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Detailed documentation of the direct effects of large eddy break-up devices on the turbulence structure in turbulent boundary layers

Trigui, Nizar, Ph.D.
The Ohio State University, 1991

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UMI
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Ann Arbor, MI 48106
Detailed Documentation of the Direct Effects of Large Eddy Break-Up Devices on the Turbulence Structure in Turbulent Boundary Layers

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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* * * * *

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Abstract

The direct effect of a single Large Eddy Break Up device on the turbulence structure in a turbulent boundary layer was investigated by acquiring detailed three dimensional measurements of all velocity components in the near field of the manipulator.

It was found that the incoming large vortical structures (eddies with scales of the order of the boundary layer thickness) are completely suppressed by the LEBU. The suppression of these large scale structures results in a drastic reduction of the entrainment of high speed potential flow. In turn, this results in a reduction of the growth rate of the boundary layer and therefore of the local skin friction, as suggested by the momentum theorem.

It was also found that the suppression of these size eddies is attributed to a direct inhibition of the normal component of velocity by the manipulator as they travel over it, and that the streamwise and spanwise fluctuations observed on top of the manipulator downstream of its leading edge are merely passive "scars" of these incoming large vortical structure, not associated to any significant active transport of momentum.

The smaller structures residing lower within the boundary layer were found to
be not directly effected by the manipulator. However, these structures were found to be indirectly effected by the overall circulation field around the manipulator that appears to either bring them closer to the wall and/or decrease their angle of inclination. Furthermore, being trapped under the manipulator, these structures are shielded from any interaction with the high speed potential flow (a major energy source), which in turn leads to a weakening of scales on a wider spectrum, as suggested by the energy cascade model.

Moreover, the wake of the manipulator was found to act as an extension to the manipulator itself to inhibit the normal component of velocity therefore shielding against normal momentum transfer between the structures trapped underneath the manipulator and the outer part of the flow field. This shielding effect is achieved by the localized introduction of small, energetic structures in the wake of the manipulator which are completely uncorrelated with those in the rest of the boundary layer.
To My wife

Hend
Acknowledgments

I would like to express my deepest gratitude to my advisor, Yann G. Guezennec, for his advice and guidance throughout the course of my Ph. D. program. His patience and enthusiasm during the hard years of this study made it possible to overcome what seemed to be insurmountable obstacles at times. I would also like to thank my dissertation committee for their comments and valuable time.

To my fellow graduate students, Woong-Chul Choi and Tom Gieseke, and to the dependable Dave Moyer, I express my gratefulness for their help and friendship over the years.

On a more personal level, I would like to thank my wife, Hend, for her patience and constant encouragements that always kept me going, my son, Amin, for bringing so much joy to my life, and my parents, Mohamed and Souad, and my brothers and sisters for implanting in me the love of knowledge and for believing in my abilities.

This work was partially supported by the National Science Foundation under Grant MSM-8709154 and the Air Force Office of Scientific Research under Grant 89-0434. Their support is gratefully acknowledged. Some of the computations for this investigation were performed on the Cray Y-MP at the Ohio Super Computer
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$C_f$  Local skin friction coefficient
$E_u$  Spectral energy associated with streamwise velocity fluctuations
$E_v$  Spectral energy associated with normal velocity fluctuations
$E_w$  Spectral energy associated with spanwise velocity fluctuations
$P$  Probability density function
$Re_\theta$  Reynolds number based on momentum thickness
$R_{\alpha\beta}$  Components of the two-point space-time correlation tensor
$T_u$  Integral time scale associated with streamwise velocity fluctuations
$T_v$  Integral time scale associated with normal velocity fluctuations
$T_w$  Integral time scale associated with spanwise velocity fluctuations
$U$  Mean streamwise velocity
$U_\infty$  Free-stream velocity
$V$  Mean Normal velocity
$W$  Mean spanwise velocity
$f$  Frequency
$t$  Time
$u$  Streamwise velocity fluctuation
<table>
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<tr>
<td>$u^+$</td>
<td>Streamwise velocity non-dimensionalised by inner wall variables</td>
</tr>
<tr>
<td>$u'$</td>
<td>R.m.s value of the streamwise velocity fluctuation</td>
</tr>
<tr>
<td>$\bar{u}v$</td>
<td>Normal turbulent momentum flux</td>
</tr>
<tr>
<td>$v$</td>
<td>Normal velocity fluctuation</td>
</tr>
<tr>
<td>$v'$</td>
<td>R.m.s value of the normal velocity fluctuation</td>
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<tr>
<td>$w$</td>
<td>Spanwise velocity fluctuation</td>
</tr>
<tr>
<td>$w'$</td>
<td>R.m.s value of the spanwise velocity fluctuation</td>
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<td>$x$</td>
<td>Downstream distance from the leading edge</td>
</tr>
<tr>
<td>$x_0$</td>
<td>Downstream position of the leading edge of the LEBU</td>
</tr>
<tr>
<td>$y$</td>
<td>Normal distance from the wall</td>
</tr>
<tr>
<td>$y^+$</td>
<td>Normal distance from the wall non-dimensionalised by inner wall variables</td>
</tr>
<tr>
<td>$z$</td>
<td>Spanwise distance from the center line of the plate</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Boundary layer thickness</td>
</tr>
<tr>
<td>$\delta_0$</td>
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<tr>
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<tr>
<td>$\delta_3$</td>
<td>Energy thickness</td>
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<tr>
<td>$\xi$</td>
<td>Non-dimensional distance from the leading edge of the LEBU</td>
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CHAPTER I

INTRODUCTION

1.1 Relevant Literature

Over the last twenty or thirty years, our view of turbulence has evolved from a purely random fluctuation field in space and time to a field dominated by a hierarchy of quasi-deterministic eddies interacting in a complex fashion. While the description of these eddies and the mechanisms responsible for their evolution are still widely debated, this conceptual view has led to the development of a large number of turbulence control schemes, whereby one alters some specific eddies or their interaction with other scales to achieve global changes in the overall characteristics of a turbulent flow. Owing to their ubiquity in engineering applications, much effort has been devoted to turbulent boundary layers, particularly to modify their viscous drag characteristics.

Many schemes have been suggested to reduce viscous drag by means of modifying the fluid properties, such as addition of polymers, by means of modifying the surface geometry, such as riblets, or by means of modifying the interaction of the
different scales in the turbulent boundary layer, such as outer flow manipulators. A comprehensive review of the various techniques and their potential applications is given by Bushnell (1983). Among the various approaches investigated, the parallel plate manipulators, also referred to as Large Eddy Break Up Devices or LEBU’s for short, have been among the most promising.

The effect of these devices on turbulent boundary layers has been studied extensively in the past decade. The first studies were aimed at investigating the potential of these devices for viscous drag reduction or at least substantial local skin friction reduction. Corke et al. (1982) have shown that a carefully designed pair of two-dimensional flat plates, placed in a tandem configuration within the boundary layer, can yield local skin friction reduction of up to 35% and a net drag reduction of up to 20%. Comparable devices have been investigated by Hefner et al. (1983), Bertelrud et al. (1982), Nguyen et al. (1984), Anders and Watson (1985), Coustols et al. (1987), and many others. The results obtained varied considerably from one study to another and were sometimes conflicting. While there was general agreement about the ability of these devices to produce sizable local skin friction reduction, there was considerable controversy to the extent, if any, of the net drag reduction potential of these devices.

This discrepancy prompted a different type of studies that was aimed at parametrically optimizing the geometry of the LEBU’s. One such an investigation was conducted by Plesniak and Nagib (1985). These investigations indicated the
marked sensitivity of the drag reduction magnitude to the geometry of the LEBU's and identified the acceptable parameters to achieve net drag reduction.

However, from such studies, it became clear that a more detailed understanding of the effects of these manipulators on the turbulence structure was required to further optimize these devices and make them less sensitive to minute geometrical changes. A number of studies dealt with documenting the changes in the various turbulence characteristics downstream of the LEBU's and identifying some possible mechanisms for these changes.

Guezennec and Nagib (1985,1990) obtained detailed measurements of various unsteady quantities in LEBU manipulated turbulent boundary layers including Reynolds stress, turbulence production, and intermittency function. They found that the velocity and vorticity fluctuations associated with the large scales were significantly inhibited by the manipulator blades and the vorticity they shed in their wakes. They also found that the manipulated boundary layers exhibited a reduced intermittency in the outer region of the boundary layer and that the turbulent momentum transfer was drastically inhibited in the normal direction. They suggested a combination of several mechanisms at play to produce the skin friction reduction observed. Those include a direct inhibition of the normal velocity component of the oncoming large eddies by the manipulators, a redistribution of the turbulent kinetic energy by the wake of the manipulators and an alteration of the mean momentum distribution by the mean circulation field around the
manipulators.

Based on the concept of a pair of counter-rotating large rollers dominating the logarithmic region of the boundary layer during the turbulence production cycle as suggested by Guezenne (1985), Nagib et al. (1987) performed a mapping of the full three-dimensional structure of the most energetic events linked to the production cycle in a LEBU manipulated boundary layer. Their results indicated that the roller structures were still identifiable in the manipulated boundary layer. However, their spatial extent and their strength were substantially reduced. The authors therefore concluded that the LEBU's act on the boundary layer by reducing the size and strength of the structures in the logarithmic region of the boundary layer.

In addition to measuring different turbulent quantities, Blackwelder and Chang (1986) and Chang and Blackwelder (1990) estimated different length scales and correlations in a passively heated boundary layer manipulated by a pair of LEBU's. Their results indicated that the Taylor microscales and the integral length scales were initially reduced, that the Taylor microscales fully recovered within a short region behind the LEBU’s while the integral length scales had a very slow rate of recovery. Their results also indicated that the large eddy scales were substantially reduced in all three directions and that the standard deviation of the position of the turbulent/non turbulent interface was drastically reduced. Blackwelder and Chang concluded that the manipulators promote drag reduction indirectly by decreasing
the growth of the boundary layer as suggested by the momentum theorem. They argued that the decrease in the boundary layer development is mainly due to the inhibition of the entrainment process in the intermittent region, which in turn causes a drastic decrease in the eddy scales in the outer and logarithmic regions. Their results are in agreement with the trends for the behavior of the turbulent/non-turbulent interface first observed by Corke et al. (1982) and later quantified by Westphal (1986) and Savill and Mumford (1988).

More recently, in an initial study to determine the effects of LEBU's on the transport of scalar contaminants and in a later detailed study of the differences in the transport mechanisms of momentum and of scalar contaminants in a LEBU manipulated boundary layer, Trigui and Guezenec (1990) were able to confirm the results of the above mentioned studies. In addition, they found that the relaxation of all the measured turbulence quantities is first initiated in the near wall region and propagated throughout the boundary layer at a rate commensurate with the turbulent lateral diffusion, hence requiring 50 to 80 boundary layer thicknesses to reach the outer edge. They also found that the heat and momentum field are effected differently by the presence of the manipulators. Since the manipulators were in thermal equilibrium with the flow and therefore no equivalent to a momentum deficit was observed in the thermal field, Trigui and Guezenec concluded that the turbulent wake shed by the blades plays a dominant role in the observed dissimilarities of effects in the momentum and thermal fields.
Other investigators, such as Lamey et al. (1990) and others, presented results that were, even if they didn't themselves stated it, in support of the overall drawn conclusion, namely that through an inhibition of the entrainment process, the LEBU's reduces the scales of the eddies in the outer and logarithmic region, resulting in a drastic decrease of the normal momentum transport and therefore a decrease in the local skin friction. This conclusion was further supported by the failure of the LEBU's to produce any skin friction reduction in fully developed turbulent channel flow as reported by Prabhu et al. (1988). Actually, since the entrainment is the main mechanism through which the large scale eddies extract their energy from the potential flow and since it has been shown by Chen and Blackwelder (1987) and others that the near wall structure responsible for most of the turbulent production is directly linked to the outer large structures, an inhibition of the entrainment process causing a reduction in the size and strength of the large outer structures can definitely induce a reduction in the turbulence production and therefore in the local skin friction.

1.2 Objectives

While all the conclusions from the above mentioned investigations seem to support the idea that the inhibition of the entrainment process is responsible for the skin friction reduction observed in LEBU manipulated boundary layers, the direct effects of the blades on the turbulence structure that cause this entrainment in-
hibition are still not understood. The mechanisms suggested by Guezennec and Nagib (1985, 1990) and further supported by Trigui and Guezennec (1990) are primarily inferred from measurements taken downstream of the LEBU's where it is hard to quantify exactly the relative role of these various processes. While all the effects on the turbulence structure are believed to occur in the immediate vicinity of the LEBU's, there is no documentation of the near flow field around and at the trailing edge of the manipulators. Moreover, there is no documentation of these direct effects of the manipulators on the incoming large vortical structures as they travel over the manipulators or the interaction of the remainder of these structures with the wake shed by the manipulators.

A more fundamental understanding of these mechanisms is essential for future design of manipulators that possess stronger and longer lasting effects on the turbulence structure. Furthermore, unlike the initial focus of the earlier work on drag reduction, there is a renewed interest in these devices for a variety of applications ranging from local skin friction reduction, to alteration of the transport of scalar contaminants, heat transfer applications, turbulence suppression for optical applications, boundary layer self-noise reduction and drag reduction applications involving a combination of techniques. Experimental investigations of some of these effects have been conducted by Trigui and Guezennec (1990), Lindemann (1986), Sommer and Petrie (1990), Keith et al. (1990), and others.

Up to now, all investigations, with the exception of a flow visualization study by
Savory et al. (1990) to the author's knowledge, have been conducted downstream of the manipulators. From such studies, it is very difficult, if not impossible, to unravel the detailed mechanisms by which the LEBU's actually alter the turbulence structure. In particular, it is impossible to separate the effects of the manipulators on the oncoming large scale structures from the effects of the shed vorticity on what is remaining of these structures downstream of the manipulators.

Therefore, in this investigation the near field of the LEBU's was investigated in great detail to elucidate these key questions. The effect of a single LEBU on the oncoming large scale structures in the boundary layer before they reach the trailing edge of the manipulator were documented in detail. Similarly, the effects of the wake shed by the LEBU on the turbulence structure in the boundary layer were also documented in detail. Moreover, the space evolution and relaxation rate of the separate mechanisms identified as responsible for the observed local skin friction reduction were also investigated.

In addition to presenting some of the conventional one- and two-point statistical turbulence measurements, the effects of the LEBU on the large-scale vortical structures and their respective relaxation rates were documented through a reconstruction of conditionally-averaged three-dimensional velocity field around the manipulator and immediately downstream of it.
CHAPTER II

EXPERIMENTAL SETUP AND INSTRUMENTATION

2.1 Experimental Setup

2.1.1 Wind tunnel

The experiments were performed in a low turbulence wind tunnel at The Ohio State University in the Mechanical Engineering Department. This wind tunnel operates in an open return mode and is capable of producing air flows ranging from 0 to 40 m/s with a turbulence intensity of less than 0.1%. In this tunnel, the flow enters from the room through a bellmouth, passes through a 5 mm mesh, 15 cm long, honeycomb and three turbulence control screens before getting to a 1.5 m long settling chamber. The flow then undergoes a smooth two-dimensional 9:1 contraction before entering the test section. The contraction profile is a smooth fifth-order polynomial designed to avoid any flow separation. At the exit of the test section, the flow undergoes a mild diffuser before reaching a 0.9 m diameter vane-axial fan. The fan is powered by a 20 hp DC motor, which operates in a closed loop
configuration with a variable speed controller. This controller guarantees constant speeds, within 0.001%, and can be adjusted either manually or by supplying an external signal with a set frequency. A schematic of the wind tunnel is shown in Figure 2-1.

2.1.2 Test section

The test section has a rectangular cross sectional area of 0.6 m by 0.45 m and is 3.6 m long. It has a heavy 2.5 cm thick aluminum frame and four large 2.5 cm thick Plexiglas windows. The windows allow easy access to the instrumentation and offer good means to visualize the flow and monitor the hardware inside the
The test section is equipped with a three dimensional traversing mechanism. The streamwise motion of this mechanism is obtained by mounting the whole apparatus on a large carriage supported by linear bearings riding on two parallel precision ground shafts. The shafts are bolted on top of the test section parallel to the flow direction. A rack and pinion assembly controls the motion of the carriage in this direction. The rack is fastened to the top of the test section, parallel to the shafts, and the pinion is attached through a speed reducer to a stepper motor mounted on the carriage itself. This carriage can travel the whole length of the test section.

The normal motion of the traversing mechanism is obtained by a similar technique. A second smaller carriage is mounted on linear bearing riding on another pair of precision ground shafts. These shafts are bolted to the large carriage perpendicular to its surface. A lead screw mounted parallel to the shafts and driven directly by a second stepper motor controls the motion in this direction. A rigid, 1 cm diameter, 1 m long, shaft attached to the small carriage protrudes into the test section through a streamwise slot in the roof of the test section. The slot extends over the whole length of the test section and is sealed by a pair of long rubber strips mounted on either side of it. The rubber seals ensure free movement of the shaft in both the streamwise and normal directions inside the test section while blocking any leakage of air in or out of the test section. The total traverse in this
direction spans the entire height of the test section.

The spanwise motion is obtained by mounting a miniature linear traversing mechanism to the end of the protruding shaft, perpendicular to its axis. The miniature traverse, supports a modular probe support holder. A stepper motor mounted on the small carriage outside the test section controls the motion in this direction through a miniature steel cable wound on its shaft and directed through a set of miniature pulleys to the probe support. The total traverse in this direction is limited to 5 cm on either side of the test section centerline. This distance was deemed sufficient for the study undertaken, especially since this part of the assembly is inside the test section and therefore needs to be as small as possible to minimize any disturbance to the flow. In addition, the different probe supports were carefully designed to keep the miniature spanwise traverse outside the boundary layer and always downstream of the measurement position.

The traversing mechanism has a resolution of 0.127mm in all three directions. It can be controlled either manually or by a computer-generated pulse train. With all the instruments in the test section, including a positioning rack that will be described later, the turbulence intensity in the test section does not exceed 0.1% at all free stream velocities over the frequency range of 1 to 10,000 Hz. A schematic of the test section and the traversing mechanism assembly is shown in Figure 2-2.
2.1.3 Test plate

The turbulent boundary layer developed over a smooth Plexiglas flat plate. This plate spanned the entire width and length of the test section. It was suspended 0.15 m above the floor of the test section leaving an effective flow cross section of 0.45 m by 0.45 m on the measurement side. The leading edge of the plate was machined to a very sharp 20 degree level on the bottom side. A 20 cm strip of #24
grit sand paper was attached 10 cm downstream of the leading edge to promote a uniform transition and to insure good two-dimensionality of the boundary layer. A 10 cm long flap was mounted at the trailing edge of the plate and was adjusted to control the overall circulation around the plate. The flap position was carefully adjusted to insure that the stagnation point was on the upper side of the plate, therefore preventing the formation of any separation bubble on the measurement side. The flap angle was checked by using a smoke-wire to visualize the flow over the plate’s leading edge and by taking a set of velocity profiles just downstream of the leading edge. A schematic diagram of the plate assembly is shown in Figure 2-3.

2.1.4 Positioning rack

In order to assist in the data acquisition of the second experiment as will be explained later, a special probe positioning rack was designed to support a probe (used as a reference probe) while maintaining minimum disturbance to the turbulent boundary layer flow. The rack was composed of a vertical guiding rectangular shaft on which a tight collar was mounted. The collar supported a long thin bar on which the probe holder was fastened. The collar had a single degree of freedom, namely it could only slide vertically along the guiding shaft. Similarly, the thin bar could only slide horizontally in the collar. The probe holder, itself, could rotate around its axis to any angle. The guiding shaft was directly bolted to the side of
the test plate and could be positioned at any downstream location by a series of 0.5 cm diameter holes in the test plate. The mounting holes were located 5 cm from the edge of the plate and were carefully sealed when not in use. A schematic of the positioning rack assembly is shown in Figure 2-4.

### 2.1.5 Manipulator (LEBU)

The manipulator was made out of a 5 cm wide, 0.127 mm thick blued spring steel strip. This type of strip is available commercially as shim stock. Great care was taken to clean the edges of the strip. In addition, in order to avoid any wrinkling of the surface of the thin manipulator due to mis-alignment of the fixed mounts or
due to any large build up of stress on the surface of the manipulator itself, a pair of holding brackets were designed. These brackets had two threaded holes that hosted the tensioning screws, a thin long slit that hosted the manipulator and a number of set screws used to hold the manipulator in this slit.

In order to allow for a greater liberty in adjusting the height of the manipulator in the boundary layer, the tensioning screws were attached to fixed mounts through
long normal slits. The fixed mounts were themselves fastened to the test plate. A schematic of the LEBU and the assembly is shown in Figure 2-5.

2.2 Instrumentation

The air free stream velocity and temperature in the test section were constantly monitored using, respectively, a pitot tube in conjunction with a Validyne pressure transducer, model P305 D-1-N-1-22-S-4, and an Omega linear thermistor array. Three hot wire probes were used during the course of the investigation: a single hot-wire probe, model TSI 1218-T1.5, a miniature two-component hot film probe, model TSI 1247-10, and a three-component hot film probe, model TSI 1295-AV-20. A rack of home made constant temperature anemometers was used to operate the different sensors. These anemometers provided adequate frequency response in excess of 50 kHz with hot-wire sensors and 10 kHz with hot-film sensors. They also provided dynamic compensation, adjustable overheat setting, and analog signal pre-linearization.

All signals were digitally acquired using a 12 bit, 16 channel A/D interface mounted on a Masscomp 55-S-05 workstation. The A/D had a maximum sampling rate of 333 kHz and resolution of 4.88 mV. The Masscomp workstation was also equipped with a 12 bits, 2 channel D/A interface that was used to generate the pulse trains needed to drive the different components of the traversing mechanism and the proper voltages needed to drive the tunnel controller. Although the
Figure 2.5: Schematic of LEBU Manipulator
A/D did not possess sample and hold circuitry, it was programmed to acquire successive channels at the maximum allowable rate resulting in a 3.33 microseconds delay between any two successive channels and 16.66 microseconds maximum delay between the first and last sampled channels. This delay was deemed acceptable at the typical sampling rate used throughout the study, namely 7 kHz.

The Masscomp workstation was equipped with a 477 Megabytes hard disk dedicated to raw data temporary storage. The raw data was archived on 8mm, 2.2 Gigabytes, tapes for permanent storage. The initial data reduction to extract the different velocity components, statistics of the flow, and all the space-time correlations was performed on the YMP/864 supercomputer at the Ohio State Super Computer Center. The rest of the data processing was performed on a DEC 3100 workstation equipped with a 1GB hard disk drive. The post-processing was performed on an Iris workstation in the Computational & Flow Visualization Laboratory at the Mechanical Engineering Department.

In addition to an assortment of fast Apollo, Silicon Graphics, and Sun workstations, this laboratory was also equipped with a regular PostScript printer, model Laserwriter II, and a color printer, model Seiko CH-5500, a color graphic recorder for making slide and 16mm movies, model Matrix 6000.
CHAPTER III

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

3.1 Experimental Procedure

The investigation was performed in two stages. An experimental investigation was first performed downstream of the manipulator to document the overall effects of the LEBU configuration on the boundary layer characteristics. Then, a second experimental investigation was performed to reconstruct the flow in the immediate vicinity of the manipulator and at few locations far downstream of the trailing edge of the manipulator. As will be explained below, the second experimental investigation provided the means of separately documenting the different mechanisms responsible for the overall changes in the turbulence structure of the boundary layer and their individual spatial evolution and relaxation rates.

3.1.1 Hot wire calibration

The different probes used throughout the study were calibrated directly inside the test section. In order to insure good dynamic response and minimum dependency
on free stream temperature, all hot-wire sensors were set to operate at an overheat ratio of 1.7. Each probe was positioned in the free stream at different tunnel speeds. After reaching steady state, a 1000 data samples was acquired at a frequency of 50 Hz. The signals acquired consisted of the hot-wire sensors linearized signals, the pressure transducer output, and the output from the linear thermistor array. A total of 20 free stream velocities, ranging from 5 to 15 m/s, were typically used in each calibration run.

3.1.2 Documentation of the downstream effects

The boundary layer investigated was nominally a zero pressure gradient, flat plate boundary layer with a free-stream velocity of 10 m/s and Reynolds number based on momentum thickness, $Re_\theta$, ranging from 1700 to 4000. A flat plate manipulator (LEBU) was placed 1.2 m from the leading edge at a small angle of attack of approximately 2 degrees. This location corresponded to a Reynolds number based on momentum thickness of about 1900. The LEBU was suspended 1.9 cm above the plate and was carefully tensioned to avoid any vibration. The regular boundary layer thickness, $\delta_0$, at this location was nominally 3.17 cm. This meant that the LEBU configuration corresponded to a cord length of 1.6 $\delta_0$ and to a height of 0.6 $\delta_0$. This configuration was chosen to maximize the effects of the manipulator on the boundary layer as suggested by Plesniak and Nagib (1985). A schematic of the LEBU configuration is given in Figure 3-1.
24 Grit Sand Paper

LEBU

U=10 m/s

1.2 m

1/δ₀ = 1.6  h/δ₀ = 0.60  α = 2°

Figure 3.1: LEBU Configuration
The mean boundary layer characteristics were documented by acquiring a set of profiles of all three components of velocity along the plate centerline at various downstream stations. The actual locations of the measurement stations are tabulated in Figure 3-2 in terms of the number of boundary layer thicknesses downstream of the leading edge of the manipulator, $\xi = (x - x_0)/\delta_0$.

A total of 49 points was collected at each profile. The points were equally spaced over a normal distance ranging from 100 wall units to 1.5 boundary layer thicknesses from the wall. At each point, long time records of the three velocity components was acquired at a frequency of 7,000 Hz. A total of 50,000 samples was acquired in each record.

In order to obtain more accurate boundary layer integral values, another documentation of both cases was performed using a single hot-wire probe. This probe had the advantage of being able to get much closer to the wall, namely within 10 wall units. At the exception of the integral boundary layer values and the skin friction values, all results that will be presented were evaluated from the three-component probe data. The boundary layer integral thicknesses and the shear velocities were evaluated from the single component probe data.

### 3.1.3 Velocity field reconstruction

This experiment consisted in acquiring five simultaneously sampled hot-wire signals: two velocity components at a fixed reference probe ("detection probe").
Figure 3.2: Measurement Stations for Single Probe Experiment
and three velocity components at a mapping probe traversed over a coarse three-dimensional sampling grid. In order to study the evolution of the large incoming vortical structures as they pass over the manipulator, the fixed probe was positioned 0.2 $\delta_0$ ($\xi = -0.2$) upstream of the leading edge of the manipulator at the same height.

A mapping was performed on $4 \times 15 \times 31$ mesh in the streamwise, normal and spanwise directions, respectively. The first normal-spanwise cross plane corresponded to a zero streamwise separation between the detection and the mapping probes. The second, third, and fourth cross stream planes corresponded to separation of 0.4 $\delta_0$, 0.8 $\delta_0$, and 1.2 $\delta_0$.

In each of the cross stream planes, the mapping spanned a total distance ranging from 0.16 $\delta_0$ to 1.2 $\delta_0$ in the normal direction and from -1.2 $\delta_0$ to 1.2 $\delta_0$ in the spanwise direction. The spatial resolution in either the normal or spanwise direction was therefore equal to 0.08 $\delta_0$ or 75 wall units. As mentioned above, the spatial resolution in the streamwise direction was much coarser, namely 0.4 $\delta_0$. A schematic for this part of the experiment is shown in Figure 3-3.

The reference probe was then positioned 0.2 $\delta_0$ downstream of the trailing edge of the manipulator ($\xi = 1.8$) and a similar mapping to the one described above was performed. The position of the reference probe was chosen as to best tag the shed vorticity from the LEBU. In order to resolve smaller scales in the wake region, it was deemed necessary to improve the spatial resolution of the mapping in the
Figure 3.3: Mapping Stations for the Two Probe Experiment Around the LEBU normal direction. Therefore, three additional horizontal grid lines were added at $y/\delta = 0.52$, $y/\delta = 0.6$, and $y/\delta = 0.68$. The addition of these points yielded a spatial resolution of the order of 0.04 $\delta_0$ or 32.5 wall units in the wake region. A schematic for this part of the experiment is shown in Figure 3-4.

At each grid point, long time records of the five velocity components was acquired at a frequency of 7,000 Hz, i.e. every 2 viscous time units ($\Delta t^+ = 2$). A
Figure 3.4: Mapping Stations for the Two Probe Experiment Immediately Downstream of the LEBU

\[ d/\delta_0 = 0.20 \quad \Delta x_1/\delta_0 = 0.00 \quad \Delta x_2/\delta_0 = 0.40 \quad \Delta x_3/\delta_0 = 0.80 \quad \Delta x_4/\delta_0 = 1.20 \]
\[ \Delta y/\delta_0 = 0.08 \quad \Delta z/\delta_0 = 0.08 \quad \Delta y^+ = 75 \quad \Delta z^+ = 75 \]

Acquisition Frequency = 7000Hz \( (\Delta t = 2) \)

Number of Samples/Channel = 50,000
total of 50,000 samples per channel was acquired in each record.

The different parts of the experiment described above had to be performed twice. The two-component detection probe was initially oriented to acquire the streamwise, \( u \), and normal, \( v \), velocity components, and then was rotated to acquire the streamwise, \( u \), and spanwise, \( w \), velocity components. This procedure was only implemented due to the fact that only one single three-component probe was available for this experiment. The procedure would have been less tedious and certainly much faster have we had two three-component probes.

This experiment as well as the experiment described in the earlier sub-section were conducted for the case of a naturally developing turbulent boundary layer at the same free stream velocity over the same flat plate. This configuration had to be investigated in order to verify the validity of the acquired data and in order to establish a basis for comparison. In the rest of the dissertation, this latter case will be referred to as the "regular" case. The one described above will be referred to as the "manipulated" case.

It is to notice that only half of the points in the spanwise direction actually needed to be collected due to symmetry of the statistics in the spanwise directions, and that a few grid points could not be measured due to the mapping probe interference with the LEBU or the detection probe. These few points were obtained through physical reasoning and careful interpolation of the neighboring points. The location of the measured points is shown in Figure 3-5 for the mapping of
the regular boundary layer, in Figure 3-6 for the mapping around the LEBU in the manipulated boundary layer, and in Figure 3-7 for the mapping downstream of the LEBU in the manipulated boundary layer. These figures represent cross stream mapping planes in the different experiments. In each of these figures, filled circular dots represent actual measurement points, hollow square dots represent points that could not be directly measured due to probes interference (these points were estimated from careful interpolations in the spanwise direction), triangular hollow dots represent points that could not be directly measured due to probe-LEBU interference (these points were estimated through careful interpolations in the normal direction or set to zero if corresponding to points on the LEBU itself), and circular hollow dots that represent points obtained from statistical symmetry or anti-symmetry which ever appropriate for the correlation term. The symmetry or anti-symmetry of the each of the correlation terms is determined from the following set of equations.

\[
R_{uu}(\Delta x, y, z; \Delta t) = R_{uu}(\Delta x, y, -z; \Delta t) \\
R_{uv}(\Delta x, y, z; \Delta t) = R_{uv}(\Delta x, y, -z; \Delta t) \\
R_{uw}(\Delta x, y, z; \Delta t) = -R_{uw}(\Delta x, y, -z; \Delta t) \\
R_{vu}(\Delta x, y, z; \Delta t) = R_{vu}(\Delta x, y, -z; \Delta t) \\
R_{vw}(\Delta x, y, z; \Delta t) = R_{vw}(\Delta x, y, -z; \Delta t) \\
R_{uw}(\Delta x, y, z; \Delta t) = -R_{uw}(\Delta x, y, -z; \Delta t)
\]
3.2 Data Reduction

3.2.1 Hot wire calibration and velocity extraction

Upon completion of the calibration acquisition, the pressure transducer signals were converted into reference free stream velocities. As described above, during calibration the sensors were positioned outside the boundary layer, therefore they were only responding to a single velocity component, namely the streamwise component. Under such conditions the effective cooling velocity on each sensor is the component of the free stream velocity normal to its axis.

The calibration data for each sensor, namely anemometer voltage output and cooling velocity, was then fitted to a fourth order polynomial using a least square procedure. Typically, an average error of the order of 0.05 % over the whole range of calibration velocities was obtained by this procedure. These polynomial fits were used to generate calibration tables for each sensor. Each table had 4096 entries corresponding to all possible discrete digitized voltage levels of the particular sensor.

\[
R_{wu}(\Delta x, y, z; \Delta t) = -R_{wu}(\Delta x, y, -z; \Delta t)
\]

\[
R_{ww}(\Delta x, y, z; \Delta t) = -R_{ww}(\Delta x, y, -z; \Delta t)
\]

\[
R_{ww}(\Delta x, y, z; \Delta t) = R_{ww}(\Delta x, y, -z; \Delta t)
\]
Points Obtained through Spanwise Interpolations

Measured Points

Test Plate

Points Obtained from Statistical Symmetry

NOT TO SCALE

Figure 3.5: Location of the Measured and Interpolated Points in the Regular Boundary Layer Case
Figure 3.6: Location of the Measured and Interpolated Points in the Mapping Around the Manipulator
Figure 3.7: Location of the Measured and Interpolated Points in the Mapping Immediately Downstream of the Manipulator
After a systematic temperature compensation, all hot-wires sensors signals acquired were converted into cooling velocities. The temperature correction used was similar to that originally proposed by Bearman (1971) which compensates the anemometer output voltage as a function of the overheat ratio and deviation from the calibration temperature.

In the case of the single-component probe, the cooling velocities were equivalent to the streamwise component of velocity. In the case of the two-component probe, a simple sum and difference technique, described in details in Appendix A, was used to extract the appropriate two velocity components from the two cooling velocities. In the case of the three-component probe, an efficient procedure, also described in Appendix A and in Choi (1989), was used to extract the three component of velocity from a system of three non-linear coupled equations.

3.2.2 One point statistics

At each downstream location, means and second order statistics, as well as spectral analysis were performed. Moreover, integral time scales based on all three velocity components were evaluated. Finally, boundary layer profiles were numerically integrated to compute the usual integral thicknesses and shape factors. The local skin friction coefficient along the plate was evaluated using various methods. In the regular boundary layer case, the friction velocity was determined from a standard Clauser plot with the usual constants and also from a two-dimensional momentum
balance equation. In the manipulated case, since it has been shown that the constants in the "law of the wall" do not hold in non-equilibrium boundary layers, only the two-dimensional momentum balance was used to compute the local skin friction coefficients along the plate.

The practical implementation of the momentum balance technique was similar to that used by Corke et al. (1982) and Plesniak et al. (1985). Although such technique is inherently inaccurate, it is the only tool available for reducing the data in manipulated, non-equilibrium turbulent boundary layers short of direct measurement by local skin friction balances. In order to validate the use of the two-dimensional balance technique, velocity profiles were acquired at different spanwise locations on either side of the plate centerline at a few downstream locations. It was found that the boundary layer thickness did not vary by more than 3% over the span of interest. Furthermore, the skin friction results obtained from this technique were only used to perform a relative comparison between the regular and manipulated cases, hence minimizing the inherent inaccuracies of the technique.

3.2.3 Velocity field reconstruction

At each mapping position, in addition to all the usual statistical quantities, such as means, second order moments, and spectral analysis, all nine components of the space-time correlation tensor were computed, yielding $R_{\alpha\beta}(\Delta x, y, \Delta z; \Delta t)$ in both the regular case and the manipulated case. From this, inferences about the
underlying spatio-temporal structure of the flows were made, and other quantities
such as convection velocities, integral scales in space and time were computed in
the usual fashion.

In order to obtain a more physical interpretation of these extensive correlation
measurements, a tool called the stochastic estimation technique was used. This
technique, described in detail in Appendix B, was first introduced by Adrian and
his co-workers (1976, 1979). Recently, it has been used extensively in the con­
text of boundary layers to obtain estimates of conditional eddies, in the sense of
classical conditional ensemble averages, by extracting information from the uncond­
ditional two-point correlation tensor. This technique is very powerful and con­
venient when dealing with three- or four-dimensional data bases, particularly to
investigate a large number of "conditions".
CHAPTER IV

REGULAR BOUNDARY LAYER

In order to demonstrate the effects of the Large Eddy Break Up Device on the mean characteristics of the boundary layer, the regular boundary layer is first documented in this chapter. Not only will the results presented here serve to establish a bench mark for comparison to the manipulated boundary layer, but they will also serve to establish a basis for comparison to the classical literature and therefore act as a testimony of the quality of the measurements and the data reduction techniques.

In the first section of this chapter, the results obtained from single point measurements are presented. These results cover a range of Reynolds number based on momentum thickness from 1900 to 3000 and are obtained from the various downstream velocity profile as described in the previous chapter. In the second section, different aspects of the four-dimensional space-time correlation tensor are presented. This correlation tensor has been obtained from the two point mapping, also described in the previous chapter. In the third and last section of this chap-

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ter, reconstructed velocity fields based on single condition stochastic estimates are presented.

4.1 One Point Statistics

The mean streamwise, normal and spanwise velocity profiles are presented in Figure 4-1 for the seven downstream measurement stations. In this figure, the measurement stations are presented in terms of a non-dimensional distance, \( \xi \), defined earlier as the number of boundary layer thicknesses downstream of the leading edge of the LEBU. While there is no LEBU in the regular case, the stations are labeled in this fashion for comparison with the manipulated results in the next chapter.

All mean velocity components are non-dimensionalized by the free stream velocity. The momentum thickness, \( \delta_2 \), is used through this section to non-dimensionalize the normal distances from the wall.

The streamwise velocity profiles at all seven stations collapse on a single line. This trend indicates a self similar, well behaved, equilibrium boundary layer. The normal and spanwise mean profiles also collapse very well on single lines that lay as expected on the y-axis with a zero value.

The absence of data close to the wall is due to relatively large size of the triple component hot wire probe used to measure the velocity profiles. Since this near wall data is actually needed to obtain accurate boundary layer integral values, as was mentioned in the previous chapter, the same boundary layer was documented
Figure 4.1: Downstream Evolution of the Mean Velocity Profiles
Figure 4.2: Downstream Evolution of the Mean Velocity Profiles in Terms of Inner Variables

using a single component hot wire probe that could be positioned much closer to the wall ($y^+ = 20$). The results from this investigation agree well with the results presented here and confirm the regularity of the boundary layer.

The self-similar behavior is further illustrated by presenting the streamwise velocity profiles in standard Clauser form for the data obtained by the single wire probe, Figure 4-2. In this figure, the profiles are represented in semi-logarithmic coordinates with $u^+$ and $y^+$ representing the velocity and distance from the wall non-dimensionalized in the usual fashion by inner wall variables.

The mean velocity profiles were appropriately integrated to obtain the different boundary layer integral thicknesses. The streamwise evolution of these integral thicknesses is shown in Figure 4-3 and agrees well with the accepted growth rate
In order to eliminate any uncertainties related to the use of the momentum balance to evaluate the shear at the wall, the data of the regular boundary layer was processed using different techniques and the results were compared to the data in the literature. The skin friction coefficients, Figure 4-4, was evaluated using the "Law of the Wall" with the constants given by Coles (1978), using the momentum balance, and the Ludwieg Tillman correlation equation. All techniques yielded similar results. The slight discrepancy between the different curves is attributed to a mild three-dimensionality of the boundary layer and to the experimental uncertainty in evaluating the $d\theta/dx$ and $dU_\infty/dx$ terms in the momentum balance equation. For the purpose of this study, measurements of absolute skin friction
coefficients are not of paramount importance since our aim is to evaluate in relative terms the alteration, if any, of the momentum transport characteristics of a turbulent boundary layer by the passive LEBU manipulators and to try to understand the mechanisms through which this alteration takes place.

The streamwise, normal, and spanwise turbulence intensity profiles are shown in Figure 4-5 for the same downstream locations. In this figure, the different turbulence intensity components are non-dimensionalized by the free stream velocity. All components of the turbulence intensity collapse well on single lines indicating again a well behaved, equilibrium boundary layer. The profile of the streamwise turbulent intensity vector tends towards zero at the outer edge of the boundary layer and reaches a value of 0.065 at the lowest measurement point. The normal
component also tends toward zero at the outer edge of the boundary layer and reach a value of 0.037 at the lowest measurement point. The spanwise component lays, as should be, between the streamwise and normal components profiles and reaches a value of 0.056 at the lowest measurement point. Some scatter in the lower parts of the spanwise turbulence intensity component is observed and is attributed to the spatial resolution of the triple wire probe in the high velocity gradient region.

At first glance, the different components of the turbulence intensity profile seem to be smaller than the widely accepted values reported in the literature. This is however not true if we remember that, due to the size of the triple-component probe used in this experiment, the closest measurement point to the wall was on average about 0.1 boundary layer thickness. This position is much higher than the position where the velocity fluctuations and the Reynolds stresses reach their highest levels.

In fact, the results obtained from the single wire experiment indicated that, lower within the boundary layer, the streamwise turbulence intensity reaches a value of about 0.12, which is indeed the acceptable value reported in the literature. Moreover, the single wire results collapsed well on the streamwise fluctuating profiles presented above, indicating that the scheme used to extract the different velocity component from the triple-component probe data is accurate and that the relatively large spatial resolution of the triple-component probe does not affect the
quality of the results.

The different components of the turbulent momentum flux are presented in Figure 4-6. The different components of the turbulent momentum flux, in this figure, are non-dimensionalized with the appropriate turbulence intensity components. All profiles of the different components of the turbulent momentum flux collapse relatively well on single lines, indicating again a well behaved, self similar boundary layer. The $\bar{uv}$ component presents a profile that agrees well with the accepted values in the literature. Namely, this non-dimensional profile tends towards zero at the outer edge of the boundary layer and towards a value of 0.41 through a large portion of the boundary layer.

The $\bar{uw}$ and the $\bar{uw}$ terms deviate from the zero value expected from the symmetry of the statistics. This deviation is attributed to a thermal contamination of one of the probe wires by other two wires. This deviation is, however, small and therefore deemed acceptable.

The vertical distribution of the various integral time scales associated with the streamwise, normal and spanwise velocity fluctuations is shown in Figure 4-7. In this figure, all time scales are made non-dimensional with the local mean streamwise velocity at the same height and by the local momentum thickness. These non-dimensional time scales can also be interpreted as non-dimensional length scales by the use of Taylor's hypothesis.

The integral time scales associated with the different components of velocity
Figure 4.5: Downstream Evolution of Turbulence Intensity Profiles
Figure 4.6: Downstream Evolution of Turbulent Momentum Flux Profiles
are hard to interpret because they represent combined effects of different aspects of the dominant structures in the boundary layer. The integral time scale associated with the streamwise velocity fluctuations represents the aggregate effect of the normal transport of streamwise momentum by the dominant structures in the boundary layer, which is mainly affected by the persistence, streamwise elongation, and orientation of the dominant structures. A long time scale associated with the streamwise velocity fluctuation might therefore indicate elongated dominant structure at a shallow angle of attack which persists for long times. The integral time scale associated with the normal velocity fluctuations represents directly the extent of the region of normal transport by the dominant structures in the boundary layer. This time however the effect is much more localized and thus is mainly affected by the size of the dominant eddies themselves. A long time scale associated with normal component of velocity might therefore indicate large dominant structures. The integral time scale associated with the spanwise velocity fluctuations is mainly affected by the size and inclination of the dominant eddies themselves. A long time scale associated with this component of velocity therefore indicate large and/or shallow dominant structures. The interpretation of the different time scales postulated above will be made clearer when the two point correlation maps are introduced in the next section.

If we now examine the results obtained from the regular boundary layer investigation, we find that the distribution of the integral time scale associated with the
streamwise velocity fluctuations, $T_u$, peaks somewhere close to the wall and seems to decrease with increasing distances from the wall and that the time scales associated with the normal and spanwise velocity fluctuations, $T_v$ and $T_w$, are much smaller than the time scale associated with the streamwise fluctuations and that their distribution seems to increase slightly with increasing distances from the wall.

In light of the interpretation of the time scales given above, these results therefore seem to suggest the presence of more elongated (or at a shallower angle) structures near the wall and a trend of larger scales with increasing distances from the wall, which is indeed what has been observed in numerous turbulent boundary layer visualization studies, such as the one by Head et al. (1978).

4.2 Two Points Statistics

In this section, the results obtained from the two points statistics are presented. These results are generated from the mapping experiment described in the previous chapter. This section includes different cross cuts of the four dimensional two-points space-time correlation tensor and inferences about the dominant structures in the flow and their convection velocities.

In all these figures, the normal distance from the wall as well as the spanwise separations between the fixed and the mapping probe are made non-dimensional by, $\delta_0$ which is defined as the boundary layer thickness measured at the streamwise location corresponding to the leading edge of the manipulator. The time separa-
Figure 4.7: Downstream Evolution of the Integral Time Scale Profiles of the Three Velocity Components
tions are made non-dimensional by the free stream velocity and \( \delta_0 \). The level of the correlations contours and their increments are maintained constant, namely ranging from -1 to 2 by steps of 0.1. The positive correlation contours are shown in solid lines and the negative contours are shown in dashed lines.

Cross cuts in the y-z plane of the nine components of the correlation tensor are first presented in Figures 4-8, 4-9, and 4-10. In these figures, iso-contours of the different components of the correlation tensor are presented at a zero separation in time and no streamwise separation.

The results presented are in good agreement with the results of Blackwelder and Kovasny (1972). The \( R_{uu} \) contours exhibit good correlation centered around the reference position. This correlation extend over the whole height of the boundary layer and to one boundary layer thickness in the spanwise direction. This means that on average, if a strong streamwise velocity fluctuation is detected at the reference point, its surrounding (within one boundary layer in height and 0.4 boundary layer on either side in the spanwise direction) is experiencing similar streamwise velocity fluctuation. The magnitude of the surrounding fluctuations obviously decays with increasing distances from the reference point. The presence of negative contours on either side of the centered positive ones suggests semi-periodicity in the spanwise direction.

The \( R_{uv} \) contours exhibits negative correlations centered around the reference point. These correlations extend almost as far as the \( R_{uu} \) correlations but are not
Figure 4.8: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Streamwise Velocity Fluctuations for Zero Streamwise and Temporal Separation
Figure 4.9: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Normal Velocity Fluctuations for Zero Streamwise and Temporal Separation
Figure 4.10: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Spanwise Velocity Fluctuations for Zero Streamwise and Temporal Separation
as strong, which means that on average, if a strong streamwise velocity fluctuation is detected at the reference point, normal fluctuations in the opposite directions are being experienced at the same point and its surroundings. The negative correlation are in agreement with the Reynolds stresses presented in the previous section.

The $R_{uu}$ contours present four different contour islands in a stacked configuration. These contours are anti-symmetric in the spanwise and normal directions. These correlations extend slightly more than the $R_{uu}$ correlation but are much less correlated. This contours indicate that on average, if a strong streamwise fluctuations is detected at the reference point, thus implying normal velocity fluctuations in the opposite direction, spanwise velocity fluctuation in the same direction are experienced below and to the right of the reference point and above and to the left of it. At the same time, spanwise velocity fluctuations in the opposite direction are being experienced below and to the left of the reference point and above and to the right of it. All these contour maps suggest the presence of two large counter rotating structures with sizes of the same order of magnitude as the boundary layer itself. By inspecting the location of maximum correlation at each of the streamwise separations (not shown here), these dominant structures are seen to be inclined at a small angle to the wall. It is to note that the inclination seen from our investigation is slightly higher than those reported by Guezenec (1986). This discrepancy is attributed to the fact that, in his mapping, Guezenec positioned his reference probe at the wall and therefore was tagging structures much further
down within the boundary layer.

The rest of the correlations can be interpreted in similar fashion as above and do suggest the same type of dominant structures. It is interesting to note however that the correlations based on the detection of strong normal component of velocity are not as strong as those based on strong detected streamwise fluctuations, which indicates that the effects of the dominant structure on the normal fluctuation are more localized than its effect on the streamwise fluctuations. It is also interesting to note that while the detection of either streamwise or normal velocity fluctuations at the reference point tags pairs of the dominant structures, the detection of spanwise velocity fluctuations tags the dominant structures themselves. These two points are in agreement with the interpretation of different time scales reported earlier.

Iso-contours of the streamwise, normal and spanwise velocity correlations are presented next in Figures 4-11 to 4-16. These cuts are presented in the t-z plane at two different normal positions, namely $y/\delta_0 = 0.48$ and $y/\delta_0 = 0.72$. The normal positions presented were chosen to correspond to a position below the manipulator and to one above it, therefore allowing for comparisons in the next chapter.

In all these figures, the top graph represents a zero streamwise separation, while the second, third, and fourth correspond respectively to streamwise separations of 0.4, 0.8 and 1.2 boundary layer thicknesses downstream of the reference probe. At both heights in the boundary layer, the streamwise velocity fluctuations are
Figure 4.11: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity Fluctuations at $y/\delta_0 = 0.48$ and for Various Downstream Separation
Figure 4.12: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity Fluctuations at $y/\delta_0 = 0.72$ and for Various Downstream Separation
Figure 4.13: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity Fluctuations at $y/\delta_0 = 0.48$ and for Various Downstream Separation
Figure 4.14: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity Fluctuations at $y/\delta_0 = 0.72$ and for Various Downstream Separation
Figure 4.15: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity Fluctuations at $y/\delta_0 = 0.48$ and for Various Downstream Separation
Figure 4.16: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity Fluctuations at \( y/\delta_0 = 0.72 \) and for Various Downstream Separation
quite strongly correlated over approximately one boundary layer thickness in the spanwise direction and three boundary layer thicknesses in the time direction. As discussed in the previous section, the streamwise fluctuating components of velocity are due to an aggregate effect of the normal transport of streamwise momentum by the dominant structures in the flow. Therefore, the $R_{uu}$ contours should not be interpreted as delimiters to the dominant structures, but rather as delimiters to the region of the boundary layer in which the streamwise fluctuations are directly affected by these dominant structures.

The normal velocity fluctuations are by comparison much less correlated and much more localized than the streamwise fluctuations extending only about half a boundary layer thickness in the either the spanwise or the streamwise directions. Also as discussed in the previous section, the normal fluctuating components of velocity directly corresponds to the normal transport action of the dominant structures in the flow. Therefore, once again, these contours should not be interpreted as delimiters for the dominant structures themselves but to the region of the structure having a strong normal fluctuations. The extent of this region of the flow is seen to be quite localized by comparison to the extent of the streamwise perturbation region.

The spanwise velocity fluctuations are also much less correlated by comparison to the streamwise fluctuations. In addition, in these figures, negative contours are observed in all downstream separation contour maps at $y/\delta_0 = 0.48$ but are not
present at $y/\delta_0 = 0.72$ maps. The absence of negative contours at levels higher than the reference point is due to the inclination of the dominant structure as will be seen later. The $R_{ww}$ contours actually represent the dominant structures themselves as described in the previous section. The extent of these correlations in the spanwise direction is directly linked to the size of the dominant structures, while the extent in the streamwise direction is related to a combined effect of the size and inclination of the dominant structures. This means that the dominant structures are indeed large, of the order of a boundary layer thickness.

It is to note that the shape of the all correlation contours and the levels of these contours does not change significantly over all the streamwise separations investigated, which suggest that Taylor’s hypothesis holds quite nicely over convection distances of the order of a boundary layer thickness.

In order to investigate the inclination and convection velocity of the dominant structures, cross cuts in the t-y plane are presented for the streamwise, normal and spanwise velocity correlations in Figures 4-17, 4-18, and 4-19.

The $R_{uu}$ contours are again quite strong and elongated extending over one boundary layer thickness in the normal direction and three boundary layer in streamwise direction. The correlation contours have ellipsoidal shapes with main axis at approximately 20 degrees to the wall. The $R_{ww}$ contours are again seen to be much less strong and much more localized, extending less than half a boundary layer in the streamwise direction. These contours also have ellipsoidal shapes but
Figure 4.17: Normal-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity for Various Downstream Separation
Figure 4.18: Normal-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity for Various Downstream Separation.
Figure 4.19: Normal-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity for Various Downstream Separation.
with main axis almost normal to the wall indicating again the localized effect of the dominant structure on the normal component of velocity.

The $R_{ww}$ correlations are also ellipses with main axis at around 30 degrees from the wall. The negative contours seen earlier in the z-t cross cuts are also apparent and correspond to the spanwise velocity fluctuations on the other side of the structure. The reason for the presence of negative contour lines at $y/\delta = 0.48$ and the absence of these negative contours at $y/\delta = 0.72$ in Figure 4-16 should become clearer from this figure.

It is to note, that the physical inclination of the structures is opposite to the one shown in Figure 4-19. This is due to the fact that this figure represent cross cuts in the y-t plane and not y-x plane. Since we just proved that Taylor's hypothesis is actually valid in this regular boundary layer flow, we could interpret the time separations as negative downstream distances therefore yielding mirror images to the ones presented or a flow field running from left to right.

By locating the highest correlation on the time axis for each streamwise separation, the convection velocity of the dominant structure was determined to be on average equal to 0.9 of the free stream velocity. This convection velocity correspond to the mean streamwise component of velocity at the height of the reference point, namely $y/\delta = 0.6$.

In conclusion, the four dimensional two-point space time correlation tensor seems to indicate that the secondary motions in the boundary layer are dominated
on the average by a pair of large counter rotating roller like structures. These structures are of the same order of magnitude as the boundary layer thickness, have a streamwise extent of the order of two boundary layer thicknesses and are inclined at 30 degree angle to the wall. Moreover, the correlation tensor maps indicated that the effect of these dominant structures on the streamwise velocity fluctuations extends over a boundary layer thickness in the normal direction, more than one boundary layer thicknesses in the spanwise direction, and more than three boundary layer thicknesses in the streamwise direction. The effects of the same structures on the normal fluctuations are much more localized in the x-z directions and extending vertically over the whole boundary layer thickness.

4.3 Velocity Reconstruction

In order to develop a more physical interpretation of the extensive space-time correlation maps, the stochastic estimation technique was used as a tool to reconstruct estimates of the three dimensional conditional velocity field associated with a typical perturbation at the reference point. As described in the previous chapter the complete space-time correlation tensor is used as a basis to determine the linear stochastic estimation coefficients, and from there, the conditional velocity field. For further details about the application and validity of the stochastic estimation technique, the reader is referred the work of Guezennec(1989), Guezennec and Trigui (1991), and the derivation in Appendix C.
The choice of the condition at the reference point is not critical to the overall conclusions drawn from the reconstructed flow field. However, it was deemed that the reconstruction of events directly linked to turbulence transport was preferable. In order to evaluate the conditions associated with such events, a formal procedure was followed.

The joint probability density function of the streamwise and normal fluctuating components of velocity at the reference probe was first determined and is presented in Figure 4-20. In this figure, the probability density function is shown as a contour map and both amplitudes of the fluctuations are normalized by the free stream velocity. The choice of the free stream velocity fluctuation over the respective r.m.s value to non-dimensionalize the velocity fluctuations was made to allow for comparisons with the results of the manipulated boundary layer case shown in the next chapter.

From this figure, we can see that the maximum probability is located near the origin and that the distribution of the contours is elongated towards the second and fourth quadrants. This result is in agreement with the results of previous investigators.

To evaluate the velocity conditions that contribute most to turbulence production, the same probability function was weighted by the Reynolds stress as shown in Figure 4-21. In this figure, positive turbulence production is shown in dashed contours while negative production of turbulence is shown in solid contours.
Fourth quadrant motions seem to contribute slightly more to the turbulence production than the second quadrant motion as seen from the levels of contours in each quadrant. This is expected at the height of the measurement point, namely 0.6 of the boundary layer thickness away from the wall, since at this height the flow is dominated by incursions of high speed potential flow toward the wall. The amplitude of the streamwise and normal velocity fluctuations maximizing the weighted probability density function in the fourth quadrant are taken to correspond to the conditions most representative for turbulence transport events. This condition corresponds to $\frac{u}{U_\infty} = 0.06$ and $\frac{v}{U_\infty} = -0.03$. These values correspond almost to $\frac{u}{u'} = 1.0$ and $\frac{v}{v'} = -1.0$. This condition will be denoted as a $Q_4$ event.

In order to estimate an appropriate value for the spanwise velocity fluctuations,
Figure 4.21: Joint Probability Density Function of Streamwise and Normal Velocity Fluctuations at the Reference Point Weighted by the Reynolds Stress

the probability density function of the spanwise velocity component was evaluated conditional on the occurrence of a $Q_4$ event. This conditional probability is shown in Figure 4-22.

By comparison to the magnitude of the r.m.s value of the spanwise velocity fluctuations, $w'/U_\infty = 0.05$, the conditional probability density function indicates that large Reynolds stress events are comprised of events with significant spanwise motion. This implies that if we choose to use the condition of zero spanwise velocity fluctuation at the reference point to reconstruct the flow, the reconstructed structures should not be regarded as typical structures in the flow but rather as average structures corresponding to the particular condition chosen. Actually, as first noted by Guezennec, Piomelli and Kim (1989) and later confirmed by
As mentioned above, the perturbation velocity field corresponding to $Q_4$ events (found to contribute most to the turbulent transport) was reconstructed using the stochastic estimation technique. The condition imposed on the reference point were chosen to be equal to $u/U_\infty = 0.06$, $v/U_\infty = -0.03$, and $w/U_\infty = 0.00$ or in terms of r.m.s values, $u'/u' = 1.0$, $v'/v' = -1.0$, and $w'/w' = 0.0$.

The spatial evolution of such a conditional structure is shown in Figure 4-23. In this figure, the cross stream planes, corresponding to actual space separation, are shown with arrows representing the normal and spanwise velocity fluctuations. The
gray surface levels in the background represent the magnitudes of the streamwise velocity perturbations with white corresponding to high positive perturbations, mid-gray to zero perturbations, and black to high negative perturbations. The scale of the arrows as well as the gray levels are kept fixed in all plots.

The flow in this figure, and actually in all the rest of the figures in this chapter, is from right to left. The first cross stream cut from the right correspond to the plane with zero streamwise separation from the reference point. The second, third and fourth correspond to streamwise separations of respectively 0.4, 0.8 and 1.2 $\delta_0$ from the reference point. The normal axis extends over a distance from zero to 1.2 $\delta_0$, the spanwise axis extends over a distance from -1.2 $\delta_0$ to 1.2 $\delta_0$, the streamwise axis extends over a distance from 0 to 1.2 $\delta_0$. It is to note that in this figure and actually in the rest of the reconstructed flow figures presented in this chapter unless otherwise stated, the streamwise axis is stretched by a factor of three to allow for a better visual representation.

From this figure we can see that a pair of counter rotating large scale eddies can clearly be identified at the first stations. As expected, these structures are centered at the same height as the reference point on either side of it and extend over a distance of one boundary layer thickness in the normal and spanwise direction. At the second station, the same two structures can still be identified but are now centered higher in the boundary layer, namely at a height $y/\delta_0 = 1.0$, suggesting that the dominant structures are inclined to the wall. By the third
Figure 4.23: Spatial Evolution of the Reconstructed Velocity Field for a $Q_4$ Event
station, $\Delta x/\delta_0 = 0.8$, the structures are no longer identifiable because they have reached the outer edge of the boundary layer.

A spatial-temporal representation of the same velocity field at the same conditions is presented in Figure 4-24. This figure represents the velocity at each downstream location on an appropriately convected time frame that accounts for the spatial streamwise distance between each plane and the reference point. Thus, in this figure, the velocity field at the first station, $\Delta x/\delta_0 = 0.00$ is plotted at time $tU_\infty/\delta_0 = 0.00$. The velocity field at the second station, $\Delta x/\delta_0 = 0.40$ is plotted at time $tU_\infty/\delta_0 = -0.40$ and so forth. From this figure, we can see again that Taylor's hypothesis holds quite well with the structure looking essentially the same at all four space-time locations.

By using Taylor's hypothesis, we can replot the spatial evolution of the structure, as in Figure 4-25. This time, however, all velocity fields are plotted at $tU_\infty/\delta_0 = -1.2$ instead of $tU_\infty/\delta_0 = 0.00$ as was done in Figure 4-23. This alternative representation of the same velocity field has the advantage of presenting the structure much earlier in their development thereby locating them much lower within the boundary layer and thus avoiding the earlier problem of having them outside the outer limit of the boundary layer at the last two stations. As expected, the roller like structures are much better defined in this figure and are more apparent throughout all the stations. A close investigation of the height at which the structures are centered at in each cross stream section indicates that, as implied
Figure 4.24: Space-Time Evolution of the Reconstructed Velocity Field for a $Q_4$ Event
from the correlation tensor, the structures are inclined about 30 degrees to the wall.
Figure 4.25: Time Shifted Spatial Evolution of the Reconstructed Velocity Field for a $Q_4$ Event
As an indication of the performance of the LEBU, the downstream evolution of the skin friction ratio between the manipulated and the regular case is shown in Figure 5-1. In this figure, the downstream distance is presented in non-dimensional form in terms of $\xi$, the number of boundary layer thicknesses downstream of the leading edge of the manipulator. As a result of a reduction of the growth rate of the manipulated boundary layer, as will be shown below, a local skin friction reduction of the order of 10% is observed. The effects of the LEBU on the skin friction slowly relax and totally dissipate by 32 boundary layers downstream of the manipulator. This result is similar in character to what has been reported by other investigators. The amount of skin friction reduction and relaxation rate obviously depends on the LEBU geometry and settings.

The difference in growth rate between the regular and manipulated boundary layers can be seen from figure 5-2, where the ratio of momentum thickness difference
Figure 5.1: Comparison of the Downstream Evolution of the Local Skin Friction Between Regular and Manipulated Cases

between manipulated and regular to the regular momentum thickness is plotted. Initially, the manipulated boundary layer exhibits a 12% step increase close to the LEBU followed by a slower growth rate. The initial jump is indicative of the device drag, while the reduced growth rate is, as was seen above, indicative of a reduction in the local skin friction.

It is important to note, figure 5-3, that while the momentum thickness does not fully recover by the last measurement station, the boundary layer thickness of the manipulated boundary layer reaches regular boundary layer values. This indicates that, even after the boundary layer recovers to regular thickness and growth rate, the turbulence structure within it may still be considerably different.

In the rest of the chapter, comparisons between several regular and manipu-
lated turbulence quantities are presented. These comparisons are made at eight measurement stations. Two of the measurements stations are around the manipulator itself, namely at 0.2 and 1.0 boundary layer thicknesses downstream of the leading edge of the manipulator corresponding to $\xi = 0.2$ and $\xi = 1.0$, respectively. Two of the measurements stations immediately downstream of the manipulator, namely 0.2 and 1.4 boundary layer thicknesses downstream of the trailing edge of the manipulator, corresponding to $\xi = 1.8$ and $\xi = 3.0$, respectively. These stations are plotted on the same figure and are referred to as near field stations. The four other measurement stations are further downstream of the manipulator, namely at $\xi = 8$, $\xi = 14.0$, $\xi = 22.0$, and $\xi = 44.0$. These stations are also plotted together on the same figure and are referred to as far field stations.
Figure 5.3: Comparison of the Downstream Evolution of the Boundary Layer Thickness Between the Regular and Manipulated Cases

For the remainder of this section, all regular profiles are plotted with solid lines and all manipulated profiles are plotted in dotted lines. In addition, in all the figures, the normal distance from the wall is non-dimensionalized by the local boundary layer thickness. The choice of the boundary layer thickness over the momentum thickness to non-dimensionalize the distance from the wall was made in order to limit the comparison to a single turbulent quantity therefore avoiding the comparison of coupled effects.

A comparison between the mean streamwise velocity profiles for the regular and manipulated case is shown in Figures 5-4 and 5-5. In these figures, the streamwise velocity is non-dimensionalized by the free-stream velocity. At the first couple of stations, namely the ones around the manipulator itself, the flow in the manipu-
lated case seems to slightly accelerate on top of the LEBU and somewhat decrease underneath it. This was actually expected since the large eddy break-up device was mounted with a small positive angle of attack and therefore acts as a small lifting airfoil with a net circulation.

Immediately downstream of the manipulator, a wake can be clearly identified on the manipulated profiles at $\xi = 1.8$ and $\xi = 3.0$. This wake, however, decays rather rapidly and is barely noticeable by $\xi = 14.0$. Beyond that distance, the profiles reach a new self-similar state, albeit different from the regular case. Specifically, the manipulated profiles seem to be less full in the bottom half of the boundary layer and fuller in the outer region. This behavior is consistent with previous findings and with the fact that the manipulated case is characterized by a lower skin friction and a reduced momentum thickness.

A comparison of the streamwise, normal, and spanwise turbulence intensity profiles between the regular and the manipulated case is shown in Figures 5-6 to 5-11 for the same downstream stations. In these figures, the different turbulence intensity components are non-dimensionalized by the free stream velocity.

Above the manipulator, the presence of the new boundary condition does not seem to have any effect on any of the components of the turbulence intensity vector, except perhaps for the normal component and very close to the LEBU itself. Immediately downstream of the manipulator, a localized excess can clearly be identified on all components of the turbulence intensity vector at $y/\delta = 0.75$. 
Figure 5.4: Comparison of the Downstream Evolution of the Mean Streamwise Velocity Profiles Between the Regular and Manipulated Cases: Near Field
Figure 5.5: Comparison of the Downstream Evolution of the Mean Streamwise Velocity Profiles Between the Regular and Manipulated Cases: Far Field
Figure 5.6: Comparison of the Downstream Evolution of Streamwise Turbulence Intensity Profiles Between the Regular and Manipulated Case: Near Field
Figure 5.7: Comparison of the Downstream Evolution of Streamwise Turbulence Intensity Profiles Between the Regular and Manipulated Case: Far Field
Figure 5.8: Comparison of the Downstream Evolution of Normal Turbulence Intensity Profiles Between the Regular and Manipulated Case: Near Field
Figure 5.9: Comparison of the Downstream Evolution of Normal Turbulence Intensity Profiles Between the Regular and Manipulated Case: Far Field
Figure 5.10: Comparison of the Downstream Evolution of Spanwise Turbulence Intensity Profiles Between the Regular and Manipulated Case: Near Field
Figure 5.11: Comparison of the Downstream Evolution of Spanwise Turbulence Intensity Profiles Between the Regular and Manipulated Case: Far Field
This excess is obviously linked to the generation of small scale structures in the wake of the manipulator. By $\xi = 14.0$, however, the presence of this manipulator wake is hardly noticeable.

Below the manipulator, the effect of the blade on the turbulence intensity vector manifests itself in terms of a reduction of all its components. This reduction appears to initiate with the normal component, close to the manipulator. With downstream distances, this reduction seems to get stronger and to propagate further down within the boundary layer. The reduction of the different components of the intensity vector seem to reach a maximum around 16 boundary layer thicknesses downstream of the trailing edge of the manipulator. Beyond this distance, a slow recovery process is observed and results in an almost complete restoration of the turbulence intensity profiles by the last measurement station, $\xi = 44.0$. This restoration is complete except in the region close to the wall for the streamwise and spanwise components. Overall, the relaxation process seems to be initiated from the wake region through redistribution of scales to equilibrate the distorted energy spectrum of the boundary layer. It is interesting to note that the relaxation of the streamwise and spanwise components lags behind the one of the normal component, which is consistent with the mixing-length concept where the normal component transports high- or low-momentum fluid, hereby creating streamwise velocity fluctuations.

A comparison of the normal turbulent momentum flux profiles between the
regular and LEBU case is shown in Figures 5-12 and 5-13. The turbulent momentum flux, in these figures, has been non-dimensionalized with the free stream velocity. Turbulent momentum flux is usually non-dimensionalized by the appropriate turbulent intensity components, but for comparison purposes, we opted to non-dimensionalized it with the free stream velocity in an attempt to keep the comparison to a single turbulence quantity, namely momentum flux, rather than to a combined effect of momentum flux and turbulence intensity.

Over the blade and immediately downstream of its trailing edge, the Reynolds stress is drastically reduced throughout the boundary layer. Furthermore, a pocket of negative Reynolds stress is created on the lower side of the wake, while a local excess is created on the upper side. This was already observed by Guezennec and Nagib (1985, 1990) and was attributed to a redistribution of the turbulent kinetic energy by a "pumping action" action of the wake. By $\xi = 8.0$, the Reynolds stress on top of the manipulator relaxes back to its regular value while it is still substantially reduced below it. By the last station, $\xi = 44.0$, the Reynolds stress recovers almost completely except close to the wall region of the boundary layer.

The relaxation rate of this normal turbulent momentum transport is quite different below and above the manipulator. While on top of the LEBU, the relaxation seems to be almost complete by 8 boundary layer thicknesses, the effects below it possesses a slower relaxation rate, of the order of 40 boundary layer thicknesses or more. Actually, below the manipulator, the maximum reduction in the normal
Figure 5.12: Comparison of the Downstream Evolution of Normal Turbulent Momentum Flux Profiles Between the Regular and Manipulated Cases: Near Field
Figure 5.13: Comparison of the Downstream Evolution of Normal Turbulent Momentum Flux Profiles Between the Regular and Manipulated Cases: Far Field
momentum transport component seems to be achieved after about 16 boundary layer thicknesses downstream of the leading edge of the manipulator. As mentioned above, this position corresponds to the location where the mean wake defect is no longer present.

This seems to suggest that the wake of the blade acts as an extension to the blade itself to shield against any communication between the turbulent structures trapped below the manipulator and the rest of the flow field. Once this shield is broken, namely at distances beyond the complete recovery of the mean wake defect, this communication is re-established and relaxation to regular boundary layer values starts.

A comparison of the downstream evolution of the integral time scales associated with the streamwise, normal and spanwise velocity fluctuations is shown in Figures 5-14 to 5-19. All time scales in these figures are made non-dimensional with the free stream velocity and the local boundary layer thickness. The non-dimensional integral time scales in these figures should not be interpreted as non-dimensional length scales since the Taylor’s hypothesis is not guaranteed to be valid in the manipulated boundary layer, which is indeed the case as will be discussed in the next section.

Around the manipulator, the time scale associated with the streamwise fluctuations, $T_u$, appears to be slightly increased below the manipulator. This increase is probably attributed to a shifting of these dominant structures towards shallower
Figure 5.14: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Streamwise Velocity Component Between the Regular and Manipulated Cases: Near Field
Figure 5.15: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Streamwise Velocity Component Between the Regular and Manipulated Cases: Far Field
Figure 5.16: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Normal Velocity Component Between the Regular and Manipulated Cases: Near Field
Figure 5.17: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Normal Velocity Component Between the Regular and Manipulated Cases: Far Field
Figure 5.18: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Spanwise Velocity Component Between the Regular and Manuplated Cases: Near Field
Figure 5.19: Comparison of the Downstream Evolution of the Integral Time Scale Profiles Associated with the Spanwise Velocity Component Between the Regular and Manipulated Cases: Far Field
angles. The stretching and shifting itself is most probably forced by the overall circulation field around the manipulator.

The time scale associated with the normal velocity fluctuations, $T_v$, exhibits a substantial reduction on top of the manipulator that appears from the first measurement station around the LEBU, $\xi = 0.2$, and that persists up to about 16 boundary layer thicknesses downstream of the leading edge of the manipulator. Below the manipulator, no major reduction can be observed, except very close to the LEBU itself. This indicates that, on top the manipulator, the normal transport transport is drastically reduced along the manipulator and its wake. The reduction of normal transport in this region is due to inhibition of the normal component of velocity by the blade itself and by its wake. Below the manipulator, the reduction of the time scale near the LEBU or the wake indicates that even if the normal transport is not substantially reduced , it is restricted to within the region under the blade (or wake).

The time scale associated with the spanwise velocity fluctuations, $T_w$, indicates that the sizes of the dominant structures above and below the manipulator are substantially reduced, perhaps more on the top than on the bottom, that this reduction in scale persists over a long downstream distance, and again seem to only start relaxing after about 16 boundary layer thicknesses from the leading edge of the manipulator. It is interesting to notice that the overall relaxation rate of this time scale lags behind that of $T_v$ in both regions of the flow.
In order to determine the effects of the LEBU on the different scales in the boundary layer, the spectra of the velocity fluctuations were investigated. The result of this investigation are presented in Figures 5-20 to 5-37, where a comparison of the downstream evolution of the frequency spectrum associated with the streamwise, normal and spanwise velocity fluctuations between the regular and manipulated case is presented. The comparison is limited to three heights in the boundary layer at each downstream location. Two of these points correspond to locations underneath the manipulator, namely at \( y/\delta = 0.24 \) and \( y/\delta = 0.48 \), and one above it, namely at \( y/\delta = 0.72 \). The spectra in these figures are presented on log-log scale with the frequency made non-dimensional by \( U_\infty \) and \( \delta_0 \), and the spectral energy made non-dimensional by the square of \( U_\infty \).

Under the manipulator, at \( y/\delta = 0.48 \), the presence of the blade is immediately felt by the normal component of velocity through a drastic suppression of a wide spectrum of scales. This suppression appears to start with the larger scales and cascades toward smaller ones with downstream distance. This suppression only start relaxing after the effect of the wake disappears, namely beyond \( \xi = 16 \). The regeneration process appears to be in reverse to the suppression process, initiating with high frequency fluctuations and then cascading toward the smaller ones. This reverse cascading process might be linked to dispersion of the small scale structures generated in the wake region of the manipulator, followed by interaction of these small scales with the different structures in the boundary layer. Further down
Figure 5.20: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Near Field
Figure 5.21: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Far Field.
Figure 5.22: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Near Field
Figure 5.23: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Far Field
Figure 5.24: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Near Field
Figure 5.25: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.24$: Far Field
Figure 5.26: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Near Field
Figure 5.27: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Far Field
Figure 5.28: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Near Field
Figure 5.29: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Far Field
Figure 5.30: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Near Field
Figure 5.31: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.48$: Far Field
within the boundary layer, namely at $y/\delta = 0.24$, similar trends can be observed but with a certain delay in reaction.

At both heights in this region of the flow, the spectrum associated with the streamwise and spanwise velocity fluctuations appear to react in a similar fashion to the presence of the LEBU but again with a certain delay of reaction. This delay in reaction indicates that the suppression of the normal component of velocity is the driving force for the reduction of the fluctuations of the other two component of velocity.

On top of the manipulator, the effect of the blade on the turbulence structure is again quite different, indicating once again different mechanisms at play below and above the manipulator. While a similar trend to the one described earlier can be observed on the frequency spectrum associated with the normal component of velocity, no changes from the regular case can be detected in the spectrum associated with the streamwise or spanwise velocities. The effects on the normal velocity fluctuations are however more intense and relax faster in this case. This later observation reinforces the idea that on top of the LEBU the streamwise fluctuations are not correlated with the normal fluctuations and are therefore merely fossils of the incoming large structures unrelated to any turbulence generation or momentum transport ("scars" convected in a passive way).

If indeed, the manipulator was breaking the incoming large eddy structures in the flow as its name suggest, Large Eddy Break-Up device an excess of small to
Figure 5.32: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Near Field
Figure 5.33: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Streamwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Far Field
Figure 5.34: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Near Field.
Figure 5.35: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Normal Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Far Field
Figure 5.36: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Near Field
Figure 5.37: Comparison of the Downstream Evolution of the Power Spectrum Associated with the Spanwise Velocity Fluctuations Between Regular and Manipulated Case at $y/\delta = 0.72$: Far Field
mid-range scales would appear in all the spectra. Since this is not the case (except for the station $\xi = 3.0$ at $y/\delta_0 = 0.48$ and $y/\delta_0 = 0.72$ where we might be detecting the scales shed in the wake itself), it is safe to conclude that the major effect of this type of manipulator on the boundary layer structure is to suppress the incoming large eddies. As suggested by the cascading process, a suppression of the large eddies results in a suppression of scales on a wide spectrum which is indeed what we observed from the above graphs.

This large eddy suppression is also responsible for the reduction of entrainment of high speed potential fluid in the boundary layer resulting in the observed decrease in the growth rate of the boundary layer and therefore in the local skin friction. The suppression of the large eddies is also responsible for the smoothing of the turbulent/non-turbulent interface reported by Chang and Blackwelder (1989) and confirmed by Trigui and Guezennec (1989).

LEBU's are therefore inappropriately labeled. A more appropriate name for these manipulators would be Large Eddy Suppressing devices, or LESU's for short.

5.2 Two points Statistics

As mentioned earlier, in order to better understand the effects of the manipulator on the incoming large scales structures in its immediate vicinity, all nine components of the space time correlation tensor were measured with respect to a fixed point located just upstream of the manipulator leading edge at a first stage and
just downstream of its trailing edge at a second stage.

Similar cross cuts to the ones presented for the regular case are presented in this section for both space-time correlation tensors of the manipulated case. In order to allow for better comparisons with the regular case all contour levels are maintained identical to the ones used in the regular case.

Cross cut in the y-z plane of all nine components of the space-time tensor are presented in Figures 5-38 to 5-40 for the correlation tensor measured around the manipulator. It is to note here, that the comparisons with the regular case are made with the appropriate cross cuts at the same time and streamwise separation (some of which are not shown in previous chapter).

In these figures, iso-contours of the different components of the correlation tensor are presented at a zero separation in time and 0.4 boundary layer thicknesses separation in the streamwise direction.

Around the manipulator, the $R_{uu}$ contours are as strong, if not slightly stronger, as the contours in the regular case. The extent of the region in which the streamwise fluctuations are directly effected seems to be as large as the regular case. This time, however, the contours are no longer centered at the same height as the reference point, as is the case in the regular boundary layer, but form two separate entities one on top and one on the bottom of the manipulator. The negative contours on either side of centered positive ones are also detected in this case, but are again separate entities on the top and on the bottom of manipulator.
Figure 5.38: Normal-Spanwise Cuts of the Space Correlation Maps of the Streamwise Velocity at 0.4 δ₀ Downstream Separation and Zero Temporal Separation: Mapping Around the LEBU
Figure 5.39: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Normal Velocity at 0.4 $\delta_0$ Downstream Separation and Zero Temporal Separation: Mapping Around the LEBU
Figure 5.40: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Spanwise Velocity at 0.4 $\delta_0$ Downstream Separation and Zero Temporal Separation: Mapping Around the LEBU
The $R_{uu}$ contours present a different picture than the $R_{uu}$ contours. While the entity can still be detected under the LEBU, no correlation can be observed on top of it. This indicates that on top the LEBU, even if the streamwise fluctuations do not get reduced by the presence of the newly imposed boundary condition, their correlation to any normal velocity fluctuations is completely annihilated. This confirms that the streamwise fluctuations detected on top of the LEBU are not related to any turbulent transport and are therefore just remnants of the streamwise fluctuations of the incoming large turbulent structures ("scars").

The $R_{uw}$ contour exhibit an interesting phenomenon. A new pair of cell structure, very much reminiscent of the structures on the boundary layer wall, is formed on top of the LEBU. This implies that on top of the manipulator, two new structures are developing, probably due to the "splatting" motion of the flow on the newly imposed boundary condition. A similar pattern can also be detected on the $R_{uw}$ contours. These newly formed structures are weak and short lived, almost disappearing by the next cross stream plane (not shown here).

Similarly, cross cut in the $y-z$ plane of all nine components of the space-time tensor are presented in Figures 5-41 to 5-43 for the correlation tensor measured in the wake of the manipulator. The $R_{uu}$, $R_{uv}$, and $R_{uw}$ contours indicate that the correlations are localized within a thin region in the wake of the manipulator. This indicates that the wake of the manipulator is actually not interacting much with the rest of the structures in the flow. The $R_{uu}$ correlation indicate that some
turbulence transport is actually taking place but that this transport is also very localized within the wake itself. The $R_{uu}$ and $R_{uw}$ contours indicate the presence of two cell like counter rotating structures dominating the flow in the wake region. These cell structures are very thin, of the order of 0.2 boundary layer thicknesses, and very elongated in the spanwise direction, of the order of one boundary layer thickness.

Overall the correlation contours seem to indicate that the wake operate under its own dynamics and that it is dissociated from the rest of the flow in the boundary layer. This confirms the idea postulated earlier of the wake acting as an extension to the manipulator itself to inhibit the communication of the turbulent structures above and below the manipulator by inhibiting the normal component of velocity. The absence of structures above and below the wake in the correlation contours should not be interpreted as a lack of structures in the boundary layer, but rather as in indication to the fact that those structures are uncorrelated with the ones in the wake.

Cross cuts in the t-z plane of the streamwise, normal, and spanwise velocity correlations are presented in Figures 5-44 to 5-49 for the tensor measured around the manipulator. Again the cuts are presented in the t-z plane at the same normal positions as the regular case, namely $y/\delta_0 = 0.48$ and $y/\delta_0 = 0.72$. Below the manipulator, the $R_{uu}$ and the $R_{uw}$ correlations are somewhat stronger and somewhat pinched when compared to the regular boundary layer case, indicating a very
Figure 5.41: Normal-Spanwise Cuts of the Space Correlation Maps of the Streamwise Velocity for Zero Streamwise and Temporal Separation: Mapping Immediately Downstream of the LEBU
Figure 5.42: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Normal Velocity for Zero Streamwise and Temporal Separation: Mapping Immediately Downstream of the LEBU
Figure 5.43: Normal-Spanwise Cuts of the Space-Time Correlation Maps of the Spanwise Velocity for Zero Streamwise and Temporal Separation: Mapping Immediately Downstream of the LEBU
slight strengthening of the u perturbation. This can possibly be attributed to the very small angle of attack of the manipulator contributing to a small contraction effect. Above the manipulator, the contours seem to be more elongated and more pinched, probably due to the acceleration of the flow in this region to clear the leading edge of the blade.

The $R_{uu}$ contours exhibit an almost total decorrelation between the normal fluctuation in the wake and both regions of the flow. This decorrelation is perhaps stronger on the top of the manipulator than in the bottom. The overall picture confirms that the direct inhibition of the normal velocity component by the LEBU is felt immediately by the incoming large vortical structures and contributes very significantly to their suppression over distances of the order of less than 0.2 boundary layer thickness (less than 1/8 of the chord length in this case). This also points to the lack of validity in applying Taylor's hypothesis even over short distances in the immediate vicinity of the manipulator. It is this inapplicability of the Taylor's hypothesis that prohibit the interpretation of these space-time contours in terms of physical spatial structures.

Similar Cross cuts in the t-z plane of the streamwise, normal, and spanwise velocity correlations are presented in Figures 5-50 to 5-55 for the tensor measured in the wake of the manipulator. The streamwise and the spanwise correlation contours, $R_{uu}$ and $R_{ww}$, decay rather rapidly above and below the manipulator, probably more so on the bottom than on the top, which indicates that the wake
Figure 5.44: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity at \( y/\delta_0 = 0.48 \) for Various Downstream Separations: Mapping Around the LEBU
Figure 5.45: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity at $y/\delta_0 = 0.72$ for Various Downstream Separations: Mapping Around the LEBU
Figure 5.46: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity at $y/\delta_0 = 0.48$ for Various Downstream Separations: Mapping Around the LEBU
Figure 5.47: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity at \( y/\delta_0 = 0.72 \) for Various Downstream Separations: Mapping Around the LEBU
Figure 5.48: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity at $y/\delta_0 = 0.48$ for Various Downstream Separations: Mapping Around the LEBU
Figure 5.49: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity at $y/\delta_0 = 0.72$ for Various Downstream Separations: Mapping Around the LEBU
operates under different dynamics than the boundary layer. The normal correlation contours $R_{uu}$ are completely non-existent in either region of the flow, again indicating that the normal velocity component is drastically inhibited by the wake.

Cross cuts in the t-y plane are presented in Figures 5-56 to 5-58 for the tensor measured around the manipulator. As mentioned above, due to the inapplicability of Taylor's hypothesis, the contours in these space-time cross cuts should not be interpreted in terms of physical spatial structures.

Around the manipulators, the $R_{uu}$ contours are immediately seen to form two different cells, one on the top and the other on the bottom. These two cells are again quite elongated in the time direction, extending about three boundary layer thicknesses in this direction. By locating the highest correlation on the time axis for each cell in each of the streamwise separations, it is seen that the convection velocity on top of the LEBU is faster than on the bottom, probably due to the acceleration of the flow above the leading edge of the manipulator. The convection velocity is actually little faster than the free stream velocity on top of the manipulator, namely of the order of 1.2 $U_\infty$, and is about 0.91 $U_\infty$ below it.

The difference in convection velocity between the top and bottom side of the LEBU probably contributes to the de-correlation of the remnants of the structures over the manipulator, ultimately delaying their reconnection further downstream of
Figure 5.50: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity at $y/\delta_0 = 0.48$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.51: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity at $y/\delta_0 = 0.72$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.52: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity at $y/\delta_0 = 0.48$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.53: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity at $y/\delta_0 = 0.72$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.54: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity at $y/\delta_0 = 0.48$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.55: Spanwise-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity at $y/\delta_0 = 0.72$ for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.56: Normal-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity for Various Downstream Separations: Mapping Around the LEBU
Figure 5.57: Normal-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity for Various Downstream Separations: Mapping Around the LEBU
Figure 5.58: Normal-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity for Various Downstream Separations: Mapping Around the LEBU
the device. This difference in convection velocity is clearly linked to the circulation field around the device and partially legitimizes the use of small positive angles of attack and sufficient long chord lengths, such as found by the parametric study of Plesniak and Nagib (1985).

The $R_{uw}$ correlations are completely non-existing from the first stations downstream of the leading edge of the manipulator in either the top or the bottom regions of flow. As a reminder, the first measurement position corresponding to $\Delta x/\delta_0 = 0.40$ is actually located 0.2 $\delta_0$ downstream of the leading edge of the manipulator. This means that the presence of the new imposed boundary condition is immediately felt by the incoming large structure through a drastic inhibition of the normal component of velocity.

Similar to what has been observed from the $R_{uu}$ contours, the $R_{uw}$ correlations also show the formation of the two distinct cells, one on top and the other on the bottom of the manipulator. It is interesting to note that beyond the second station (first measurement station on top of the LEBU), the correlation contours, both for $R_{uu}$ and $R_{uw}$, seem to be quite similar indicating that after the initial abrupt change of the turbulence structure due to the imposed no-slip condition, the flow appears to reach a new "frozen turbulence" state. It is also interesting to note that the overall envelopes of the contours in the different cross sections around the LEBU appear to be similar to that of the contours upstream of the leading edge of the manipulator for both $R_{uu}$ and $R_{uw}$. This indicates that the streamwise
and the spanwise fluctuations are merely scars of the fluctuations associated with the incoming large vortical structures. This obviously not the case for the normal velocity fluctuations.

Cross cuts in the t-y plane are presented in Figures 5-59 to 5-61 for the tensor measured in the wake of the manipulator. The streamwise velocity fluctuation at the reference point are seen to be initially very strongly correlated with the streamwise fluctuations inside the wake itself as was expected. These fluctuations are, however, much less correlated outside this region. The strong correlation within the wake region decays very rapidly (by comparison to the turbulent boundary layer dynamics) with downstream distances. In addition, very distorted positive and negative contour cells are apparent at all downstream separations throughout the boundary layer, indicating that the structures developed in the wake region are convecting at different rates than the rest of the boundary layer structures. Overall, it is seen that the wake is evolving under its own dynamics and not those of the turbulent boundary layer. Similar conclusions can be drawn from the $R_{ww}$ contours.

The $R_{ww}$ correlations are again seen to be almost completely non-existing throughout the boundary layer at all downstream separations. This indicates that the normal velocity fluctuations in the wake are completely uncorrelated with the normal fluctuations in the rest of the boundary layer suggesting that no normal momentum transport between the two region of the flow can possible take place through
Figure 5.59: Normal-Time Cuts of the Space-Time Correlation Maps of the Streamwise Velocity for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.60: Normal-Time Cuts of the Space-Time Correlation Maps of the Normal Velocity for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
Figure 5.61: Normal-Time Cuts of the Space-Time Correlation Maps of the Spanwise Velocity for Various Downstream Separations: Mapping Immediately Downstream of the LEBU
the wake. Therefore, the wake is seen to act as an extension to the manipulator itself to shield against any communication between the structures trapped under the LEBU and the rest of the flow field.

5.3 Velocity Reconstruction

To further illustrate the structural changes to the large incoming vortical eddies as they pass over the LEBU, the stochastic estimation technique was again used as a tool to reconstruct estimates of the three-dimensional conditional velocity field associated with a typical perturbation impinging on the leading edge of the manipulator. The choice of the "condition" is again not critical to the conclusions being drawn but the reconstruction of events directly linked to the turbulence transport was again deemed preferable.

For the reconstruction of the flow around the manipulator itself, this meant that the same condition as the one used to reconstruct the flow of the regular boundary layer needed to be used, namely \( \frac{u}{U_\infty} = 0.06 \), \( \frac{v}{U_\infty} = -0.03 \), and \( \frac{w}{U_\infty} = 0.00 \). It should be clear that the choice of zero magnitude for the spanwise component of velocity at the reference point will yield spanwise-symmetric structures as described in the previous chapter. It should also be clear that more likely values for the spanwise velocity component of velocity at the reference point will be randomly ranging within plus or minus one r.m.s. and would yield strongly asymmetric structures as pointed out by Choi and Guezennec (1990).
The space-time evolution of such a conditional structure is presented in Figure 5-62. This figure, and actually all the figures in the rest of this chapter, will be presented at the same perspective view point, same gray levels, and vector scales as in the regular case. As described in the previous chapter, Taylor's hypothesis was quite valid in the regular boundary layer, with the structures from such a space-time plot looking essentially identical for the four space-time locations. In this manipulated case, however, the strength of the vortical motion is considerably weakened by the first position throughout the boundary layer over the LEBU and the strength of the streamwise perturbations is considerably lessened by the same station, particularly above the LEBU. Needless to say that in this case Taylor's hypothesis looses its validity. It should be emphasized that this figure does not show a spatial representation of eddies over the LEBU, but rather illustrates the fast changes in the turbulence structures in the flow.

Such a representation is given in Figure 5-63, which depicts the spatial structure with zero delay times, i.e. the true spatial structure with no use of Taylor's hypothesis. Again, the "condition" is the same as the one investigated in the previous figure. By the first measurement station around the LEBU, namely $\Delta x/\delta_0 = 0.4$, the formation of a weak secondary pair of eddies can be observed on top of the manipulator. This secondary pair of eddies is probably due to a "splatting" effect as inferred in the previous section. It is short lived and dissipates almost completely by the next station, namely $\Delta x/\delta_0 = 0.8$. The remnant of the original
Figure 5.62: Space-Time Evolution of the Reconstructed Velocity Field Over the LEBU
eddy passing below the manipulator is reasonably unaffected at this station, but represents more of a fossil perturbation not associated any more with a vortical structure. By the last station, $\Delta z/\delta_0 = 1.2$, the remaining perturbation is considerably weaker than in the regular case. The formation of the secondary pair of eddies on top of the LEBU can be better seen from Figure 5-64, which shows a comparison of the reconstructed structure at the $\Delta z/\delta_0 = 0.4$ station at zero time separation between the regular and the manipulated case.

It is to note that by placing the reference position at the same height as the manipulator, namely $y/\delta_0 = 0.6$, we were only able to tag on the largest of structures, namely structures of the same order of magnitude as the boundary layer thickness, centred at the height of the manipulator. The reconstructed flow field in the manipulated case therefore indicate that this type of structures get totally suppressed by the manipulator. Smaller structures that are centred lower within the boundary layer are obviously not affected in a similar fashion. Actually from the single point statistics presented earlier, we can conjecture that such structures are not directly effected by the presence of the LEBU, but that they are deprived from their main source of energy, namely larger structures as suggested by the cascade model.

The condition imposed at the reference point for the reconstruction of the flow structures that contribute most to the turbulence transport downstream of the manipulator followed the same procedure that was used in the previous chap-
Figure 5.63: Spatial Evolution of the Reconstructed Velocity Field Over the LEBU
Figure 5.64: Comparison of the Velocity Field at $\Delta x/\delta_0 = 0.4$ Over the LEBU Between Regular and Manipulated Cases
Figure 5.65: Joint Probability Density Function of Streamwise and Normal Velocity Fluctuations at the Second Reference Point

Namely, the joint probability density function of the streamwise and normal components of velocity was first determined, Figure 5-65. This figure shows the probability density function as contour maps. Opposite to what has been observed in the regular case, the maximum probability is not located near the origin but at a position where the normal component is at zero and the streamwise component is about 0.065 of the free stream velocity, which is indicative of a high negative skewness of the streamwise velocity fluctuations. Moreover, the contours seems to be elongated along the streamwise axis, indicating again that the normal transport is very drastically reduced.

The same joint probability function was then weighted by the magnitude of the Reynolds stress and plotted in Figure 5-66. Similar to what have been obtained
in the regular case, the levels of contours of the weighted probability function indicate that fourth quadrant motions contribute slightly more to the turbulence transport. This time, however, the contours are reduced and spread over a larger region. The streamwise and normal velocity fluctuations maximizing the weighted probability density function in this fourth quadrant are taken to correspond to the conditions most representative for turbulence transporting events. This condition corresponds to $u/U_\infty = 0.06$ and $v/U_\infty = -0.03$. These values correspond almost to $u/u' = 0.4$ and $v/v' = 0.7$.

Conditional on the occurrence of such a dominant fourth quadrant event, the probability density function of the spanwise velocity component was then evaluated and plotted on Figure 5-67. By comparison to the regular case, this probability this
probability density function is very much reduced and diffused over a wider range of spanwise fluctuation. If the spanwise fluctuations were made non-dimensional with their r.m.s values, the width of the curve in the regular and manipulated cases will not be much different, which means if we once again choose to the condition of zero spanwise velocity fluctuation to reconstruct the flow, the resulting velocity field should be interpreted in a similar as before, namely as averaged velocity fields and not typical instantaneous ones.

The reconstructed spatial representation of the flow field in this region is shown in Figure 5-68. From this figure, we can clearly see that the structures developed in the wake region decay within less than a boundary layer thickness indicating that these structures follow the dynamics of the wake and not that of the boundary.
Figure 5.68: Spatial Evolution of the Reconstructed Velocity Field Immediately Downstream of the LEBU
layer. Moreover, a closer look indicates the formation of a narrow region in the
wake where the normal velocity fluctuation are almost non-existing. This thin sheet
seems to act as a shield between the two regions of the boundary layer and can be
better seen from Figure 5-69, which shows again a comparison of the reconstructed
flow at $\Delta x/\delta_0 = 0.4$ station for a zero time separation between the regular and the
manipulated case.

It is to note again that by placing the reference point in the wake of the ma-
nipulator we were only able to tag the structures shed in this wake. Therefore,
the reconstructed flow field, is not representative of the structures in the bound-
dary layer but rather the ones in the wake. The results shown here, even if not
visually very interesting, are very important because they indicate that the wake
is evolving under its own dynamics and that the structures within it are basically
not interacting much with the rest of the boundary layer structures.
Figure 5.69: Comparison of the Velocity Field at $\Delta x/\delta_0 = 0.4$ Immediately Downstream of the LEBU Between Regular and Manipulated Cases
CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In summary, the direct effect of a single Large Eddy Break Up device on the turbulence structure in a turbulent boundary layer was investigated by acquiring detailed three dimensional measurements of all velocity components in the near field of the manipulator.

It was found that:

• The incoming large vortical structures (eddies with scales of the order of the boundary layer thickness) are completely suppressed by the LEBU. The suppression of these large scale structures results in a drastic reduction of the entrainment of high speed potential flow. In turn, this results in a reduction of the growth rate of the boundary layer and therefore of the local skin friction, as suggested by the momentum theorem.

• The suppression of these size eddies is attributed to a direct inhibition of the normal component of velocity by the manipulator as they pass over it.
The streamwise and spanwise fluctuations observed on top of the manipulator downstream of its leading edge are merely passive "scars" of the incoming large vortical structure, not associated to any significant active transport of momentum.

The smaller structures residing lower within the boundary layer are not directly effected by the manipulator. However, these structures are indirectly effected by the overall circulation field around the manipulator that appears to either bring them closer to the wall and/or decrease their angle of inclination. Furthermore, being trapped under the manipulator, these structures are shielded from any interaction with the high speed potential flow (a major energy source), which in turn leads to a weakening of scales on a wider spectrum, as suggested by the energy cascade model.

The wake of the manipulator acts as an extension to the manipulator itself to inhibit the normal component of velocity therefore shielding against normal momentum transfer between the structures trapped underneath the manipulator and the outer part of the flow field. This shielding effect is achieved by the localized introduction of small, energetic structures in the wake of the manipulator which are completely uncorrelated with those in the rest of the boundary layer.

In addition to describing the main mechanisms through which LEBU's alter the turbulence structure to achieve local skin friction reduction in turbulent boundary layers, the results of this study provide concrete explanations for most of the reported changes in this turbulence structure. In particular, they provide an
explanation for the observed relative smoothness of the turbulent/non-turbulent interface reported by Chang and Blackwelder (1990) and by many others (a result of the suppression of the larger scales). They also provide an explanation for the decrease in the size the dominant structure downstream of the manipulator reported by Nagib et al. (1987) (also a result of the suppression of the large scales). They provide an explanation of the significant difference in the effects of LEBU on the transport of momentum and of scalar contaminants such as heat, observed by Trigui and Guezennec (1990) (no equivalent to a wake is present in thermal field). In addition, they partially legitimize the use of small positive angle of attack and sufficiently long chord lengths, as was found in the parametric study of Plesniak and Nagib (1985) (a need for a favorable overall circulation field to trap small structures under LEBU wake).

This investigation also establishes the stochastic estimation technique as a viable tool for extracting important information about flow fields from correlation maps which are otherwise hard to interpret.

6.2 Recommendations

In light of the results of the present study, a better understanding of the mechanisms responsible for the reduction of the local skin friction is obtained. This better understanding can be used to design LEBU’s and LEBU geometries that will yield stronger and longer lasting effects on the boundary layer. One suggestion
is to separate the LEBU's by longer streamwise distances when mounted in a tandem configuration. The acceptable values for this separation is about 10 boundary layer thicknesses. The results obtained from this study indicate that, from the stand point of a further manipulation the turbulence structure, no advantage is gained by placing the manipulators at such close separation. In fact a penalty in terms of device drag is always paid when a device is introduced in the flow. Therefore minimizing the number of manipulators in a flow by extending the separation between them to match the life expectancy of their wakes (i.e. about 20 boundary layer thicknesses in our study) should reduce this penalty and thereby allow for a better chance for net drag reduction.

Another suggestion is to place the manipulators with a slight offset in the normal direction, thereby restricting the trapped structures under the LEBU to regions closer and closer to the wall, and therefore suppressing larger and larger scales. This LEBU geometry, however, will suffer a penalty is paid in terms of a larger device drag.

On a more fundamental level, a better understanding of the interaction of scales in LEBU manipulated boundary layer should be obtained through a similar three dimensional mapping to the ones performed in this investigation but with two or more reference probes. The additional reference probes should be placed in other regions of the boundary layer (near wall region, log region, intermittent region, outer region) to tag on a whole hierarchy of scales. Such an experimental data
could then be used in conjunction with the multi-condition stochastic estimation technique to investigate the indirect effects of the suppression of the large scales by the LEBU on the rest of the boundary layer. Pseudo-dynamics of the flow can then be obtained by imposing actual measured time sequences as conditions at the reference points to investigate the interactions of the different size structures in the flow. Not only would such an experimental investigation provide valuable information about LEBU manipulated boundary layers, but it would also provide a more fundamental understanding of turbulent boundary layers through a better understanding of the link between inner and outer structures.
Appendix A

VELOCITY EXTRACTION

A.1 Two-Components Probe

In this section, a simple technique to extract the appropriate two velocity components from a two-component hot-wire probe is described. This is a simple technique based on the assumption that the effective cooling of a given sensor is only affected by the component of velocity vector perpendicular to it axis. In the absence of a third velocity component signal, this assumption is in agreement with the Jorgensen (1971) model that will be discussed in the next section.

Let us define $q_1$ and $q_2$ as the effective cooling velocities obtained from a two-components probe. Consider, for example, a probe positioned to extract the streamwise and normal components of velocity, as in Figure A-1. One can express:

\begin{align}
q_1 &= u \cos \alpha_1 + v \sin \alpha_1 \\
q_2 &= u \cos \alpha_2 - v \sin \alpha_2
\end{align}

(A.1) (A.2)

where $u$ and $v$ are the streamwise and normal velocity components and $\alpha_i$ are the
absolute value angle between the streamwise axis and the axis of the respective sensor.

If both angles, $\alpha_i$, are equal to $\frac{\pi}{4}$ as is the case in this study, the equations reduce to:

\begin{align*}
q_1 &= \frac{u + v}{\sqrt{2}} \\
q_2 &= \frac{u - v}{\sqrt{2}}
\end{align*}

(A.3) (A.4)
The sum and difference of the above equations yield:

\[ q_1 + q_2 = \sqrt{2}u \tag{A.5} \]
\[ q_2 - q_2 = \sqrt{2}v \tag{A.6} \]

which can be transformed to yield explicit equation in \( u \) and \( v \) as:

\[ u = \frac{q_1 + q_2}{\sqrt{2}} \tag{A.7} \]
\[ v = \frac{q_1 - q_2}{\sqrt{2}}. \tag{A.8} \]

A.2 Three-Components Probe

In this section, an elaborate scheme to extract the three velocity components from a three-component hot-film probe is described. This scheme was initially developed by Choi (1988). As in the two-dimensional case, the Jorgenson effective cooling model is used:

\[ q^2 = u_N^2 + k_1u_T^2 + k_2u_B^2, \tag{A.9} \]

where \( u_N \) is the velocity component normal to the sensor in the plane of the prongs, \( u_T \) is the velocity component tangential to the sensor and \( u_B \) is the velocity component bi-normal to the sensor, i.e. normal to the sensor and perpendicular to the prongs. Now, if we further assume that the effects of the velocity component tangential to the sensor are negligible when compared to the effects of the other two components, and that the effect of the component of velocity bi-normal to the
Figure A.2: Schematic of the Three-Component Probe Positioning

sensors is the same as the one due to the normal component, therefore yielding a value of 0 for $k_1$ and a value of 1 for $k_2$, the effective velocity reduces to:

$$q^2 = u_N^2 + u_B^2$$  \hspace{1cm} (A.10)

Defining $q_1$, $q_2$, and $q_3$ to be the the cooling velocities obtained from a probe positioned as in Figure B-1, one can express:

$$q_1^2 = (u \cos \alpha_1 + v \sin \alpha_1)^2 + w^2$$  \hspace{1cm} (A.11)
\[ q_1^2 = (u \cos \alpha_1 - v \sin \alpha_1)^2 + w^2 \]  
\[ q_2^2 = (u \cos \alpha_2 - v \sin \alpha_2)^2 + w^2 \]  
\[ q_3^2 = (u \cos \alpha_3 - w \sin \alpha_3)^2 + v^2 \]  

where \( u, v, \) and \( w \) are respectively the streamwise, normal, and spanwise velocity components and the \( \alpha_i \) are the absolute value angles between the streamwise axis and the axis of the respective sensor in the plane of the sensor as shown in the figure.

In terms of a spherical coordinate system, the different components of velocity can be written as:

\[ u = ||\vec{V}|| \cos \phi \cos \theta \]  
\[ v = ||\vec{V}|| \cos \phi \sin \theta \]  
\[ w = ||\vec{V}|| \sin \phi \]  

where \( ||\vec{V}|| \) is the velocity magnitude and \( \phi \) and \( \theta \) define the two angles of the velocity vector with respect to the probe axis (\( \phi \) in the \((u,w)\) plane and \( \theta \) in the \((u,v)\) plane).

The effective cooling velocities can therefore be written as:

\[ q_1^2 = (||\vec{V}|| \cos \phi \cos \theta \cos \alpha_1 + ||\vec{V}|| \cos \phi \sin \theta \sin \alpha_1)^2 + (||\vec{V}|| \sin \phi)^2 \]  
\[ q_2^2 = (||\vec{V}|| \cos \phi \cos \theta \cos \alpha_2 - ||\vec{V}|| \cos \phi \sin \theta \sin \alpha_2)^2 + (||\vec{V}|| \sin \phi)^2 \]  
\[ q_3^2 = (||\vec{V}|| \cos \phi \cos \theta \cos \alpha_3 + ||\vec{V}|| \sin \phi \sin \alpha_3)^2 + (||\vec{V}|| \cos \phi \sin \theta)^2 \]
If all the angles, \( \alpha_i \), are equal to \( \frac{\pi}{4} \), as is the case in the present study, the equations reduce to:

\[
q_1^2 = \frac{(||\vec{V}|| \cos \phi \cos \theta + ||\vec{V}|| \cos \phi \sin \theta)^2}{2} + (||\vec{V}|| \sin \phi)^2 \tag{A.20}
\]

\[
q_2^2 = \frac{(||\vec{V}|| \cos \phi \cos \theta - ||\vec{V}|| \cos \phi \sin \theta)^2}{2} + (||\vec{V}|| \sin \phi)^2 \tag{A.21}
\]

\[
q_3^2 = \frac{(||\vec{V}|| \cos \phi \cos \theta + ||\vec{V}|| \sin \phi)^2}{2} + (||\vec{V}|| \cos \phi \sin \theta)^2 \tag{A.22}
\]

Now, if one divides all three equations by \( ||\vec{V}||^2 \sin^2 \phi \), one obtains:

\[
\frac{q_1^2}{||\vec{V}||^2 \sin^2 \phi} = \frac{1 + 2 \cos \theta \sin \theta}{2 \tan^2 \phi} + 1 \tag{A.23}
\]

\[
\frac{q_2^2}{||\vec{V}||^2 \sin^2 \phi} = \frac{1 - 2 \cos \theta \sin \theta}{2 \tan^2 \phi} + 1 \tag{A.24}
\]

\[
\frac{q_3^2}{||\vec{V}||^2 \sin^2 \phi} = \frac{1 + \sin^2 \theta}{2 \tan^2 \phi} + \frac{\cos \theta}{\tan \phi} + \frac{1}{2} \tag{A.25}
\]

One can add the first two equations to obtain:

\[
\frac{q_1^2 + q_2^2}{||\vec{V}||^2} = \cos^2 \phi (1 + 2 \tan^2 \phi) \tag{A.26}
\]

By subtracting the second equation from the first, one obtain:

\[
\frac{q_1^2 - q_2^2}{||\vec{V}||^2} = \cos^2 \phi \sin 2\theta \tag{A.27}
\]

and can recast the third one as:

\[
\frac{q_3^2}{||\vec{V}||^2} = \frac{\cos^2 \phi}{2} (1 + \sin^2 \theta + 2 \cos \theta \tan \phi + \tan^2 \phi) \tag{A.28}
\]

The solution to this system of equations can be obtain as follows: an initial guess of the velocity vector magnitude is chosen. Since the angle of the velocity
vector is limited to be within the acceptance cone, i.e. \(-\frac{\pi}{4} < \theta < \frac{\pi}{4},\) some restrictions can be obtained to the allowable magnitude of the velocity vector \(\vec{V}\):

\[
\frac{2}{3}(q_1^2 + q_2^2) \leq \|\vec{V}\|^2 \leq q_1^2 + q_2^2 \quad \text{(A.29)}
\]

\[
q_1^2 \leq \|\vec{V}\|^2 \quad \text{(A.30)}
\]

\[
q_2^2 \leq \|\vec{V}\|^2 \quad \text{(A.31)}
\]

The flow angle \(\phi\) is evaluated from the following implicit equation using the modified bisection method:

\[
\cos^2 \phi(1 + 2 \tan^2 \phi) = \frac{q_1^2 + q_2^2}{\|\vec{V}\|^2} \quad \text{(A.32)}
\]

The flow angle \(\theta\) is then explicitly evaluated from the following equation:

\[
\sin 2\theta = \frac{q_1^2 - q_2^2}{\|\vec{V}\|^2 \cos^2 \phi} \quad \text{(A.33)}
\]

The norm of the velocity vector can then be recomputed using:

\[
\|\vec{V}\|^2 = \frac{2q_3^2}{(1 + \sin^2 \theta + 2 \cos \theta \tan \phi + \tan^2 \phi) \cos^2 \phi} \quad \text{(A.34)}
\]

New flow angles are recomputed and the procedure is repeated until convergence of all three variables is reached. In the case where multiple solutions are obtained, the one with the smallest deflection angle \(\phi\) is chosen. This choice was made in accordance with the probability density function of flow angles in turbulent boundary layers. The three velocity components are then computed explicitly using equations B-6, B-7, and B-8.
Appendix B

FORMULATION OF THE STOCHASTIC ESTIMATION

The stochastic estimation technique was first introduced by Adrian (1976) and later improved by Adrian (1979) and Tung and Adrian (1980) to include higher order estimates and by Guezennec (1989) to include time dependency. This technique is basically derived from the Rayleigh-Ritz optimization technique in which an estimate of the conditional velocity vector at a location \( \bar{x} \) and at time \( t \) is obtained given a condition or a set of conditions at one or multiple points separated in space and/or time.

Let us restrict the derivation for the simplest case of a single condition. In this case, one can write:

\[
\hat{V}(\bar{x}, t; \bar{r}, \tau) = \langle \bar{V}(\bar{x}, t) | \bar{V}(\bar{r}, \tau) \rangle, \tag{B.1}
\]

where \( \bar{V}(\bar{x}, t; \bar{r}, \tau) \) represents the conditional average of the velocity vector \( \bar{V} \) at a location \( \bar{x} \) and at time \( t \) given a condition at location \( \bar{r} \) and at time \( \tau \).
With conventional ensemble averaging techniques, such as the ones introduced by Blackwelder and Kaplan (1976) and by Willmarth and Lu (1972), this quantity is evaluated by averaging the velocity vector around the given condition when it is satisfied. The decision over whether the condition is satisfied or not is usually determined on the basis of an a priori set threshold level and the averaging is usually performed over an a priori set number of data samples. With this procedure, in order to guarantee the convergence of all statistics of the conditional averaged velocity, very long time records are required since only a small portion of the sampled data is used. In addition, since this method requires certain pre-set averaging parameters, such as the threshold and the hold time, a certain bias is introduced in the resulting conditional averaged velocity.

In the stochastic estimation technique, however, the conditional average of the velocity vector is obtained from unconditional statistics, namely it is estimated by a Taylor expansion in powers of $\bar{V}(\vec{r}, \tau)$ as:

$$
\hat{u}_i(\vec{x}, t; \vec{r}, \tau) = A_{ij}(\vec{x}, t)u_j(\vec{r}, \tau) + B_{ijk}(\vec{x}, t)u_j(\vec{r}, \tau)u_k(\vec{r}, \tau) + ... \quad (B.2)
$$

The unknown coefficients of the estimate are chosen to minimize the mean square error between the conditional velocity and the field. Let

$$
e_i = < \hat{u}_i(\vec{x}, t; \vec{r}, \tau) - u_i(\vec{x}, t) >^2 \quad (B.3)
$$

represents this mean square error. The conditions necessary for this quantity to be a minimum are that its derivatives with respect to all the coefficients $A_{ij}, B_{ijk},$
etc. vanish for all values of $i, j, k$, etc. This is equivalent to writing:

\[
\frac{\partial e_i}{\partial A_{ij}(\vec{x}, t)} = \frac{\partial e_i}{\partial B_{ijk}(\vec{x}, t)} = \ldots = 0.
\] (B.4)

Differentiating and rearranging the terms results in the following system of equations:

\[
A_{ik}(\vec{x}, t) < u_j(\vec{r}, \tau)u_k(\vec{r}, \tau) > + B_{ik}(\vec{x}, t) < u_j(\vec{r}, \tau)u_k(\vec{r}, \tau)u_l(\vec{r}, \tau) > + \ldots = < u_j(\vec{r}, \tau)u_i(\vec{x}, t) >
\] (B.5)

\[
A_{il}(\vec{x}, t) < u_j(\vec{r}, \tau)u_k(\vec{r}, \tau)u_l(\vec{r}, \tau) > + B_{ilm}(\vec{x}, t) < u_j(\vec{r}, \tau)u_k(\vec{r}, \tau)u_l(\vec{r}, \tau)u_m(\vec{r}, \tau) > + \ldots = < u_j(\vec{r}, \tau)u_k(\vec{r}, \tau)u_l(\vec{x}, t) >
\] (B.6)

etc, which can symbolically be represented as:

\[
[C][M] = [F],
\] (B.7)

where $[C]$ represents the matrix of unknown coefficients in the stochastic estimation expression, $[M]$ represents the matrix of moments of order $2^n$ at the reference position $\vec{r}$ at the reference time $\tau$, and $[F]$ represents the matrix of $n$-th order two point space-time correlations, $n$ being the truncation order of the Taylor series.

It has been shown by Guezennec (1989) that the leading order term of the stochastic estimation expression captures most of the essence of the estimated
velocity vector. Therefore, one can neglect the second and higher order terms in the Taylor series expansion. In this case, the estimate reduces to:

\[ \bar{u}_i(\bar{x}, t; \bar{r}, \tau) = A_{ij}(\bar{x}, t)u_j(\bar{r}, \tau) \]  

(B.8)

Therefore, the unknown coefficients can be evaluated by solving the following linear system of equations:

\[ A_{ik}(\bar{x}, t) < u_j(\bar{r}, \tau)u_k(\bar{r}, \tau) >= < u_j(\bar{r}, \tau)u_i(\bar{x}, t) > \]  

(B.9)

for all i and j values. In matrix form, this system of equation can be written as:

\[
\begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
< u_r > < v_r > < w_r > \\
< u_r > < v_r > < w_r > \\
< u_r > < v_r > < w_r > \\
\end{bmatrix}
\begin{bmatrix}
< u_r > < v_r > < w_r > \\
< u_r > < v_r > < w_r > \\
< u_r > < v_r > < w_r > \\
\end{bmatrix}
\]

(B.10)

where \( u_r, v_r, \) and \( w_r \) represent the different velocity components at the reference point, namely \( u_i(\bar{r}, \tau) \), and \( u, v, \) and \( w \) represent the different components of the velocity vector at the point of interest, namely \( u_i(\bar{x}, t) \). The linear estimate of the conditionally averaged velocity at position \( \bar{x} \) and at time \( t \) can be expressed as:

\[
\begin{bmatrix}
\bar{u}(\bar{x}, t; \bar{r}, \tau) \\
\bar{v}(\bar{x}, t; \bar{r}, \tau) \\
\bar{w}(\bar{x}, t; \bar{r}, \tau)
\end{bmatrix}
= \begin{bmatrix}
A_{11} & A_{12} & A_{13} \\
A_{21} & A_{22} & A_{23} \\
A_{31} & A_{32} & A_{33}
\end{bmatrix}
\begin{bmatrix}
u_c(\bar{r}, \tau) \\
v_c(\bar{r}, \tau) \\
w_c(\bar{r}, \tau)
\end{bmatrix}
\]

(B.11)

where \( u_c, v_c, \) and \( w_c \) are any conditions on the three components of velocity at the reference position \( \bar{r} \) at time \( \tau \).

As described above, once the coefficients of the linear estimate are determined, any condition on the velocity vector at the reference point can be imposed. Since
the bulk of the computation is only performed one single time, it is easy to inves-
tigate many different conditions, even with a three dimensional data base. This
is one of the major incentives for its use over the classical ensemble averaging
technique. With the latter technique, the whole averaging procedure has to be
repeated for every single condition, and therefore, it is usually not economically
feasible to consider many conditions.
Bibliography


