$$  \hspace{1cm} (3.13)

and the total uncertainty in the mean-squared velocity was:

$$\Delta \mu^2 = \frac{N - 1}{\chi^2_{N-1,1-\alpha/2}} \mu^2 + \frac{2Z_{\alpha/2} \sqrt{\mu^2} S_{U} p U^{(p-1)p}}{\sqrt{N}}$$  \hspace{1cm} (3.14)

where $Z_{\alpha/2}$ is the standardized normal random variable for a $100(1 - \alpha)\%$ confidence interval, $N$ is the number of samples, $m = N - 1$, $p = 1/n$ ($n =$ exponent in hot-wire calibration equation) and $S_{U}$ is the variance of the calibration data from the linearized calibration equation given by:

$$S_{U}^2 = \frac{1}{N} \sum \left( \frac{E_i - A_i}{B_i} - U_i \right)^2$$  \hspace{1cm} (3.15)

The first and second terms on the right-hand sides of eqns (3.13) and (3.14) represent the contributions due to the finite sample size and random error in the calibration, respectively. $\Delta U$ and $\Delta \mu^2$ were evaluated for a 95% confidence interval in the near-wall, logarithmic and outer
regions of the boundary layer at each measurement station and subsequently averaged over all the stations. The maximum values obtained in each region are shown in Table 11 normalized on $U_{ref}$.

Table 11 also shows the ratio of the finite sample-size uncertainty to the calibration random-error uncertainty. It can be seen that the calibration random-error uncertainty is more than an order of magnitude smaller than the finite sample-size uncertainty and as such it was neglected in the subsequent uncertainty analysis of the spectral results.

The uncertainties in the spectral results were estimated using the formulas given in Bendat and Piersol (1986). The uncertainties in the coherence function, power spectrum, cross spectrum and phase shift are given by eqns (3.16), (3.17), (3.18) and (3.19), respectively:

\begin{align}
\Delta \gamma^2 &= \frac{Z_{a2} \sqrt{2} \gamma^2 (1 - \gamma^2)}{\gamma \sqrt{N_z}} \quad \text{(3.16)} \\
\Delta \Phi_{aw} &= \frac{Z_{a2} \Phi_{aw}}{\Delta f T} \quad \text{(3.17)} \\
\Delta \Phi_{ij} &= \frac{Z_{a2} \Phi_{ij}}{\gamma \sqrt{N_z}} \quad \text{(3.18)} \\
\Delta \Phi &= \frac{Z_{a2} \Phi (1 - \gamma^2)!}{\gamma \sqrt{2 N_z}} \quad \text{(3.19)}
\end{align}

The normalized 95% confidence intervals for the spectral results are given in Table 12.

The 95% confidence interval for the coherence length scale was estimated from:

\[ \Delta L_\gamma = \frac{\Delta \gamma_{0.27}}{|\frac{d\gamma^2}{ds}|} \quad \text{(3.20)} \]

where $s$ is the spatial separation and $\gamma_{0.27}^2$ is the 95% confidence interval in $\gamma^2$ at $\gamma^2 = 0.27$. A maximum value of $\Delta L_\gamma = 0.54$ mm was obtained using the experimental data to estimate $\frac{d\gamma^2}{ds}$.
The 95% confidence interval for the convective wave speed was estimated from:

$$\Delta U_c = \left| \frac{dU_c}{d\Phi} \right| \Delta \Phi$$  \hspace{1cm} (3.21)$$

with $U_c = \frac{2\pi f \Delta x}{\Phi}$ and $\left| \frac{dU_c}{d\Phi} \right| = \frac{2\pi f \Delta x}{\Phi^2}$ resulting in

$$\frac{\Delta U_c}{U_c} = \frac{\Delta \Phi}{\Phi}$$  \hspace{1cm} (3.22)$$
4 EXPERIMENTAL RESULTS

4.1 VERTICAL HOT-WIRERAKE RESULTS

4.1.1 MEAN AND MEAN-SQUARED VELOCITIES

The mean and mean-squared velocity profiles measured by the hot-wire rake are shown in Figs 20a, 20b and 21a, 21b, respectively. The profiles measured by Ölcmen (1990) with a LDV at the same locations have also been plotted for comparison. The mean-velocity profiles measured by the hot-wire rake follow the same general trend as the LDV profiles, showing an approximate logarithmic region in the middle and a wake region near the outer edge of the boundary layer. The mean-squared velocity profiles measured by the rake also follow the same general trend as the LDV profiles, showing the characteristic "S" shape at stations 4, 5 and 6, which is not found in two-dimensional boundary layers. However, the hot-wire rake profiles show a larger degree of scatter compared to the LDV profiles. For a substantial number of points, the difference between the LDV and hot-wire measurements appears to be larger than the uncertainties for the mean and mean-squared velocities given in Table 6. The scatter in the results is quite random and appears much like that caused by an insufficient number of data samples, i.e., finite sample-size error. However, that is unlikely to be the case as the present set of results was computed over a fairly large number of samples (512000) which resulted in the rather low uncertainties given in Table 6. As the scatter is larger than the known uncertainties, the results point to an unaccounted source of random error. A possible source of this error is vibration of the rake caused by flow
interference which was visually observed during the experiment. The flow interference experienced by the rake is more severe than that experienced by ordinary hot-wire probes because of its larger size and the presence of a flat plate behind the sensors (Fig 7). As the flow within the boundary layer is skewed relative to the local free-stream, it would have impinged on the flat plate at a non-zero angle of attack, thereby causing flow interference. There was no way of accounting for this effect in the calibration of the rake, since the angle at which the flow is skewed varies through the boundary layer.

4.1.2 POWER SPECTRA

The power spectrum of the u fluctuations measured by the rake at selected Y locations are shown in Figs 22a - 22g for stations 0 - 6, respectively, normalized with the outer scaling proposed by Perry, Lim and Henbest (1985). Figures 23a - 23g show the same power spectra normalized with the inner scaling proposed by the same authors. In these plots,

\[
\overline{u^2} = \int_0^\infty \Phi_\infty(f) \, df
\]

(4.1)

\[
\frac{\Phi_\infty U}{2\pi\delta} = \phi(k\delta)
\]

(4.2)

\[
\frac{\Phi_\infty U}{2\pi Y} = \phi(kY)
\]

(4.3)

where \(\phi(k\delta)\) and \(\phi(kY)\) represent the power spectrum given as a function of \(k\delta\) and \(kY\), respectively.

Except for the data from the Y location nearest to the wall, the normalization with inner scaling appears to collapse the data better in the high wave-number range. The region of collapse shows an approximate, but not strictly constant, -5/3 slope. Normalized with outer scaling, the spectra appear to collapse into two groups in the high wave-number range. The spectra from the

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three nearest Y locations to the wall up to approximately Y* = 300 collapse into one group and the spectra from the other Y locations further from the wall collapse into a second group. The region of collapse of the spectra from the first group again shows an approximate but not strictly constant -5/3 slope whereas the second group of spectra collapse into a region with a slope greater than -5/3. These results indicate that the spectral characteristics of the Y* < 300 region of the boundary layer are different from the those of the Y* < 300 region. For the first group of spectra within the Y* < 300 region, $\overline{u'^2}$ is not a strong function of Y. This means that dimensional plots of the spectra must collapse in the low wave-number range. On the other hand, the second group of spectra were obtained from the outer region of the boundary layer where $\overline{u'^2}$ varies strongly with Y.

These results are somewhat different from those obtained by Ahn (1986) for a two-dimensional boundary layer with $Re_\theta = 6428$ in the same facility. Normalized with outer scaling, the spectra obtained by Ahn showed a distinct $k^{-5/3}$ region away from the wall, corresponding to the inertial subrange discussed by Hinze (1975). Near the wall, Ahn's spectra showed a $k^{-1}$ region where a strong production of turbulence energy takes place (Klebanoff, 1954). Since the flow at station 0 is only weakly three dimensional, it is expected that the spectra obtained there would be quite similar to Ahn's results. However, Figs 22a and 23a clearly indicate that this is not the case. This would seem to indicate that three-dimensional effects are still significant at this station.

4.1.3 COHERENCY AND COHERENCE LENGTH SCALES

The spatial variation of the coherency between the upstream sensor and the hot-wire rake at selected frequencies are shown in Figs 24a - 24d for four Y locations of the upstream sensor at station 3. The results at the other stations were very similar and the overall trends were not noticeably affected by the increasing three dimensionality of the flow further downstream. The
Y' locations of the upstream sensor in Figs 24a, 24b, 24c, 24d are 109, 174, 241 and 306, respectively, which correspond to the region of the boundary layer populated mainly by transverse vortices (Robinson, 1989b). These coherency results reflect the extent of flow structures in the Y direction at the position of the rake after they have registered on the upstream sensor. For all Y locations of the upstream sensor, the maximum coherency at all frequencies occurs at the rake sensor that has a common Y location (ΔY = 0) with the upstream sensor, i.e. the rake sensor that is directly downstream of the upstream sensor. This implies that the flow structures are convected downstream with no appreciable component of velocity normal to the wall. At all frequencies, the coherency decays with increasing ΔY in both the positive and negative directions. However, the rate of decay at low frequencies is noticeably smaller than at high frequencies, reflecting the greater extent of the larger structures in the Y direction.

In general, the levels of coherency at all frequencies and ΔY spacings shown in Figs 24a - 24d increase with the Y location of the upstream sensor, indicating an increase in the size and/or strength of the flow structures consistent with Clark and Markland's (1971) observation that the lifetimes of the transverse vortices increase with Y location and their diameters increase during their lifetimes. The greatest increase in the coherency occurs for fδ/U* > 0.276 (f > 200 Hz) at ΔY = 0.

Figures 25a - 25d show the spectral variation of the coherency between the upstream sensor and the rake at station 3 for the same Y locations of the upstream sensor that were shown in Figs 24a - 24d. With the frequency expressed on a logarithmic scale, a common feature of these results is a region of near-constant coherency at low frequencies indicating the existence of a range of structure sizes which are approximately equally correlated over the spatial separation of the two sensors. In order for the coherency to remain constant, the sizes of these structures must be equal to or larger than the spatial separation of the sensors. The upper frequency limit of this
constant coherency region is maximum when $\Delta Y = 0$ and decreases with increasing $\Delta Y$ as the structures at the smaller end of the range fall outside the increasing spatial separation. Beyond the near-constant coherency frequency range, the coherency falls rapidly with frequency at a constant slope until it reaches zero.

Once formed, coherent structures decay over a finite lifetime before they are destroyed. In the present test flow, an indication of the rate of decay of the structures may be obtained by comparing the coherence length scales "measured" by the upstream sensor and the rake sensor at the same $Y$ location. The length scale "measured" by the upstream sensor is related to the size of a typical structure after it has traveled a distance of $\Delta X_u$ downstream to the rake whereas the length scale "measured" by the rake sensor is related to the size of the structure as it registers simultaneously on several sensors of the rake. The difference between the two length scales is then an indication of the extent to which the size of the structure has decayed during its motion between the upstream sensor and the rake.

The "upper" coherence length scale ($L_{up}$) "measured" by the upstream sensor and the rake sensor at the same $Y$ location are shown in Figs 25a - 26g for stations 0 - 6, respectively, for two $Y$ locations of upstream sensor. The streamwise spacing between the upstream sensor and the rake is $\Delta X^* = 415, 315, 310, 351, 401, 415$ and 399 for stations 0 - 6, respectively. The length scales measured by both sensors at all frequencies appear to remain relatively constant between stations 0 and 3 but decrease significantly from stations 3 to 6. As discussed in chapter 3, the maximum uncertainty ($\Delta L_u$) in the coherence length scale is 0.54 mm, which translates into $\Delta L_u/\delta = 0.014$ for a typical $\delta$ of 39 mm. Except for $Y/\delta = 0.035$ at station 2 and $Y/\delta = 0.041$ at station 3, the difference between the two length scales are within the combined uncertainties (0.28) of the two measurements. The two exceptions appear to be anomalous results as the difference between the length scales remain nearly constant with frequency, implying that the structures of all sizes decay
equally over the given streamwise spacing, which is not physically realistic. The net conclusion is, therefore, that there is no appreciable decay in the structure size at all frequencies over the range of $\Delta X^*$ that was measured. This is consistent with Kline's (1992) conclusion from a survey of existing literature that transverse vortices persist for up to $\Delta X^* = 1000$, which is about two and a half times the largest $\Delta X^*$ spacing between the upstream sensor and the rake.

The spatial variation of the coherency between the $u$ velocity fluctuations measured by sensor #1 at the bottom of the hot-wire rake and the other sensors of the rake at selected frequencies are shown in Figs 27a - 27g for stations 0 - 6, respectively, and the corresponding results between sensor #16 at the top of the hot-wire rake and the other sensors of the rake are shown in Figs 28a - 28g for stations 0 - 6, respectively. For all stations, sensor #1 is at approximately $Y/\delta = 0.01$ and sensor #16 is at approximately $Y/\delta = 0.65$. The coherency at each frequency has been plotted with the $\Delta Y$ spacing normalized with the "inner" (Figs 27a - 27g) or "outer" (Figs 28a - 28g) coherence length scales at that frequency. As can be seen from Figs 27 and 28, this normalization appears to collapse the results at a given station at different frequencies onto one curve for the inner region and another for the outer region of the boundary layer particularly for the upstream stations. Note that even though the results for $\gamma^2 < 0.27$ may be statistically uncertain, they also collapse onto one curve. Thus we can say that, in general:

$$\gamma^2 = f(\Delta Y/L_\gamma)$$

(4.4)

At all frequencies, the function $f$ in eqn (4.4) is closely approximated by an exponential-decay function:

$$\gamma^2 = \exp(-k\Delta Y/L_\gamma)$$

(4.5)

which is represented by the solid lines in Figs 27 and 28 with the decay constants ($k$, and $k_\omega$)
determined by a least-squares fit.

The values of the decay constants are summarized in Table 13 and the regression coefficients of the least-squares fit are given in Table 14. Because the choice of the exponential-decay model is empirical, \( k_i \) and \( k_o \) are determined to a certain extent by the "goodness of fit" of the exponential-decay model equation (4.5). Since \( k_i \) and \( k_o \) were obtained by fitting eqn (4.5) to the results over the range of \( 0 < \Delta Y/L_{yo} < 4.5 \), they represent the average rate of decay of \( \gamma \) over this range. As \( k_i \) is generally smaller than \( k_o \), this would seem to indicate that the flow structures in the inner region are more coherent than the structures in the outer region. However, Figs 27 show that the inner region results for \( \Delta Y/L_{yi} < 1 \) generally fall about on or below the exponential least-squares fit, while Figs 28 show that \( \gamma^2 \) is above the exponential least-squares fit for \( \Delta Y/L_{yo} < 1 \). A direct comparison of the results for \( \Delta Y/L_{yo} < 1 \) shows that \( \gamma \) actually decays faster in the inner region than in the outer region. The results thus indicate that, relative to their coherence length scales, the structures in the outer region are more coherent in the \( Y \) direction for \( \Delta Y/L_{yi} < 1 \) than the structures in the inner region.

A typical set of results for the spectral variation of the coherency between the \( u \) velocity fluctuations measured by sensor \#1 and the rest of the hot-wire rake is shown in Fig 29a for station 3. The corresponding set of results for sensor \#16 at the same station is shown in Fig 29b. The results at the other stations are very similar and the overall trends are not noticeably affected by the increasing three dimensionality of the flow further downstream. In general, the results are similar to those obtained between the upstream sensor and the rake. As before, there is the near-constant coherency region at low frequencies, followed by a rapid fall of \( \gamma^2 \) with frequency in a constant-slope region. The similarity between the results for the upstream sensor and sensor \#1 is not surprising, bearing in mind that the length-scale results for the upstream and rake sensors indicate that there is very little change in the structures at the lower end of the rake as they move.
between the upstream sensor and the rake. The results for sensor #16 has a slightly greater bandwidth for the region of near-constant coherency but otherwise exhibits similar trends to those of sensor #1. However, the ΔY separation between adjacent sensors at the top of the rake near sensor #16 are bigger than those at the bottom, and the greater bandwidth of the near constant coherency region implies that, for a given frequency within the near-constant coherency bandwidth, the outer-region structures are highly correlated over a greater distance and hence larger than the inner-region structures near the bottom of the rake.

The spectral variation of the $L_y$ length scale "measured" by sensor #1 at all stations is shown in Fig 30a and the corresponding results for the $L_{yo}$ length scale "measured" by sensor #16 at all stations is shown in Fig 30b. For all stations, sensor #1 is at approximately $Y/\delta = 0.01$ and sensor #16 at approximately $Y/\delta = 0.65$. The regions on the abscissa marked "$f_e \delta/U_e$" and "$f_o \delta/U_e$" represent the ranges of the average near-wall ejection frequencies and the outer-region intermittency frequencies, respectively. The ejection frequencies ($f_e$) were measured by the traversable wall-sensor probe at stations 1, 4 and 6 and are discussed in Section 5.2 while the intermittency frequencies ($f_o$) were measured with the parallel-sensor probe at all stations and are discussed in Section 4.3.1.

The most striking feature of these results is that the $L_{yi}$ length scale exhibits a distinct reduction of up to 0.2δ at low frequencies as the flow becomes increasingly three dimensional moving from station 0 to station 6, whereas the $L_{yo}$ length scale seems to be affected to a much smaller extent. A possible explanation for the observed reduction of $L_{yi}$ in the inner region is that the structures are stretched in the spanwise (Z) direction by the increasing three dimensionality of the flow, thereby causing them to contract in the Y direction. Consistent with the present results, this effect would be greater in the near-wall region where the skewing of the flow is stronger than in the outer region where the skewing of the flow is weaker (Ölçmen, 1990).
Another possible explanation for the reduction of $L_{yi}$ is that the near-wall flow structures and the outer-region flow structures are convected from different regions upstream as the flow becomes increasingly three dimensional. Thus, they are less correlated and therefore have a lower Y coherence length scale.

It is interesting to note that the reduction of $L_{yi}$ as the flow moves downstream occurs in conjunction with a fall in the magnitude of the turbulent shear stresses (Ölçmen, 1990). From Fig 23a, it can be seen that the frequency range over which $L_{yi}$ is affected includes the average ejection frequencies. Bearing in mind that the near-wall ejections of low-speed streaks are responsible for the production of most of the turbulent shear stresses, it seems possible that there is a link between the simultaneous reduction of $L_{yi}$ and the magnitude of the turbulent shear stresses. A hypothesis which is consistent with the present results is that the ejections of the low-speed streaks in the near-wall region are triggered by the passage of larger structures above them. If the intensity of the ejections (and hence the magnitude of the turbulent shear stresses produced) depends on the size of the triggering structure, then a reduction in the structure size would cause a reduction in the magnitude of the turbulent shear stresses, in line with the present results.

### 4.1.4 PHASE RESULTS

The phase shift between adjacent sensors of the rake are shown in Figs 31a to 31g for stations 0 - 6, respectively. The set of plots in each figure represents a time-averaged profile of the structure front angle at each frequency. Except for the pair of sensors at the top of the rake, the general trend at all Y locations at all stations is for the phase measured by the lower sensor of each pair to lag behind that measured by the upper sensor with the lag increasing with frequency. This indicates that the front of the flow structures is slanted upwards so that the upper sensor of each pair registers the structure ahead of the lower sensor. Also, from the variation of
the phase with frequency, it can be inferred that the smaller structures are inclined at a greater angle than the larger structures. At high frequencies, the phase shift is the greatest for the lowest pair of sensors and decreases with increasing, Y indicating that the inclination of the eddies decreases with increasing Y.

4.2 HORIZONTAL HOT-WIRE RAKE RESULTS

4.2.1 MEAN VELOCITIES

The spanwise mean-velocity profiles measured by the rake are shown in Figs 32a - 32g for stations 0 - 6, respectively. The mean velocities here have been expressed in local free-stream coordinates. At stations 0 and 1, there is a small negative spanwise velocity gradient at all Y locations with the mean velocity increasing slightly in the negative $\Delta Z$ direction (away from the wing). Station 2 shows an almost zero spanwise velocity gradient at most Y locations, the exceptions being at the edge of the boundary layer where there is a small positive spanwise velocity gradient. Beginning at station 3, the profiles at all Y locations exhibit positive spanwise velocity gradients. The magnitudes of the positive spanwise velocity gradients reach their maximum values at stations 4 and 5 before falling somewhat at station 6. These results may be interpreted in terms of the mean-flow results from Ölçmen's (1990) study of the wing-body junction flow. Ölçmen's results indicates that the pressure gradient along the line connecting the measurement stations is positive between stations 0 and 2 and negative thereafter. The magnitude of the pressure gradient along a parallel line is greater closer to the wing than it is further away. As a result, the flow between stations 0 and 2, where the pressure gradient is positive, is retarded closer to the wing, resulting in a negative spanwise velocity gradient. Between stations 2 and 6,
the sign of the pressure gradient is reversed and the flow experiences a greater acceleration closer to the wing, resulting in a positive spanwise velocity gradient. The pressure gradient along the line of the measurement stations reaches its greatest negative value at stations 4 and 5, resulting in the relatively large positive spanwise velocity gradients observed at these two stations.

4.2.2 COHERENCY AND COHERENCE LENGTH SCALES

The spectral variation of the coherency between the u velocity fluctuations measured at several spanwise locations at station 0 is shown in Figs 33a and 33b for two selected Y locations. The results were nearly the same for the other stations and did not appear to be significantly affected by the three dimensionality of the flow as it moved downstream between station 0 and station 6. The results for the first two pairs of sensors adjacent to the measurement location (ΔZ/δ = ±0.053, ±0.105) show a high degree of symmetry, with the coherency being nearly equal over all frequencies. The variation of coherency with frequency is similar to that obtained for the vertical rake measurements with a region of near-constant coherency at low frequencies followed by a rapid fall in the coherency in a region of constant slope. The bandwidth of the near-constant coherency region increases with increasing Y. For larger ΔZ separations, the coherency falls with the magnitude of ΔZ. At any particular ΔZ separation, the coherency increases with Y at all frequencies.

A typical set of results for the spatial variation of coherency in the Z direction is shown in Figs 34a and 34b for station 3 at two selected Y locations, one near the wall, and the other in the outer region. The spanwise variation of γ² was quite symmetrical with respect to the sign of ΔZ, showing no noticeable effect of the three dimensionality of the flow. As was the case with the spatial variation of γ² in the Y direction, the results at different frequencies appear to collapse
onto a single curve when plotted against the spanwise spacing normalized on the coherence length scale (\(|\Delta Z|/L_{yz}\)). The solid lines in Figs 34a and 34b represent the function:

\[
\gamma^2 = \exp(-k_z |\Delta Z|/L_{yz})
\]  

(4.6)

where the decay constant \(k_z\) was determined through a least-squares fit of the experimental results. The values of \(k_z\) for all stations and Y locations are summarized in Table 15 and the regression coefficients of the least-squares fit are given in Table 16. The values of \(k_z\) are generally about twice as large as those of \(k_i\) and \(k_o\) obtained for the spatial variation of \(\gamma^2\) in the Y direction. This is a consequence of the difference in the definitions of \(L_{\gamma_i}\), \(L_{\gamma_o}\) and \(L_{yz}\). Because \(L_{yz}\) (Fig 19b) is a "two-sided" length scale while \(L_{\gamma_i}\) (Fig 19a) and \(L_{\gamma_o}\) are "single-sided" length scales, \(L_{yz}\) is generally larger than \(L_{\gamma_i}\) and \(L_{\gamma_o}\), thereby forcing \(k_z\) to be larger than \(k_i\) and \(k_o\) in eqns 4.4 and 4.5.

From Table 15, it can be seen that the maximum values of \(k_z\) do not occur at or near the edge of the boundary layer, but rather at Y locations 6, 7 and 8 which correspond approximately to the region \(0.3 < Y/\delta < 0.6\) (Table 5). The values of \(k_z\) near the edge of the boundary layer at \(Y/\delta \approx 0.8\) are consistently lower than those from the \(0.3 < Y/\delta < 0.6\) region.

The spanwise coherence length scales in free-stream coordinates (\(L_{yz}\)) are shown in Figs 35a - 35g for stations 0 - 6, respectively. As before, the arrows marked "\(f_e \delta/U_e\)" on the abscissa of Figs 35b, 35c and 35g represent the mean frequency of ejections near the wall at stations 1, 4 and 6, respectively. As was the case with \(L_{\gamma_i}\), the spanwise length scales appear to be reduced by the increasing three dimensionality of the flow. Away from the wall, the reduction of \(L_{yz}\) takes place downstream of station 1. Near the wall, however, \(L_{yz}\) does not show any change until the flow reaches downstream of station 3.
4.3 PARALLEL-SENSOR PROBE RESULTS

4.3.1 INTERMITTENCY RESULTS

The intermittency at the outer three Y locations of each measurement station was determined using an intermittency-detection algorithm based on the one described by Hedley and Keffer (1974a). The algorithm is illustrated in Figs 36a, 36b, 36c for $Y/\delta = 0.46, 0.72$ and 1.15, respectively, at station 0. From the normalized $u$ component of velocity, the algorithm computes successively the detector $[d(t)]$, criterion $[c(t)]$ and indicator $[s(t)]$ functions defined as:

$$d(t) = \left( \frac{\frac{d}{dt} \left( \frac{u(t)}{u_{rms}} \right)}{u_{rms}} \right)^2$$

(4.7)

$$c(t) = \frac{1}{2T_w} \int_{T_w}^{T} d(t) \, dt$$

(4.8)

$$s(t) = \begin{cases} 0 & c(t) < S_L \\ 1 & c(t) \geq S_L \end{cases}$$

(4.9)

The fluid is considered turbulent when $s(t) = 1$ and non-turbulent when $s(t) = 0$ and the intermittency $\beta$ is obtained by time averaging $s(t)$, i.e.:

$$\beta = \frac{1}{T_0} \int_{T_0}^{T} s(t) \, dt$$

(4.10)

The smoothing-window width $T_w$ and Schmitt-trigger level $S_L$ were calibrated by forcing the results at station 0, where the flow is nearly two dimensional, to match as closely as possible Klebanoff's (1955) results for a two-dimensional boundary layer.

The intermittency distribution across the outer half of the boundary layer is shown in Fig 37 for all the measurement stations. The solid line is a complementary error function which was fitted closely to the results using least-squares regression. Hedley and Keffer (1974b) found that a complementary error function matched their results rather well in a two-dimensional, zero
pressure gradient boundary layer. The complementary error function was also found to describe the earlier intermittency results of Klebanoff (1955) and Corrsin and Kistler (1955) rather well. Both of these earlier results were obtained for two-dimensional boundary layers. To the author’s knowledge, there is no previously reported result of intermittency measurements in three-dimensional boundary layers. From Fig 37, it can be seen that the present results are also quite well represented by a complementary error function. The standard deviation of the distribution is \( \sigma/\delta = 0.21 \) and the mean location of the boundary layer edge defined by \( \beta = 0.5 \) is \( Y/\delta = 0.85 \). Both these values are slightly higher than those reported by previous researchers for two-dimensional boundary layers (Table 17).

4.3.2 DIRECTIONAL CHARACTERISTICS OF COHERENT STRUCTURES

In a two-dimensional boundary layer, there is no mean motion in the spanwise direction (by definition) and the coherent structures are convected in the streamwise direction on the average. However, in the three-dimensional boundary layer of the present study, the flow is subjected to a spanwise pressure gradient imposed by the presence of the wing which can be expected to affect the direction of motion of the coherent structures. The spanwise pressure gradient in local free-stream coordinates (\( \partial P/\partial Z \)) increases between stations 0 and 3, reaching its peak positive value at station 3 after which it decreases to its peak negative value at station 6 (Table 1b). Ölçmen’s (1990, 1993b) study showed that this pressure gradient caused the local mean-velocity vector within the boundary layer to skew away from the wing at a greater angle than the local free-stream velocity vector. The difference in the directions of the mean-velocity vectors within the boundary layer and at the freestream was found to vary with \( Y \) location, with the maximum occurring near the wall in general. In addition, the velocity gradient and turbulent shear-stress vectors were also measured by Ölçmen and found to be different from each other and
a function of $Y$ location.

In order to study the effect of the spanwise pressure gradient on the motion of the coherent structures within the three-dimensional boundary layer of the wing-body junction flow, the angular variation of the coherency measured by the parallel-sensor probe was examined. The variation of the coherency at selected frequencies with the angular position of the measurement axis (Chapter 2) of the parallel-sensor probe at various $Y$ locations is shown in Figs 38 - 44 for stations 0 - 6, respectively. In these plots, $\beta$ is the angle of the probe measurement axis relative to the $X$ axis of the wind-tunnel coordinate system defined with the same sign convention as $\beta_{FS}$. The abscissa of the plots ($\beta - \beta_{FS}$) thus represents the angular position of the probe measurement axis relative to the local free-stream direction, with a positive value of $\beta - \beta_{FS}$ indicating that the probe measurement axis is skewed at a greater angle away from the wing than the local free-stream velocity. In these measurements, the coherency is maximum when the measurement axis of the probe coincides with the local mean convective velocity vector of the flow structures since this will result in the same structures registering on both sensors most of the time. As the measurement axis of the probe diverges increasingly from the local mean convective velocity vector, an increasing number of structures will fail to register on both sensors resulting in a drop in the coherency. As such, the angle at which the peak coherency occurs in Figs 38 - 44 represents the direction of the local mean convective velocity vector of the coherent structures in the flow. For comparison, the directions of the local mean-flow, mean-velocity gradient and turbulent shear-stress vectors in the $X$-$Z$ plane measured by Ölçmen (1990) have been marked on each plot with the arrows labeled "U", "G" and "S", respectively, where they fall within the angular range of the present measurements. Where they fall outside the angular range of the measurements, their values have been indicated at the top right-hand corner of the plot.

At station 0, the coherency has a peak at approximately $\beta - \beta_{FS} = 5^\circ$ up to $Y/\delta = 0.45$
for frequencies below $f\delta/U_e = 0.149$. There is no significant coherency above $f\delta/U_e = 0.614$ and the angle of peak coherency does not exhibit significant change with frequency. The small value of $\beta - \beta_{FS}$ reflects the near two-dimensional mean-flow structure at this station with the spanwise pressure gradient within the boundary layer having only a small effect on the mean motion of the coherent structures. At all $Y$ locations, the angle of peak coherency is close to the direction of the mean-velocity vector in the $X-Z$ plane observed by Ölçmen. Up to $Y/\delta = 0.45$, the peak in the coherency for frequencies below $f\delta/U_e = 0.149$ becomes less distinct as $Y$ increases. At $Y/\delta = 0.45$, there is a high level of near-constant coherency over a range of angles instead of a distinct peak.

This broadening of the coherency peak with increasing $Y$, which can be observed at all the measurement stations, may be explained in view of the spanwise coherence length scale results (Figs 35a - 35g) obtained from the horizontal hot-wire rake measurements. The results shown in Figs 35a - 35g indicate that the spanwise size of the structures increases with $Y$ for all frequencies at station 0. As the size of the structures get bigger, the probability of a typical structure registering on both sensors even when its direction of motion is not coincident with the measurement axis of the probe increases. Therefore, at small angles of misalignment between the measurement axis of the probe and the direction of mean motion of the structures, most of the large structures are still registering on both sensors of the probe, thereby giving rise to the region of high coherencies spread over a range of angles observed at $Y/\delta = 0.45$.

The results at station 1 exhibit trends which are quite similar to those at station 0. Except for $Y/\delta = 0.29$ and 0.46, the peak coherency again occurs at approximately $\beta - \beta_{FS} = 5^\circ$ for frequencies below $f\delta/U_e = 0.153$, close to the mean-flow angles measured by Ölçmen at this station. At $Y/\delta = 0.29$ and 0.46, the peak coherency appears to occur at $\beta - \beta_{FS} = -10^\circ$ which is a somewhat abrupt change from the other $Y$ locations. However, at these two $Y$ locations, there
is only a small change, within experimental uncertainty, in the value of the coherency over the range $-10^\circ < \beta - \beta_{FS} < +5^\circ$ which includes Ölcmen’s mean-flow angles.

Beginning at station 2, the increasing three dimensionality of the flow is reflected in the greater values of $\beta - \beta_{FS}$ where the peak coherency occurs, and its variation with $Y$ location. The results indicate that the spanwise pressure gradient within the boundary layer has an effect on the motion of the coherent structures that is qualitatively similar to the mean flow. For stations 2, 3 and 4, the peak coherency near the wall ($Y/\delta < 0.1$) generally occurs at a value of $\beta - \beta_{FS}$ that is about $5^\circ$ smaller than the mean flow, i.e. the motion of the coherent structures is less skewed relative to the local free-stream velocity than the mean flow near the wall. For $Y/\delta > 0.1$, the discrepancy between the two angles becomes smaller with increasing $Y$ and is virtually zero for $0.4 < Y/\delta < 0.5$. For stations 5 and 6, there is close agreement between the mean-flow angles obtained by Ölcmen and the angle of peak coherency at all $Y$ locations.

At station 2, the peak-coherency angle falls from $10^\circ$ to $5^\circ$ between $Y/\delta = 0.018$ and 0.45 while at station 3, the angle falls from $15^\circ$ to $10^\circ$ between $Y/\delta = 0.021$ and 0.52. The results at station 4 exhibit a high degree of coherency over a larger frequency bandwidth than the earlier upstream stations with a distinct peak in the coherency up to $f\delta/U_e = 1.427$. At low frequencies, the peak coherency shifts from $\beta - \beta_{FS} = 15^\circ$ at $Y/\delta = 0.018$ to $\beta - \beta_{FS} = 5^\circ$ at $Y/\delta = 0.46$. Station 4 also shows a variation of the peak-coherency angle with frequency that is absent from the upstream stations. At $Y/\delta = 0.016$, the peak-coherency angle at $f\delta/U_e = 0.287$ and above is $5^\circ$ greater than the angle at lower frequencies, indicating that motion of the smaller scale structures is more skewed relative to the local free-stream velocity vector than the larger scale structures. At $Y/\delta = 0.029$, the frequency at which the peak-coherency angle begins to differ from its low-frequency value shifts upwards. Here, the peak coherency above $f\delta/U_e = 0.853$ occurs at an angle
that is $5^\circ$ greater than the angle at lower frequencies.

As with station 4, the results at station 5 also exhibit a high degree of coherency up to $f \delta/U_e = 1.413$ but does not show any change in the peak-coherency angle with frequency. The peak-coherency angle varies from $15^\circ$ at $Y/\delta = 0.017$ to $5^\circ$ at $Y/\delta = 0.43$. At station 6, the bandwidth of high coherency falls to $f \delta/U_e = 0.568$ and below, similar to stations 0 to 3. The peak-coherency angle increases from $10^\circ$ at $Y/\delta = 0.017$ to $15^\circ$ at $Y/\delta = 0.027$ before falling to $0^\circ$ at $Y/\delta = 0.46$. The upper limit of the high-coherency frequency bandwidth fails to approximately $f \delta/U_e = 0.284$. The peak-coherency angle decreases from approximately $10^\circ$ at $Y/\delta = 0.017$ to $5^\circ$ at $Y/\delta = 0.46$ in fairly good agreement with the mean-flow angle.

In order to examine the relationship between the direction of mean motion of the coherent structures and the mean-flow angle more closely, the results for the peak-coherency angle at each $Y$ location were further refined by calculating a maximum-coherency angle ($\beta_m - \beta_{FS}$) through a curve fit. $\beta_m - \beta_{FS}$ was determined from the maximum point of a parabola which was fitted through the peak-coherency angle and the two angular positions on either side of it. Profiles of $\beta_m - \beta_{FS}$ together with the mean-flow, mean-velocity gradient and turbulent shear-stress angles measured by Ölcmen (1990) are shown in Figs 45a - 45g for stations 0 - 6, respectively.

At all stations and frequencies, there does not appear to be any qualitative similarity between the maximum-coherency angle and the mean-velocity gradient or turbulent shear-stress angles.

Near the wall, at stations 0 and 1 (Figs 45a and 45b), $\beta_m - \beta_{FS}$ is generally less than $5^\circ$ at all frequencies, reflecting the weak three dimensionality of the flow at these two stations. The flow here behaves quite like a two-dimensional boundary layer and there is not much skewing in the motion of the coherency structures. Away from the wall, there is some scatter in $\beta_m - \beta_{FS}$.
caused by the broadening of the peak in the $\gamma^2$ vs. ($\beta - \beta_{FS}$) results, which increases the uncertainty in $\beta_m - \beta_{FS}$ due to the parabola-fitting algorithm.

At stations 2, 3 and 6 (Figs 45c, 45d and 45g), the three dimensionality of the flow causes motion of the coherent structures to skew away from the wing with $\beta_m - \beta_{FS}$ attaining values > $10^\circ$ in general. Comparing $\beta_m - \beta_{FS}$ with the mean-flow angle ($U$), it can be seen that while $U$ decreases from its maximum value near the wall to approach $\beta - \beta_{FS} = 0$ at the edge of the boundary layer, $\beta_m - \beta_{FS}$ decreases only slightly, moving away from the wall. This results in a lag between $\beta_m - \beta_{FS}$ and $U$ in the outer region of the boundary layer, i.e. the mean motion of the coherent structures appears to be skewed at a greater angle away from the wing than the mean flow. At stations 4 and 5 (Figs 45e and 45f), the mean motion of the coherent structures exhibits a further qualitative change with a noticeable decrease in $\beta_m - \beta_{FS}$ moving away from the wall. At these two stations, the profile of $\beta_m - \beta_{FS}$ is quite similar to that of $U$, indicating that the mean motion of the coherent structures follows the mean flow quite closely.

4.3.3 CONVECTIVE WAVE SPEED

The spectral variation of the convective wave speed ($U_c$) normalized on $q (= \sqrt{U^2 + W^2}$) is shown in Figs 46a - 46g for stations 0 - 6, respectively. As discussed in Chapter 3, the maximum uncertainty in the convective wave speed results presented here is about $\pm 20\%$. The convective wave speed in these plots were calculated from eqn (3.8) with the angular position of the probe corresponding to the peak-coherency angle in Figs 38 - 44. This was done since this angular position represents the direction of mean motion of the coherent structures as previously discussed. The effect of angular misalignment on the convective wave speed results was examined by calculating $U_c$ for angular positions of the probe corresponding to $\beta = \beta_m \pm 5^\circ$. A typical set
of results for station 3 is shown in Figs 46h and 46i for $\beta = \beta_m - 5^\circ$ and $\beta = \beta_m + 5^\circ$, respectively. As can be seen, the effect of misalignment in $\beta$ is to increase the apparent convective wave speed at all frequencies. This is probably due to the reduction of the effective distance over which a typical structure has to travel to register on both sensors of the probe which reduces the phase shift [$\Phi(f)$] in eqn (3.8). This in turn causes the calculated value of $U_c$ to be overestimated because the same value of $\Delta s$ (= 4.81 mm) was used for all angular positions.

The normalized results for $U_c$ at all stations appear to be distinctly different from those obtained by Ahn (1986) for two-dimensional boundary layers with $Re_{\theta} = 3270$ and 6428 in the same facility that was used for the present study. Ahn’s results, which were consistent with those of Favre et al. (1967) and Sternberg (1967), showed that $U_c$ approached the local mean velocity $\overline{U}$ at high wave numbers (small-scale structures) for all $Y$ locations, while at low wave numbers (large-scale structures), $U_c > \overline{U}$ for $Y/\delta < 0.23$ and $U_c < \overline{U}$ for $Y/\delta > 0.23$. On the other hand, the results shown in Figs 46a - 46g for the present flow indicate that $0.6 < U_c/q < 1$ at high wave numbers and $U_c/q > 1$ at low wave numbers for all $Y$ locations. Also, normalizing $U_c$ on $q$ does not appear to collapse the results at high wave numbers, unlike the two-dimensional case.

Since the profiles of the maximum coherency angle ($\beta_m - \beta_m^s$) presented in Figs 45a - 45g indicate that, in general, the direction of the mean motion of the coherent structures is not coincident with the local mean velocity in the X-Z plane ($q$), there is some uncertainty here about the correct parameter to normalize $U_c$ in order to collapse the results at high wave numbers. Apart from $q$, $U_c$ was also normalized on the component of $q$ in the direction of maximum coherency [i.e. $q\cos(U - \beta_m)$; $U =$ mean-flow angle] to check if the results collapsed better, but this was found to be not the case. To the author’s knowledge, there is no previously reported result for $U_c$ in three-dimensional boundary layers available in the literature. As such, further investigation is needed and the issue of the correct normalization parameter is still to be resolved.
The near-wall results for $U_c$ are shown in Figs 47a - 47g with $U_c$ normalized on the friction velocity ($U_f$). These results are again different from those obtained by Ahn (1986) whose results indicated that $U_f/U_c \to 15$ for $Y^+ < 40$, consistent with the observations of Kline et al. (1967). As can be seen from Figs 47a - 47g, the ratio $U_f/U_c$ does not show a consistent trend at high wave numbers over all the stations. An important difference between the present set of results and those of Ahn is that the present results were obtained mostly from the $110 > Y^+ > 40$ range, which is out of the region of collapse reported by Ahn. The results shown in Figs 47a - 47g were also renormalized with a turbulent shear-stress velocity defined as:

$$U_{urn} = \sqrt{(-\overline{uv})^2 + (-\overline{vw})^2}$$  \hspace{1cm} (4.11)

where $-\overline{uv}$ and $-\overline{vw}$ were taken from Ölzmen’s (1990) measurements. A typical set of results for station 3 is shown in Fig 47h. As can be seen, the $U_c$ results do not collapse well under this form of normalization.

4.4 ROTATABLE WALL-SENSOR RESULTS

The rotatable wall-sensor measurements were made at stations 1, 4 and 6 in order to study the effect of the spanwise pressure gradient on the motion of the coherent structures very near the wall in an analogous manner to the parallel-sensor probe measurements. The angular variation of the coherency measured by the rotatable wall-sensor probe near the wall is shown in Figs 48a, 48b and 48c for stations 1, 4 and 6, respectively. In each of the plots, the direction of the local mean skin-friction vector measured by Ailingter (1990) has been marked on the abscissa with the arrow labeled "$\beta_{w} - \beta_{fs}$". The overall levels of coherency at all frequencies are somewhat lower than
the corresponding results for the parallel-sensor probe, a result which is most likely due to the larger spacing between the sensors of the rotatable wall-sensor probe. At stations 1 and 4, the results exhibit a significant coherency only below $f/\delta/U_\infty = 0.153$ and 0.139, respectively, while at station 6, the cutoff frequency falls to $f/\delta/U_\infty = 0.085$. The peak-coherency angles at stations 1, 4 and 6 are $5^\circ$, $15^\circ$ and $5^\circ$, respectively, at all frequencies. There appears to be no consistent trend relative to the mean skin-friction angle $\beta_w - \beta_{FS}$. At station 4, the peak-coherency angle $(\beta_m - \beta_{FS})$ is close to $\beta_w - \beta_{FS}$, but $\beta_m - \beta_{FS}$ is less than and greater than $\beta_w - \beta_{FS}$ at stations 1 and 6, respectively.

Comparing the rotatable wall-sensor results with those of the parallel-sensor probe, it can be seen that the angles of peak coherency at the wall and at the lowest Y location of the parallel-sensor probe ($Y/\delta = 0.017$) are close in value, as expected.

### 4.5 TRAVERSABLE WALL-SENSOR SPECTRAL RESULTS

The power spectra of the fluctuating wall shear stress ($\tau'_w$) measured by the fixed sensor of the traversable wall-sensor probe at stations 1, 4 and 6 are shown in Fig 49. The spectra here have been plotted as $\Phi^* \text{ vs. } f^*$, where $\Phi^*$ and $f^*$ are defined as:

$$\Phi^* = \frac{U_t^2 \Phi_{\tau'}}{2\pi \nu U_w^2}$$ (4.12)

$$f^* = \frac{2\pi \nu f}{U_t^2}$$ (4.13)

This form of normalization was found by Devenport and Simpson (1989) to collapse the $\tau'_w$
spectra that they measured quite well. Their measurements were carried out with a hot-wire array positioned in the sublayer across the line of low shear near the nose of the same wing-body junction flow that was used in the present study. For the present set of results, the spectra at stations 4 and 6 appear to have been collapsed quite well by the normalization, but not the spectrum at station 1. The constant-slope regions of all three spectra do not appear to exhibit any fall off at high frequencies. As a result, the Corcos (1963) correction for attenuation of the power spectrum due to finite sensor size was not applied. The spectra at stations 4 and 6 exhibit a constant -3 slope region which was also found in the spectra measured by Devenport and Simpson. The spectrum at station 1 shows an excess of energy at high frequencies and a deficit of energy at low frequencies compared to the spectra at stations 4 and 6. Devenport and Simpson compared the $\tau_\alpha$ spectrum from an equilibrium two-dimensional boundary layer to their results and observed a similar trend for the behavior of the two-dimensional spectrum. The present results are consistent with those of Devenport and Simpson as the flow at station 1 is relatively more two-dimensional than at stations 4 and 6.
5 STRUCTURE OF NEAR-WALL EJECTION/SWEEP EVENTS

5.1 SPANWISE STRUCTURE OF EJECTIONS/SWEEPS

The spanwise variation of the cross-correlation coefficient and coherency measured by the traversable wall-sensor probe are shown in Figs 50a, 50b and 50c for stations 1, 4 and 6, respectively. The cross-correlation coefficient results at all three stations show two distinct regions separated at approximately $\Delta Z_w^* = 50$. For $\Delta Z_w^* < 50$, $R_{\pi}$ falls rapidly and monotonically with increasing $\Delta Z_w^*$. However, for $\Delta Z_w^* > 50$, the rate at which $R_{\pi}$ decreases becomes much smaller, and the cross-correlation curve is marked by peaks at certain $\Delta Z_w^*$ for stations 1 and 4. The peaks occur at approximately $\Delta Z_w^* = 85, 135$ and 200 for station 1, and $\Delta Z_w^* = 110, 180$ and 270 at station 4. For station 1, the coherency results show a major contribution to the cross-correlation peaks from $f_{\delta}/U_e = 0.068$ (43 Hz) with secondary contributions from $f_{\delta}/U_e = 0.010$ (6 Hz) and $f_{\delta}/U_e = 0.149$ (100 Hz). The results at station 4 are similar except that the contributions from $f_{\delta}/U_e = 0.009$ (6 Hz) and $f_{\delta}/U_e = 0.062$ (43 Hz) are approximately equal with a small contribution from $f_{\delta}/U_e = 0.141$ (100 Hz). On the other hand, the cross-correlation curve for station 6 does not exhibit the same peaks shown by the other stations.

The form of the near-wall, spanwise cross-correlation curves that have been obtained in the present study is different from those observed by Antonia and Bisset (1990) in the near-wall
region of a two-dimensional, zero pressure gradient boundary layer with $Re_a = 2200$. Antonia and Bisset used a spanwise hot-wire array with ten sensors to examine the structure of the near-wall flow between $Y^+ = 5$ and $Y^+ = 40$. At all $Y^+$ locations, they obtained cross-correlation curves which decayed smoothly to zero and exhibited no positive correlation peaks. At $Y^+ = 15$, the correlation curve reached zero at a spanwise spacing of $\Delta Z^+ = 100$.

The correlation peaks in the present set of results indicate the presence of flow structures with a preferred spanwise spacing in the near-wall region. From what is currently known about the near-wall flow structure (Robinson, 1991; Kline, 1992), there are two alternative models which account for the behavior of the cross-correlation curve. The first model is that the peaks represent the passage of the low-speed streaks in the sublayer that are associated with the ejection process. The streaks have been observed to occur at a mean spanwise spacing of $\Delta Z^+ \approx 100$ for two-dimensional boundary layers (Kline et al., 1967) which is comparable to the spacing of the peaks in the cross-correlation curve. Although several alternative theories exist, the formation mechanism of the streaks is still an unresolved issue. If adjacent streaks are formed from the same parent structure, they would have similar $u$ velocity signatures and would reveal themselves as positive peaks in the cross-correlation curve.

The second model which accounts for the correlation peaks is the sweep of high-speed fluid from the outer region of the boundary layer towards the near-wall region. In this scenario, a high-speed structure moving towards the near-wall region from the outer region breaks up into secondary structures which impact on the wall at regular intervals. These secondary structures, having been formed from the same parent structure, would have similar $u$ signatures and thus show up as positive peaks in the cross-correlation curve.

In order to determine which of the two models is applicable in the present study, a conditional correlation was performed on the data. The correlation of the signals from the two
sensors were conditioned on the occurrence of an ejection at the fixed sensor location as determined by the modified u-level burst-detection algorithm of Luchik and Tiederman (1987). The results are shown in Figs 51a, 51b and 51c for stations 1, 4 and 6, respectively. At all three stations, the conditional cross-correlation coefficient is noticeably higher than the conventional cross-correlation coefficient over the entire range of $\Delta Z^*$'. Also, the peaks on the conditional results are relatively higher than those on the conventional results. These results would seem to indicate that it is the low-speed streaks which are responsible for the shape of the cross-correlation curve. The $\Delta Z^*$ locations at which the peaks occur are then indicative of the mean spanwise spacing (in local free-stream coordinates) of the streaks. Also, from the coherency results, it may be concluded that the streaks are primarily low-frequency structures with most of their energy concentrated below $f \delta/U_e = 0.15$ (100 Hz).

5.2 EJECTION FREQUENCIES AND WALL SHEAR-STRESS POWER SPECTRA

Strickland and Simpson (1975) employed a statistical model to show that the distribution of frequencies represented by successive peaks in the short-time autocorrelation of the fluctuating wall shear stress is the same as the first moment of its power spectrum. Since the short-time autocorrelation period is one of the best indicators of the ejection frequency of the low-speed streaks in the sublayer (Bogard and Tiederman, 1986), their result established a means of determining the mean ejection frequency from the first moment of the wall shear-stress power spectrum. They tested their result at a number of streamwise locations within a two-dimensional boundary layer with positive as well as negative streamwise pressure gradients and found a close
correspondence between the mean ejection frequency \( f_e \) and the frequency at the peak of the first moment of the wall shear-stress power spectrum \( f_\tau \), with agreement between the two frequencies generally within 15%.

In the present study, the relationship between \( f_e \) and \( f_\tau \) was examined using the data obtained at stations 0, 4 and 6 with the traversable wall-sensor probe. Figure 52 shows a typical short-time autocorrelation of the fluctuating wall shear stress at station 1 with the first positive correlation peak at \( \Delta t = 7 \) ms corresponding to an instantaneous ejection frequency of approximately 143 Hz. However, as there were insufficient data to construct a histogram of the ejection frequencies using the autocorrelation method, the ejection frequencies were determined instead using the modified u-level burst-detection algorithm described by Luchik and Tiederman (1987).

The histograms of the ejection frequencies are shown in Figs 53a, 53b and 53c for stations 1, 4 and 6, respectively, and the first moments of the \( \zeta_\nu \) power spectra are shown in Figs 54a, 54b and 54c for stations 1, 4 and 6, respectively. The histograms of the first moments of the \( \tau_\omega \) power spectra were truncated at 10.7 Hz before \( f \Phi_\nu(f) \) became negligible because the frequency resolution of the FFT employed to compute \( \Phi_\nu(f) \) was insufficient to fill the bins of the histograms properly at low frequencies. The agreement between \( f_e \) and \( f_\tau \) is fairly good at stations 1 and 4, but \( f_\tau \) is somewhat higher than \( f_e \) at station 6. However, \( f_\tau \) is probably slightly overestimated at all the stations due to the missing contribution from the low-frequency end of the histogram. Hence the true difference between \( f_e \) and \( f_\tau \) is probably smaller than the results indicate at stations 1 and 6, but larger at station 4.

It is interesting to note that the ejection frequencies are highest at station 1 and decrease somewhat at station 4 before rising slightly again at station 6. As the ejection process is supposed to be responsible for the majority of the turbulent shear-stress production, it would be reasonable
to expect a correlation between the maximum turbulent shear stresses and the ejection frequency at each station. The maximum magnitudes of the turbulent shear-stress vectors ($\sqrt{\overline{u'v'}^2 + \overline{vw'}^2}$) in the X-Z plane measured by Ölçmen (1990) were 1.71 m²/s², 1.20 m²/s² and 1.08 m²/s² at stations 1, 4 and 6, respectively. The maximum shear-stress and ejection frequency are both greatest at station 1 and then fall to somewhat lower values at the other two stations. Although there is a slight negative correlation between the shear-stress magnitude and ejection frequency at stations 4 and 6, the uncertainties in $\sqrt{\overline{u'v'}^2 + \overline{vw'}^2}$ at these two stations are quite large (~35%) and the rather close values in both the ejection frequency and maximum shear stress does not eliminate the possibility that there exists a correlation between the maximum turbulent shear stresses and the ejection frequency. Further investigations are needed to confirm this.
6 EXAMINATION OF THE FLOW STRUCTURE

6.1 THE EXPONENTIAL-DECAY MODEL

The exponential-decay model for the coherency measured between two points with a spacing of $\Delta X$ in the streamwise direction is:

$$\gamma = \exp(-k_2 \frac{2\pi f \Delta X}{U_c})$$  \hspace{1cm} (6.1)

where $k_2$ is a decay constant. Equation (6.1) results from the model equation for the cross spectrum of surface pressure fluctuations proposed by Corcos (1964) and Brooks and Hodgson (1981). It assumes that the quantity whose coherency is being modeled behaves as a traveling wave between the two points under consideration. This becomes apparent if one notes that the wave number is given by $k = 2\pi f / U_c$ and $k \Delta X = \Phi$ where $\Phi$ is the phase shift. Equation (6.1) then becomes:

$$\gamma = \exp(-k_2 \Phi)$$  \hspace{1cm} (6.2)

which indicates that the square root of the coherency decays exponentially with the phase shift between two points.

Equation (6.1) was used by McGrath and Simpson (1987) to correlate the coherency of wall pressure fluctuations in a two-dimensional boundary layer with zero as well as favorable pressure gradients. To the author's knowledge, there is no previously reported reference of any attempts to correlate the coherency of velocity fluctuations in boundary layers or other types of
flows. McGrath and Simpson measured the pressure fluctuations at two locations on the wall using microphones with streamwise spacings in the range of $0.20 < \Delta x/\delta_1 < 0.75$, where $\delta_1$ is the displacement thickness of the boundary layer. They found that their coherency results were well described by eqn (6.1) for small values of the phase shift, i.e. when $2\pi f \Delta x/U_c = \Phi < 5$ radians.

In the present study, eqn (6.1) was fitted to the coherency between the $u$ velocity fluctuations measured by the slant-wire probe upstream and the hot-wire rake sensor at the same $Y$ location, for three $Y$ locations of the slant-wire probe at each station. The decay constant $k_x$ in the model was determined using a least-squares regression. The streamwise spacing between the upstream sensor and hot-wire rake was in the range of $0.91 < \Delta x/\delta < 1.24$ for all the measurements. A typical set of results obtained at station 2 are shown in Figs 55a - 55c. The results for all the measurement stations are summarized in Table 19 which gives the decay constants for the model, and Table 20 which gives the regression coefficients ($r_x$) for the least-squares fit of the model to the results. The $Y$ locations of the upstream sensor for all the results are given in Table 21. As is apparent from Figs 55a - 55c, the exponential-decay model appears to represent the coherency results quite well. The measured values of the coherency are slightly overpredicted by the model at small values of the phase shift but overall, the measured and predicted values of the coherency are close. The performance of the exponential-decay model in describing the streamwise coherency results can be judged from the regression coefficients given in Table 11. For all the cases examined, $r_x$ is greater than 0.97 and exceeds 0.99 in many cases.

The results presented in Table 19 indicate that, with the exception of stations 5 and 6, the value of the decay constant $k_x$ falls with increasing $Y$ location. A smaller value of $k_x$ is associated with a slower rate of decay of the coherency in the streamwise direction which implies the presence of larger flow structures. The results are thus consistent with the increasing size of flow structures with $Y$ location which has been observed in the past (Robinson, 1989b).
There is no consistent trend in the variation of the decay constant between the stations, but $k_x$ is generally smaller at stations 4, 5 and 6 than at the other stations further upstream. It is likely that this difference in $k_x$ is due to the difference in the pressure gradients between the downstream and upstream stations. According to Schloemer (1967), the decay of the coherency of wall pressure fluctuations in the streamwise direction is smaller for favorable pressure gradients than for zero pressure gradients. The pressure gradient in local free-stream coordinates measured by Ölçmen (1990) at each station is shown in Table 1b. The pressure gradients at stations 1 and 2 are adverse while stations 3, 4, 5 and 6 have favorable pressure gradients although the magnitudes of $\partial C_p/\partial x$ at stations 2 and 3 are very small. The variation of $k_x$ between favorable and adverse pressure gradients in the present set of results is thus qualitatively in line with Schloemer's results.

6.2 TIME-AVERAGED STRUCTURE WAVEFRONTS

Brown and Thomas (1977) performed measurements in a two-dimensional, zero-pressure gradient boundary layer with a momentum thickness Reynolds number of $Re_\theta = 10160$ using a wall-shear probe and an array of four hot-wire sensors positioned at various $Y$ locations to examine the large-scale structures in the flow. By employing a time-delayed correlation between the wall-shear probe and each sensor of the hot-wire array, they were able to detect and determine the shape of the time-averaged wavefront of the large-scale structures in the $X$-$Y$ plane of the flow. Their results showed a wavefront which was an approximate straight line inclined at 18° to the wall. This angle of inclination was found to correspond closely to the wavefront of large-scale structures observed in flow visualizations performed independently by Falco (1977). This inclined
wavefront was later attributed to a horseshoe vortex model proposed by Brown and Thomas after performing further correlations of their data. This horseshoe vortex model was able to account for many features of the flow inferred by Brown and Thomas from their correlations, including an apparent linkage between the passage of large-scale structures in the outer region and the occurrence of the ejection cycle near the wall.

In the present study, the wavefront of the flow structures in the X-Y plane was determined from the vertical hot-wire rake measurements using an algorithm based on time-delayed correlation similar to the one used by Brown and Thomas. The objective of the algorithm was to calculate the coordinates of the structure wavefront at the Y locations of the hot-wire rake sensors. A time-delayed correlation was first performed on each pair of adjacent sensors of the hot-wire rake to check for the presence of an inclined structure wavefront similar to that observed by Brown and Thomas. A typical set of time-delayed correlation curves calculated from the data acquired at station 0 is shown in Fig 56. The time-delayed correlation coefficient in Fig 56 is defined as:

\[ R_d = \frac{\langle u_i(t+\Delta t) u_{i+1}(t) \rangle}{\sqrt{\langle u_i^2 \rangle \langle u_{i+1}^2 \rangle}} \]  \hspace{1cm} (6.2)

where \( u_i \) is the fluctuating streamwise velocity component measured by sensor \( i \) of the rake. At all Y locations, the peak value of \( R_d \) occurred at a small but discernible positive time shift indicating the presence of an inclined structure wavefront. For each pair of sensors \( i \) and \( i+1 \) (\( i = 1, 2, \ldots, 15 \)) located at \( Y_i \) and \( Y_{i+1} \), respectively, the optimum time shift (\( \Delta t_i \)) which maximized \( R_d \) was noted. The difference in the streamwise position of the structure wavefront at \( Y_{i+1} \) and \( Y_i \) was then calculated by multiplying the optimum time shift by the average of the mean velocities at the two Y locations, i.e.
\[ \Delta X_i = 0.5(U_i + U_{i+1})\Delta t_i \] (6.3)

With \( \Delta X_i \) given by eqn (6.3), the X coordinate of the structure wavefront at location \( Y_{i+1} \) could then be calculated from the X coordinate of the wavefront at location \( Y_i \) as:

\[ X_{i+1} = X_i + \Delta X_i \] (6.4)

The structure wavefront at each station was constructed point by point starting from the bottom of the rake with sensor \#1 (\( i = 1 \)), where \( X_i \) was defined to be 0.0 and calculating \( X_2, X_3, \ldots, X_n \) successively using eqn (6.4). As the \( Y_i \)'s were already known from the locations of the hot-wire sensors, the calculation of the \( X_i \)'s completed the definition of the shape of the structure wavefront. As was the case with Brown and Thomas, the algorithm described here neglects any rotation or distortion of the structures and assumes that the structures are convected along at the local mean velocity. Hence, it is only expected to provide an approximate picture of the shape of the structure wavefront.

The shape of the structure wavefronts determined using the algorithm described above is shown in Figs 57a - 57g for stations 0 - 6, respectively. The calculated coordinates \((X_i, Y_i)\) of the wavefront are represented by the symbols and the line through the points was determined through a least-squares regression. The angle of inclination \((\alpha_i)\) of the wavefront determined from the regression analysis and the regression coefficient \((r_i)\) are shown in Table 22 for all the stations. The wavefronts at all the stations appear to be inclined straight lines, consistent with the results of Brown and Thomas. However, the angles of inclination of the wavefronts in the present set of results \((49^\circ-58^\circ)\) are about three times greater than what Brown and Thomas observed \((-18^\circ)\).

Looking at the variation of \( \alpha_i \) between stations 0 and 6, it is evident that this discrepancy in \( \alpha_i \) is probably not due to any three-dimensional effect in the flow. The increasing three dimensionality of the flow as it moves from station 0 to station 6 appears to have only a slight
effect on $\alpha_j$, causing it to increase by a few degrees. Also, $\alpha_j$ is still relatively large (49.3°) at station 0 where the flow is nearly two dimensional.

There is some question here about the correct velocity to use in eqn (4.9) in calculating the successive streamwise positions of the structure wavefront. As previously discussed, the time shift $\Delta t$ in eqn (6.3) was determined from a time-delayed correlation between signals from adjacent sensors of the hot-wire rake. Such a correlation would be dominated by the low-frequency component of the signals representing the large-scale structure of the flow. As the results for the convective wave speed shown in Figs 46a - 46g indicate, the large-scale (low wave number) structures are generally convected at a somewhat higher speed than the local mean velocity. Assuming that $U_c/q = 1.2$ at low wave numbers and $q = 1.1 U$, then substituting $U_c$ for $0.5(U_{rj} + U_{rj+1})$ in eqn (4.10) would have increased the calculated values of $\Delta X_j$ by approximately 30%. This in turn would have reduced the calculated wavefront angle ($\alpha_j$) by approximately 13%.

It is speculated here that the chief mechanism which determines the angle of inclination of the large-scale structures is the mean-velocity gradient normal to the wall. It seems plausible, if not likely, that the mean-velocity gradient would have the effect of stretching and tilting the flow structures after they are formed, thereby determining $\alpha_j$ to a large degree. A larger mean-velocity gradient would therefore result in a smaller $\alpha_j$ and vice versa. This proposed linkage between the mean-velocity gradient and $\alpha_j$ is purely speculative, since, to the author's knowledge, there is no previously reported result of any investigation into such a linkage. If true, then the discrepancy in $\alpha_j$ might be explained if the mean-velocity gradient in the present test flow is smaller than the gradient in the flow employed by Brown and Thomas. Using the ratio $U_c/\delta$ as a rough estimate of the mean-velocity gradient and comparing the test conditions of Brown and Thomas ($Re_\theta = 10160$, $U_c = 36$ m/s, $\delta = 40$ mm) with those of the present experiments ($Re_\theta = \ldots\ldots$)
5936, \( U_e = 27 \text{ m/s}, \delta = 38 \text{ mm} \), it can be seen that this is indeed the case as Brown and Thomas obtained their results with a higher \( U_e \) coupled with an approximately equal \( \delta \).
7 CONCLUSIONS

An experimental study of coherent structures in a three-dimensional turbulent boundary layer around a wing-body junction has been carried out. Measurements were performed at seven locations with a sixteen-sensor hot-wire rake, a parallel-sensor hot-wire probe, a rotatable wall-sensor probe and a traversable wall-sensor probe. The major conclusions are as follows:

Normalized with the inner scaling proposed by Perry, Lim and Henbest (1985), the power spectra of the $u$ velocity fluctuations collapse in the inertial subrange with a $-5/3$ slope, similar to spectra obtained in two-dimensional boundary layers (Ahn, 1986). However, the outer flow scaling proposed by the same authors do not collapse all the spectra onto a single curve. Instead, the spectra from the outer and inner regions collapse into two distinct groups.

The spatial variation of coherency in the $Y$ direction at various frequencies collapses onto a common curve when the spacing in the $Y$ direction is normalized by the $Y$ coherence length scale. This curve is closely approximated by an exponential-decay model function over the range $0 < \Delta Y/L_{yo} < 4.5$. A direct comparison of the results between the inner and outer regions over the range $\Delta Y/L_{yo} < 1$ shows that the flow structures in the outer region are more coherent in the $Y$ direction over the distance of the coherence length scale than those in the inner region.

Comparisons of the $Y$ coherence length scale in the range of $109 < Y^+ < 306$ measured by the upstream sensor and the hot-wire rake sensor with the same $Y$ location shows that there is little change in the size of the coherent structures over streamwise distances of up to $\Delta X^+ = 415$. This result appears largely unaffected by the three dimensionality of the flow.
For frequencies below \( f_\delta/U_e = 0.2 \), the \( \gamma \) coherence length scale of the turbulence near the wall \( (L_{\gamma}) \) is reduced by up to \( 0.2 \delta \) by the increasing three dimensionality of the flow. A similar effect is not observed for the coherence length scale in the outer region \( (L_{\gamma o}) \). The reduction in \( L_{\gamma i} \) occurs in conjunction with a reduction in the turbulent shear stresses, implying a link between the two effects.

At each \( \gamma \) location, the angular variation of the coherency between the \( u \) velocity fluctuations measured by each sensor of the parallel-sensor probe shows a distinct peak which corresponds to the direction of mean motion of the coherent structures in the X-Z plane. This direction is different from and lags by several degrees the mean-flow angle in general. There is very little variation of the direction of maximum coherency with frequency (structure size).

The spectral variation of the convective wave speed through the boundary layer is distinctly different from corresponding results obtained for a two-dimensional boundary layer (Ahn, 1986). The results away from the wall do not collapse well when normalized by the mean velocity in the X-Z plane or its component in the direction of mean motion of the coherent structures. Similarly, the results near the wall do not collapse well when normalized by the friction velocity or a reference velocity based on the turbulent shear stresses.

The distribution of intermittency in the outer region is well described by the complementary error function which also fits the intermittency results for two-dimensional boundary layers (Klebanoff, 1956). The three dimensionality of the present test flow does not appear to have any significant effect on the intermittency distribution or the mean passage frequency of the turbulent/non-turbulent interface in the outer region.

The mean ejection frequency near the wall measured with the modified \( u \)-level burst-detection algorithm proposed by Luchik and Tiederman (1987) agrees quite well with the frequency at the peak of the first moment of the wall shear-stress power spectrum, consistent with
the results of Strickland and Simpson (1975). At the three stations where the ejection frequencies were measured, there is a correlation (within experimental error) between the mean ejection frequency and the magnitude of the turbulent shear stresses, consistent with the central role played by the ejection process in the production of the turbulent shear stresses.

The spatial variation of the long time-averaged cross-correlation coefficient of the fluctuating wall shear stress ($\tau'_w$) in the spanwise direction normal to the local wall shear-stress direction reveals the presence of flow structures with a preferred spanwise spacing near the wall. At two of the measurement stations, this spanwise spacing was found to be $\Delta Z_w = 85$ and 110. Conditional correlations of $\tau'_w$ indicate that these structures are probably the low-speed streaks in the sublayer which are involved in the ejection process. Examination of the spanwise variation of the coherency measured at the same locations show that the ejection process occurs mostly at frequencies below $f \delta/U_e < 0.15$ ($f < 100$ Hz).

The streamwise variation of the coherency of the $u$ velocity fluctuations appears to be well described by the exponential-decay model proposed by Corcos (1964) and Brooks and Hodgson (1981) for the coherency of wall pressure fluctuations. The decay constant in the model decreases with increasing $Y$ location, consistent with the increasing size of the coherent structures with $Y$ (Robinson, 1989b).

Time-delayed correlations of the $u$ velocity fluctuations over a range of $Y$ locations in the boundary layer indicate the presence of a linear wavefront in the X-Y plane inclined at approximately 50° to the wall. A similar wavefront inclined at 18° which was detected by Brown and Thomas (1977) in a two-dimensional boundary layer was attributed to an inclined horseshoe vortex model which was able to account for many of the observed features of the flow. The wavefront angle in the present set of results may be overestimated due to the difference in the convective wave speed of the large-scale flow structure and the local mean velocity. The
difference in the angle of inclination of the wavefront between the present set of results and those of Brown and Thomas is probably due to differences in the mean-velocity gradient normal to the wall.
REFERENCES


Jorgensen, F.E.; "Directional Sensitivity of Wire and Fibre Film Probes"; *DISA Information*, No 11, pp 31-37; 1971.


REFERENCES


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Table 3a: Positions of rake and slant-wire probe for vertical hot-wire rake measurements

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Table 5: Y/δ locations of horizontal hot-wire rake measurements
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<td>$\gamma^2$</td>
<td>$\Delta \gamma^2/\gamma^2$ (%)</td>
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Table 13: Decay constants \((k_i, k_o)\) in the exponential-decay model of the spatial variation of coherency in the Y direction.

<table>
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<th>(k_o)</th>
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Table 14: Regression coefficients ($r$) in the exponential-decay model of the spatial variation of coherency in the Y direction.

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Table 15: Decay constants ($k_z$) in the exponential-decay model of the spatial variation of coherency in the Z direction.

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<tr>
<td>6</td>
<td>4.09</td>
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<td>7</td>
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<tr>
<td>9</td>
<td>3.03</td>
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Table 16: Regression coefficients ($r_z$) in the exponential-decay model of the spatial variation of coherency in the Z direction.

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<td>Klebanoff (1955)</td>
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<tr>
<td>Corrsin and Kistler (1955)</td>
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<td>Y location #</td>
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Table 20: Regression coefficients ($r_u$) in the exponential-decay model of the coherency between the upstream sensor and the hot-wire rake with $\Delta X$ spacing only. $n_u$ is the rake sensor number at the same Y location as the upstream sensor.

<table>
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<th>$n_u = 5$</th>
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<td>0.991</td>
<td>0.991</td>
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Table 21: Y/δ locations of the upstream sensor in the exponential-decay model of the coherency between the upstream sensor and the hot-wire rake with ΔX spacing only. nₜ is the rake sensor number at the same Y location as the upstream sensor.

<table>
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<tr>
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<tr>
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</tr>
<tr>
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Table 22: Angles of inclination and regression coefficients of time-averaged wavefronts constructed from time-delayed correlations of vertical hot-wire rake data.
Fig 1: Distribution of vortices through a two-dimensional, turbulent boundary layer (from Robinson, 1991).
Fig 2: Perspective view of wing-body junction.
Fig 3: Oil flow visualization on the test wall around the wing.
Fig 4: Definition of coordinate axes and free-stream and wall shear-stress angles.
Fig 5: Plan view of measurement locations relative to the wing. The scale on the plot is in inches.
Fig 6: Side view of Virginia Tech boundary-layer tunnel test section.
Fig 7: Hot-wire rake.
Fig 8: Parallel-sensor probe.
Fig 9: Rotatable wall-sensor probe.
Fig 10: Traversable wall-sensor probe.
Fig 11: Frequency response of modified Miller-type anemometer channel 1.
Fig 12: Schematic diagram of the electronic connections for hot-wire rake measurements.
Fig 13: Vertical hot-wire rake measurements.
Fig 14: Horizontal hot-wire rake measurements.
Fig 15: Parallel-sensor probe measurements.
Fig 16: Rotatable wall-sensor probe measurements.
Fig 17: Calibration histograms for rotatable wall-sensor at station 4.
Fig 18: Traversable wall-sensor probe measurements.
Fig 19a: Definition of "inner" coherence length scale ($L_{\gamma}$) at a given frequency.
Fig 19b: Definition of spanwise coherence length scale ($L_{xz}$) for a given frequency.
Fig 20a: Mean-velocity profiles in free-stream coordinates. Y-axis scale applies to the profile at station 0. Remaining profiles are offset successively by 0.3.
Fig 20b: Mean-velocity profiles in free-stream coordinates. Y-axis scale applies to the profile at station 4. remaining profiles are offset successively by 0.3.
Fig 21a: Mean-squared velocity profiles in free-stream coordinates. Y-axis scale applies to the profile at station 0. remaining profiles are offset successively by 0.004.
Fig 21b: Mean-squared velocity profiles in free-stream coordinates. Y-axis scale applies to the profile at station 4. remaining profiles are offset successively by 0.004.
Fig 22a: Power spectra of u velocity fluctuations at station 0 normalized with outer scaling.
Fig 22b: Power spectra of u velocity fluctuations at station 1 normalized with outer scaling.
Fig 22c: Power spectra of $u$ velocity fluctuations at station 2 normalized with outer scaling.
Fig 22d: Power spectra of u velocity fluctuations at station 3 normalized with outer scaling.
Fig 22e: Power spectra of $u$ velocity fluctuations at station 4 normalized with outer scaling.
Fig 22f: Power spectra of u velocity fluctuations at station 5 normalized with outer scaling.
Fig 22g: Power spectra of u velocity fluctuations at station 6 normalized with outer scaling.
Fig 23a: Power spectra of u velocity fluctuations at station 0 normalized with inner scaling.
Fig 23b: Power spectra of u velocity fluctuations at station 1 normalized with inner scaling.
Fig 23c: Power spectra of $u$ velocity fluctuations at station 2 normalized with inner scaling.
Fig 23d: Power spectra of u velocity fluctuations at station 3 normalized with inner scaling.
Fig 23e: Power spectra of $u$ velocity fluctuations at station 4 normalized with inner scaling.
Fig 23f: Power spectra of u velocity fluctuations at station 5 normalized with inner scaling.
Fig 23g: Power spectra of u velocity fluctuations at station 6 normalized with inner scaling.
Fig 24a: Spatial variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.041$, $\Delta X_u/\delta = -0.179$, $\Delta Z_u/\delta = 0.003$. 
Fig 24b: Spatial variation of coherency between the \( u \) velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at \( Y_{1} \delta = 0.072, \Delta X_{1} / \delta = -0.179, \Delta Z_{1} / \delta = 0.003. \)
Fig 24c: Spatial variation of coherency between the $u$ velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.099$, $\Delta X_U/\delta = -0.179$, $\Delta Z_U/\delta = 0.003$. 
Fig 24d: Spatial variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.128$, $\Delta X_u/\delta = -0.179$, $\Delta Z_u/\delta = 0.003$. 
Fig 25a: Spectral variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.041$, $\Delta X_u/\delta = -0.179$, $\Delta Z_u/\delta = 0.003$. 
Fig 25b: Spectral variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.072$, $\Delta X_u/\delta = -0.179$, $\Delta Z_u/\delta = 0.003$. 
Fig 25c: Spectral variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_c/\delta = 0.099$, $\Delta X_c/\delta = -0.179$, $\Delta Z_c/\delta = 0.003$. 
Fig 25d: Spectral variation of coherency between the u velocity fluctuations measured by the upstream sensor and the hot-wire rake at station 3. The upstream sensor is at $Y_u/\delta = 0.128$, $X_u/\delta = -0.179$, $Z_u/\delta = 0.003$. 
Fig 26a : Comparison between the "upper" Y coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same Y location at station 0.
Fig 26b: Comparison between the "upper" \( Y \) coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same \( Y \) location at station 1.
Fig 26c: Comparison between the "upper" Y coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same Y location at station 2.
Fig 26d: Comparison between the "upper" Y coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same Y location at station 3.
Fig 26e: Comparison between the "upper" Y coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same Y location at station 4.
Fig 26f: Comparison between the "upper" $Y$ coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same $Y$ location at station 5.
Fig 26g: Comparison between the "upper" Y coherence length scales measured by the upstream sensor and the hot-wire rake sensor at the same Y location at station 6.
Fig 27a: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 0. Sensor #1 is located at $Y/\delta = 0.014$. Solid line represents exponential decay with $k_i = 1.44$. 
Fig 27b: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 1. Sensor #1 is located at Y/δ = 0.035. Solid line represents exponential decay with k = 1.34.
Fig 27c: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 2. Sensor #1 is located at $Y/\delta = 0.035$. Solid line represents exponential decay with $k_i = 1.34$. 
Fig 27d: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 3. Sensor #1 is located at $Y/\delta = 0.041$. Solid line represents exponential decay with $k_i = 1.18$. 
Fig 27e: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 4. Sensor #1 is located at $Y/\delta = 0.039$. Solid line represents exponential decay with $k_i = 1.11$. 
Fig 27f: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 5. Sensor #1 is located at \(Y/\delta = 0.034\). Solid line represents exponential decay with \(k_i = 1.18\).
Fig 27g: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 6. Sensor #1 is located at Y/δ = 0.035. Solid line represents exponential decay with k_i = 1.30.
Fig 28a: Spatial variation of coherence in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 0. Sensor #16 is located at Y/δ = 0.662. Solid line represents exponential decay with k = 1.53.
Fig 28b: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 1. Sensor #16 is located at Y/δ = 0.660. Solid line represents exponential decay with k₀ = 1.54.
Fig 28c: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 2. Sensor #16 is located at Y/δ = 0.645. Solid line represents exponential decay with k_0 = 1.41.
Fig 28d: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by rake #16 and the rest of the rake at station 3. Sensor #16 is located at $Y/\delta = 0.753$. Solid line represents exponential decay with $k_o = 1.50$. 
Fig 28e: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 4. Sensor #16 is located at $Y/\delta = 0.666$. Solid line represents exponential decay with $k_o = 1.58$. 
Fig 28f: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 5. Sensor #16 is located at $Y/\delta = 0.621$. Solid line represents exponential decay with $k_0 = 1.63$. 

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Fig 28g: Spatial variation of coherency in the Y direction between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 6. Sensor #16 is located at Y/δ = 0.666. Solid line represents exponential decay with k_y = 1.71.
Fig 29a: Spectral variation of coherency between the u velocity fluctuations measured by sensor #1 and the rest of the rake at station 3. Sensor #1 is located at $Y/\delta = 0.011$. 
Fig 29b: Spectral variation of coherency between the u velocity fluctuations measured by sensor #16 and the rest of the rake at station 3. Sensor #16 is located at $Y/\delta = 0.753$. 
Fig 30a: Spectral variation of "inner" coherence length scales ($L_{yi}$) at all stations. $Y$ locations on the legend apply to the "fixed" sensor in the measurement.
Fig 30b: Spectral variation of "outer" coherence length scales ($L_{yc}$) at all stations. $Y$ locations on the legend apply to the "fixed" sensor in the measurement.
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$\beta = \beta_m$
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\[ \beta = \beta_m \]
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<table>
<thead>
<tr>
<th>$Y/\delta$</th>
<th>$Y^+$</th>
<th>$\beta_R$s (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.021</td>
<td>40.6</td>
<td>15</td>
</tr>
<tr>
<td>0.033</td>
<td>64.1</td>
<td>15</td>
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<tr>
<td>0.052</td>
<td>102</td>
<td>10</td>
</tr>
</tbody>
</table>
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VITA

The author was born on February 20, 1962 in Johor Baru, Malaysia. He was awarded a Bachelor's degree in engineering with honors after completing the Mechanical Engineering program at the National University of Singapore in March, 1986. Upon graduation, he worked as a research assistant for a year before enrolling in the Masters of Engineering (M.Eng) program at the same university. He completed his M.Eng degree in July, 1989 and subsequently joined the Aerospace and Ocean Engineering Department at Virginia Polytechnic Institute and State University to pursue a Ph.D in Aerospace Engineering. He is currently a student member of AIAA.