Turbulent boundary layer over riblets: Conditional analysis of ejection-like events

Arturo Baron and Maurizio Quadrio
Dipartimento di Ingegneria Aerospaziale del Politecnico di Milano, Milano, Italy

Experimental data obtained with single-sensor hot-wire anemometry in the turbulent boundary layer over a flat and a riblet surface are conditionally analyzed by means of the U-level technique. Attention is focused on the ejection events, as detected by the conditional algorithm: their frequency of occurrence, as well as the probability density distributions of their duration, time separation, and intensity are determined. The ensemble-averaged ejection event is also considered, and the concept of grouping is introduced in order to gain information on the frequency of the overall bursting process. On the basis of the conditional analysis, the modifications induced by the riblets in the turbulent boundary layer are evidenced and described. It turns out that the turbulent structures in the near-wall region of the riblet flow are characterized by smaller time and length scales in the streamwise direction. The results obtained are also interpreted in the frame of proposed conceptual models for the bursting cycle of near-wall turbulence, in which the inflectional spanwise instability of the low speed streaks is dynamically relevant.

Keywords: turbulence; riblets; drag reduction; conditional analysis

Introduction

Turbulence is of such importance that many research institutions reserve intense activity for turbulence studies, which can range from basic experimental research to numerical direct or large-eddy simulation of turbulent flows, to the assessment of sophisticated and general turbulence models. In the last two decades, in particular, considerable efforts have been successfully devoted to the development of a variety of techniques aimed at reducing the skin friction in turbulent wall-bounded flows, which is generally higher than that encountered in laminar flows (Falco et al. 1989; Bushnell and Hefner 1990; Coustols and Savill 1992; Bushnell 1992).

Among these techniques, attention is focused on those surface-mounted longitudinal grooves, called riblets, which have been extensively studied in the last years by several authors (see Walsh 1990, for a complete review). This technique is particularly attractive for several reasons: properly designed riblets can achieve up to 10% in turbulent skin friction reduction (Bechert 1993), and their effectiveness is not affected by moderate misalignment to the mean flow, by compressibility, nor by pressure gradients, provided a number of problems related to maintenability are solved. It must be noted, however, that their operating principle is not fully understood, despite two recent direct numerical simulations by Chu and Karniadakis (1993) and by Choi et al. (1993) that definitely provided detailed information on the turbulent flow field over riblets.

Identification of organized structures in the apparently random evolution of turbulent flows (see for example Kline et al. 1967) can be considered to be the starting point for investigations on turbulent drag reduction. Despite the use of a still unrigorous and often ambiguous nomenclature, an encouraging consensus seems to have been reached on the definition of these so-called coherent or organized structures and on the fundamental events that characterize their interactions, often referred to in the past as the "bursting cycle." A key role in this process has been played by both visual observations (e.g. Kline et al. 1967; Head and Bandyopadhyay 1981) and, in more recent years, by the direct numerical simulation of turbulent flows at low Reynolds numbers in simple geometries. The fundamental work of Robinson (1991) can be considered as the most exhaustive study of the kinematics of the vortical structures in canonical flows to date.

According to several models for the dynamics of turbulence in the near-wall region, developed in recent years, most of the vorticity in the viscous sublayer is concentrated in the spanwise component; while, in the inner layer, the basic vortical structures are the well-known quasi-streamwise vortices. Very near the wall, the prevailing transverse shear layer (ω_y, ω_z) is pushed away by the spanwise and normal-to-the-wall velocity components w and v, which, in turn, are governed by ω_x. The consequent three-dimensionality of the prevailing shear layer is related to the undulatory motion of the low-speed streaks, associated with the inflectional instability due to the gradients $\partial u/\partial y$, and $\partial u/\partial z$ (Blackwelder 1992). However, even in the most (recent and) exhaustive models, disputable points and open questions are still present, and their solution requires combined recourse to theo-

Address reprint requests to Professor Arturo Baron, Dipartimento di Ingegneria Aerospaziale del Politecnico di Milano 40, Via C. Golgi–20133 Milano, Italy.

Received 8 August 1994; accepted 9 June 1996

Int. J. Heat and Fluid Flow 18:188–196, 1997

655 Avenue of the Americas, New York, NY 10010

0142-727X/97/$17.00
PII S0142-727X(96)00087-2

retical speculations and further analysis of physical information on turbulent flowfields.

Classical statistical tools have been applied for many years to the analysis of time sequences of measured values of various physical turbulent quantities, and the use of statistical moments, correlation functions, and energy spectra provided essential information for the development and validation of several theoretical models of turbulence. However, despite their remarkable intensity and dynamical meaning, most of the primary turbulent structures have a short characteristic timescale and are embedded in a background random field, so that essential information on the dynamics of turbulence is blurred by the long-time averaging procedures of statistical analysis. Therefore, independent of the experimental or numerical origin of the physical data, exhaustive information can only be extracted from the available massive databases through use of appropriate conditional analysis techniques.

The aim of the present paper, which constitutes the natural evolution of the research published in Baron and Quadrio (1993), is twofold. First, the preliminary, and somewhat still uncertain, considerations drawn in that paper on the mechanisms through which riblets are believed to affect the bursting cycle in near-wall turbulence are reexamined and confirmed through the use of the U-level conditional analysis technique applied to velocity signals supplied by single-sensor hot-wire anemometry. Secondly, the modifications in the bursting process caused by the presence of riblets are discussed in the frame of a general model for the dynamics of near-wall turbulence.

Experimental conditions

Experiments have been performed in the test section of the open return $L7^+$ low-speed wind tunnel at the Von Kàrmàn Institute for Fluid Dynamics (Bruxelles), operated to obtain a thick boundary layer with a nominally zero pressure gradient. Experimental conditions are briefly summarized in the following, while more detailed information on equipment and procedures has been given in Baron and Quadrio (1993). The dimensions of the test section of $L7^+$ (1700-mm long, 300-mm wide, and 93-mm high) were probably inadequate to allow an exhaustive analysis of the scaling of such quantities as the ejection frequency with the Reynolds number (Shah and Antonia 1989), but were sufficient for the comparison of two different flows at nominally the same Reynolds number.

In the present experiment, the riblet surface had small streamwise triangular grooves with a height and spanwise spacing of 0.7 mm, machined in its central part (200-mm wide). These dimensions, normalized by the viscous length scale, are equivalent to $s^+ = 12$ and $h^+ = 12$ wall units; i.e. corresponding to the well-known range of optimum performance of riblets.

A single hot-wire probe has been used with length 0.5 mm and diameter of 5 microns. The length of the sensor might be thought of as a severe limitation of the present experimental measurements. Considering previous studies (Willmarth and Sharma 1984), these dimensions are believed to allow a spatial resolution sufficient to investigate the main features of the near-wall turbulent structures. The fact that the qualitative picture that emerges from the present work does not conflict with known information on riblet flows can be considered as an *a posteriori* evidence for this assertion.

Velocity signals were sampled at a sampling rate of 6250 Hz (approximately $t^+ = 0.8$), for a duration of 30 seconds. At the measurement station, the uniform free-stream velocity U_{ext} was equal to 5.7 m/s, and the Reynolds number of the boundary layer, based on the momentum thickness, was $Re_\theta = 1150$. The friction velocity has been computed for both surfaces as reported in Baron and Quadrio (1993). The obtained values have been checked against results from a Clauser chart analysis, proving their consistency. Measurements have been repeated at ninety vertical locations within the turbulent boundary layer, the thickness of which is approximately 25 mm for both the flat plate and the riblet flow. Results acquired at ten of these locations are examined in the following.

Conditional analysis techniques

Conditional analysis techniques have been designed to extract, from the time history of some physical variable, essential and possibly quantitative information on those particular *events* related to the coherent structures typical of turbulent flows. As mentioned above, these structures are embedded in a random field and the average (i.e., more probable or dominant) characteristics of an event can only be determined if they are separated from the random part of the signal. However, this is not a trivial task, because the very concept of "conditional" detection weakens the generality of the information obtained. In other words, the results a conditional analysis technique can provide are intrinsically dependent on that peculiar feature of the signal which is somewhat arbitrarily regarded as the distinctive aspect of a particular event. In addition, the dependence on the parameters involved in each of the conditional analysis techniques affects the physical meaning of the extracted information.

In the present work, attention is focused on one particular conditional analysis technique, known as U-level. Among the

Notation

f	frequency
h	riblet height
L	threshold for U-level technique
Re_θ	Reynolds number based on momentum thickness
s	riblet spacing
t	time
T_e	time interval between adjacent ejections
U_{ext}	mean free-stream velocity
x, u, ω_x	streamwise coordinate, velocity (fluctuation), and vorticity components
y, v, ω_y	normal-to-the-wall coordinate, velocity, and vorticity components
z, w, ω_z	spanwise coordinate, velocity, and vorticity components

Greek

τ_e	time interval for grouping ejections

Superscripts

$+$	nondimensionalization with wall variables u_τ and ν

Subscripts

e	relative to ejections
b	relative to bursts

various techniques developed for the identification of the coherent structures in turbulent wall bounded flows, U-level has been chosen, because it has been evaluated by Bogard and Tiederman (1986) as one of the most suitable algorithms for the analysis of single-point velocity measurements in near-wall turbulent flows, and probably the best for single-wire measurements. In addition U-level has the advantage of being autoconditional, because the input for the detection algorithm is a function of the velocity signal itself.

The U-level technique

The conditional averaging technique known as U-level was first introduced by Lu and Willmarth in 1973. U-level operates on the streamwise velocity component and detects an event when the value of the velocity signal is lower than L times the rms value of the velocity signal itself (i.e., $u < -L \cdot u_{\mathrm{rms}}$), where L is a threshold value of the order of unity.

From a physical point of view, it is clear that U-level, which can be considered as a high-pass filter, should detect, in the turbulent signal, only those parts related to the central phase of the low-speed streaks, the well-known feature of the near-wall region of turbulent boundary layers (Figure 1). U-level was originally designed to detect the low-speed streaks; however, it is well known (Kim et al. 1987) that in the near-wall region, events with negative u are correlated with events with positive v, v being the velocity component normal-to-the-wall. As a consequence, as shown by Bogard and Tiederman (1986), the probability that in correspondence of an U-level detection v is directed outwards is very high. These events, which belong to the II quadrant of the (u, v) plane, are commonly referred to as ejections. The study by Bogard and Tiederman (1986), based on accurate comparisons between detections from conditional techniques and visual observations, concludes that the Quadrant technique, based on two-wire measurements, is the best suited for the detection of the ejections. However, Bogard and Tiederman report also that U-level is able to detect a very high percentage of the visually observed ejections, while the probability of detecting a false ejection is almost negligible.

In the present work, in order to avoid any misunderstanding, a working definition is adopted for the events of ejection, according to which an ejection, or more exactly an ejection-like event, is an event detected by the U-level technique. The output of U-level obviously depends on the selected threshold value L. Moreover, it may be important to choose the variables carefully for the nondimensionalization of the results, especially when dealing with the comparison of flat and riblet flow data. In the literature, evidence can be found for the validity of the inner scaling, at least for low and moderate Reynolds numbers (Shah and Antonia 1989). Friction velocity, however, is always determined with some uncertainty, and this may be particularly crucial considering that it appears squared in nondimensional frequencies. For this reason, results have been tentatively plotted with both scalings, and, because no appreciable differences have been observed, the viscous scaling has been maintained.

The concept of grouping

The entire cycle of production and regeneration of turbulence in the near wall region of the boundary layer is usually referred to as a *burst*. It is well known (Luchik and Tiederman 1987) that a single bursting cycle can contain one or more ejection events so that, if the bursting frequency has to be inferred from information of the ejection frequency, it is essential to determine the number of ejections which are *grouped* in a single burst.

The grouping process requires that the maximum time interval τ_e between ejections belonging to the same burst be properly evaluated. This quantity can be determined by using various methods (Luchik and Tiederman 1987; Bogard and Tiederman 1987) based on the concept that the probability density function of the occurrence of ejections *versus* the time interval T_e between adjacent events may be thought of as the superposition of two distinct temporal distributions: one for the ejections from the same burst and one for the ejections from different bursts. The resulting probability density function is schematically shown in Figure 2 and allows τ_e to be defined as the time interval for which the global distribution has a relative minimum.

In the present work, the cumulative exponential distribution (CED) technique (Luchik and Tiederman 1987) is used to compute τ_e. This method is based on the comparison of the cumulative probability density function of T_e, computed for the experimental data, and an exponential distribution function for randomly distributed events, modified for the condition that $T_e \geq T_0$, T_0 being the finite average duration of the ejections (Figure 3). In other words, the probability density function of the experimental data (symbols in Figure 3) is compared with a probability function for random events separated by more than T_0 (solid line). For low values of the time interval T_e, the experimental data show a higher probability density function; thus, revealing the presence of a number of ejections belonging to the same burst, because the bursts themselves are known to be randomly distributed in time. For high values of T_e, on the other hand, experimental data fall below the straight line. Therefore, τ_e is determined as the abscissa of the crossing point of the two probability density functions. Accordingly, and considering the working definition of an ejection reported above, a burst is here defined as an event composed of a number of ejections separated by a time interval smaller than τ_e.

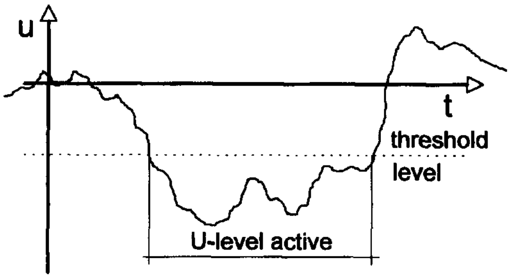

Figure 1 Schematic of a typical velocity pattern recorded by a fixed probe in correspondence of a low-speed streak and the related behavior of the U-level technique

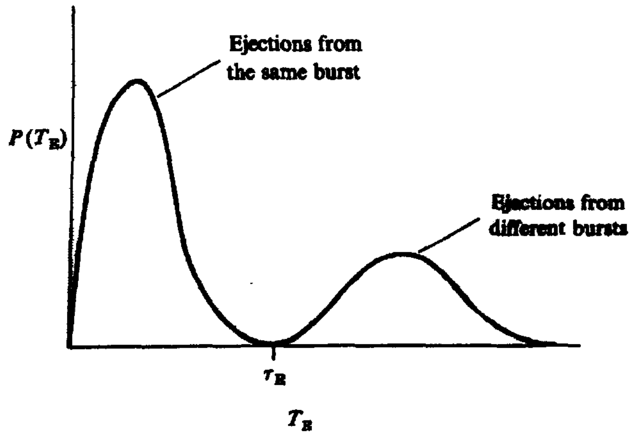

Figure 2 Schematic showing idealized probability distribution for time between ejections (after Luchik and Tiederman 1987)

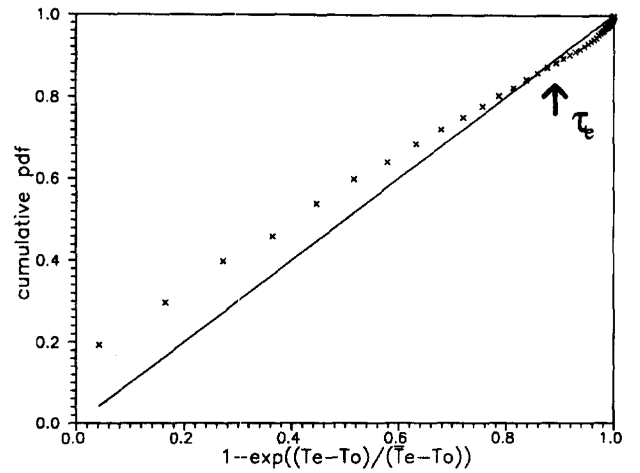

Figure 3 Example of determination of τ_e with the CED technique

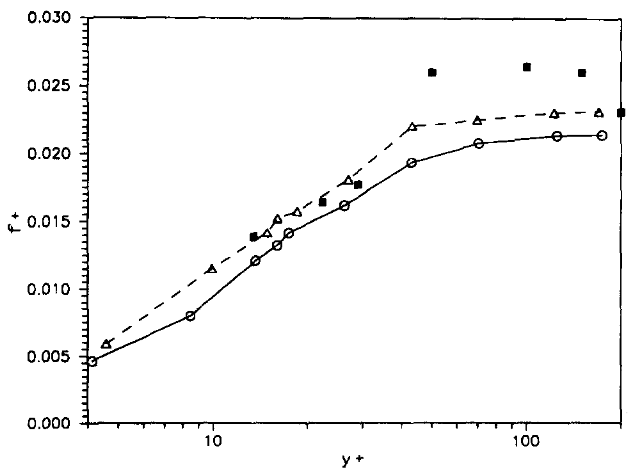

Figure 4 Frequency of occurrence of ejections as a function of the distance from the wall. *U*-level technique with $L = 1.3$; solid line: flat surface; dotted line: riblet surface; comparison data after Bogard and Tiederman (1986) (squares) concern only the flat surface case

As Luchik and Tiederman (1987) pointed out, results inferred for a particular value of τ_e in terms, for example, of average time between bursts, can be highly dependent on the type of conditional technique and mainly on the values of the threshold level. Luchik and Tiederman were able to show that, in the canonical turbulent boundary layer, a range of values for the thresholds can be determined, where the average time between bursts is approximately independent on the conditional technique and on the threshold and is consistent with average times deduced from flow visualizations.

Results

Conditional analysis, based on the *U*-level technique, has been used to investigate the modifications induced by the riblets on the so-called ejection-like events, a working definition of which was given in the conditional analysis techniques section. Among the properties of the ejections which are expected to be modified by the presence of the riblets, the frequency of occurrence f_e, intensity and distribution in time are analyzed in the following. In addition, the ensemble-averaged ejection event is considered, and the grouping procedure is applied in order to educe some information on the bursting process; i.e., on the whole turbulence production cycle over the riblets.

Single events

The frequency of occurrence of ejections f_e is recognized as one of the main characteristics of the bursting process (to such a point that it has been sometimes erroneously interpreted as the frequency of the entire turbulence regeneration process itself) and has, therefore, been examined in most of the works on the dynamics of near-wall turbulence. Possible modifications in the ejection frequency, induced by riblet surfaces, have been discussed by various authors (e.g., Choi 1989; Hoosmand et al. 1983; Schwarz van Manen et al. 1991), even if their conclusions can still be considered somehow controversial and undefined.

The *ejection frequency* f_e is reported in Figure 4, computed with the *U*-level conditional technique and plotted as a function of the distance from the wall, for both the riblet and the flat plate flows. A similar plot, based on the same experimental dataset, but analyzed with the variable interval time averaging (VITA) conditional technique, was reported in Baron and Quadrio (1993), showing a similar qualitative behavior. The absolute values of f_e, for the flat plate flow, as well as their dependence on the distance from the wall, were shown there to compare very well with previous experimental results (e.g. Shah and Antonia 1989), which are computed with different conditional techniques. In Figure 4, experimental data from Bogard and Tiederman 1986) are also plotted. This dataset is derived from similar experiments and concerns the canonical case, but, again, the frequencies are computed by using different conditional techniques. The data presented here are computed by means of the quadrant technique, with the threshold level set according to a method suggested by Comte-Bellot et al. (1978). The comparison with these data must, therefore, be interpreted exclusively in a qualitative way, but there is indication that both the absolute values of f_e and their dependence on the distance from the wall are well predicted by the present technique. The data of Figure 4, where a threshold level of $L = 1.3$ has been used, support the conclusion that the difference between the ejection frequencies over the two surfaces is not dramatic, but nevertheless, unquestionable. Ejection frequency data, obtained by using different values of the threshold L and not reported in this paper, show that the increase in the frequency of the events is enhanced by reducing the threshold levels and always confirm that the ejections are more frequent within the riblet flow.

The *intensity* of the ejection events is not a precisely defined quantity, even if it seems reasonable to relate the intensity to the minimum value $u_{\min}$ reached by the fluctuating velocity during the ejection event. In Figure 5 the probability density function of $u_{\min}$ is reported for the flat and libletted surfaces, for a distance of 16 and 170 wall units over the flat surface. The events have been detected with $L = 1.3$, and the distributions have been normalized so that their integral is unity. In general, it appears that near-wall events have a wider intensity distribution; while, far from the wall, the most probable intensities are more concentrated near the threshold value of the conditional technique (i.e., the weakest events are the most probable ones). Due to the definition of the *U*-level technique, the two probability density functions are identically zero for $u > -Lu_{\mathrm{rms}}$ and show no appreciable differences for higher values of u. The data reported in Figure 5, as well as those computed at any other distance from the wall, tend to exclude the possibility of a modification of the intensity of the ejections caused by the riblets.

Another quantity worth considering is the *duration* of the ejections. For each event, the duration is defined as the time interval during which the conditional technique is active. Figure

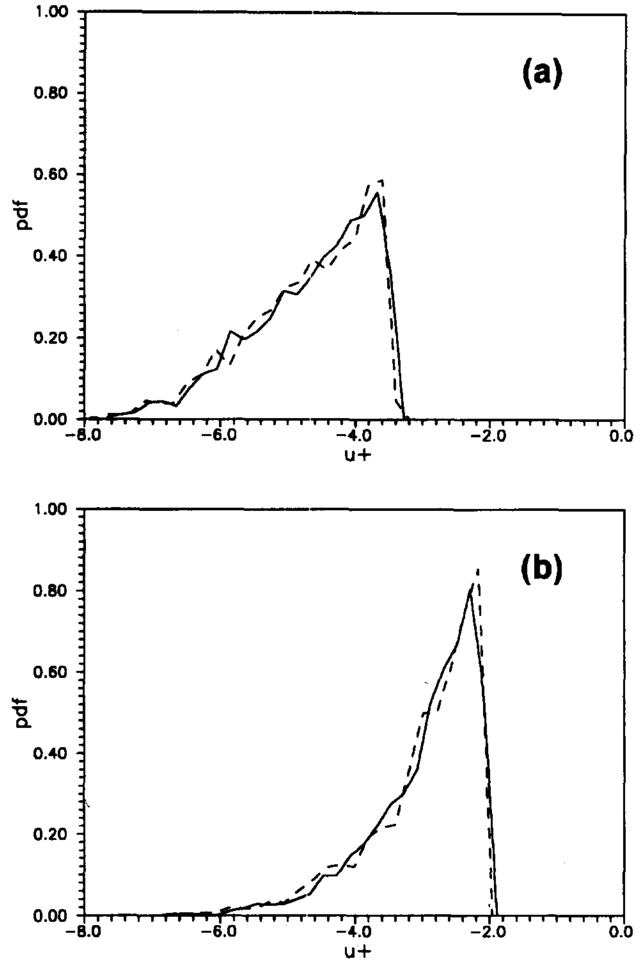

Figure 5 Probability density function for the minimum of the fluctuating streamwise component of the velocity during the events of ejection, at 16 (a) and 170 (b) wall units from the wall; solid line: flat surface; dotted line: riblet surface

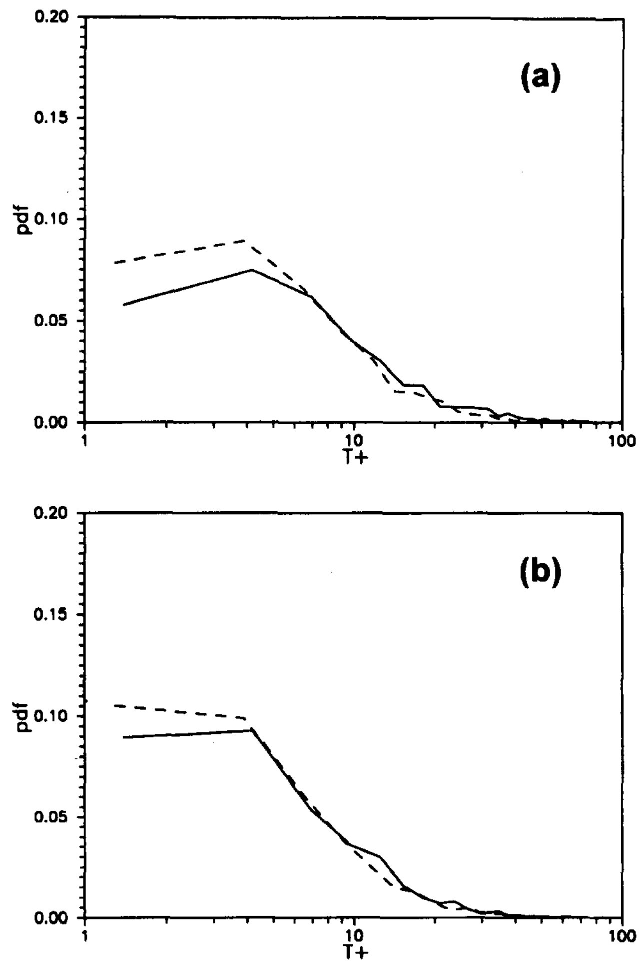

Figure 6 Probability density functions for the duration of events of ejection at 9 (a), 16 (b), and 27 (c), and 70 (d) wall units from the wall; solid line: flat surface; dotted line: riblet surface

6 a,b,c,d reports the probability density function for the duration of the ejection-like events for the riblet and the flat plate flows, computed at various locations among the coordinate normal to the wall (9, 16, 27, and 70 wall units, respectively). The events were computed with $L = 1.3$, and the distributions were normalized so that their integral is unity. In general, the duration of the events tends to diminish by increasing the distance from the wall, due to the break-up of the coherent structures, so that the probability density functions tend to be more peaked towards smaller values of the duration. If attention is focused on the difference between the two flows, it becomes quite evident that, near the wall, shorter events are more probable for the riblet flow; while, as the distance from the wall is increased, any difference in the probability density functions of the duration of ejections tends to vanish.

Similar conclusions can be reached by examining the probability density functions of the time interval between the end of an event and the beginning of the following one. We call this the "time interval between the ejections," where the beginning and the end of the events are identified, as before, by the on/off switching of the U-level technique.

Figure 7 shows the probability density function of the time interval between the ejections, detected with $L = 1.3$, at 16 (a) and 70 (b) wall units, which clearly reveals that, in the riblet flow, the ejections tend to follow each other more closely. As the distance from the wall increases, it can be seen that both the distributions tend to peak towards higher values, and again the differences between flat and riblet flows become less and less evident.

In the riblet flow, increased frequency and reduced duration of the ejections could exactly compensate. However, there also exists the possibility that either the frequency increase prevails, or the duration decrease is more relevant. To check this point, a parameter we call *intermittency*, in analogy with the well-known intermittency factor for the outer region of turbulent boundary layers, is introduced and computed. The intermittency of the signal acquired from hot-wire anemometry is here defined as the ratio between the sum of the durations of the ejections (as detected by the U-level technique) and the total time. In this way, an indicator is computed of the relevance of the ejection-like events detected by the conditional technique, related to their persistence in time.

In Figure 8 the intermittency factor is plotted *versus* the distance from the solid wall, for both the ribletted and the flat surfaces. As a general observation, it can be said that, for both flows, the detected events become more persistent in time, while the low momentum fluid elements travel away from the wall towards the buffer layer. This is evidenced by the increase in the intermittency factor and can be interpreted as a consequence of the streamwise stretching induced by the mean shear. In the

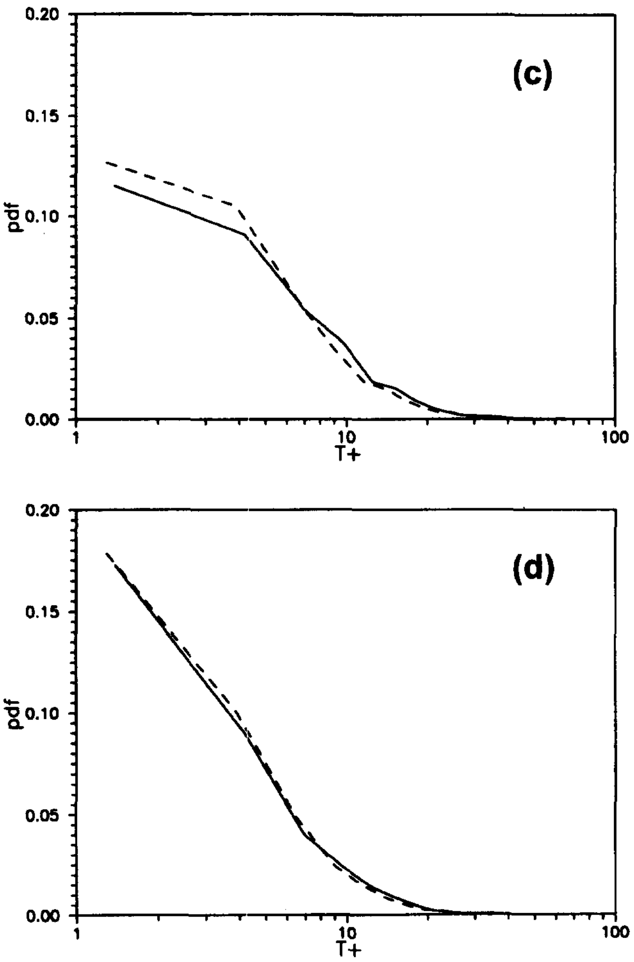

Figure 6 (*Continued*).

buffer layer, the ejections detected by U-level (with the threshold L set at 1.3) last for approximately 12% of the total time. If the flows over flat and riblet surfaces are compared, there is no clear indication of substantial differences: except for the measurement point adjacent to the wall, the intermittency is more or less similar for both surfaces. Analogous results have also been drawn by examining the data for different values of the threshold L. The substantial similarity of the intermittency factors for the flat plate and the riblets can be considered as a further indication of the balancing between the increase of the number of events per unit time and the reduction in their duration.

The ensemble-averaged event

Part of the information on the ejections and their modifications in the riblet flow can be more concisely inferred by examining the average ejection event, defined as the ensemble average of all of the ejections detected by U-level. As a trigger point (i.e., the centering point of the ensemble average), the middle of the event has been used.

The average ejection event is shown in Figure 9 at 16 (a) and 70 (b) wall units from the solid wall, for a threshold value set at $L = 13$, For the first distance from the wall, the results are compared with the conditionally averaged longitudinal velocity pattern educed, for the canonical flow, by Luchik and Tiederman (1987). It must be noted, however, that they used what they call a *modified* U-level technique, with a threshold of $L = 1.0$, and the central point of the event as the trigger point. Consequently, the comparison can have only a qualitative value, even if the behavior of the averages turns out to be very similar. Looking at the

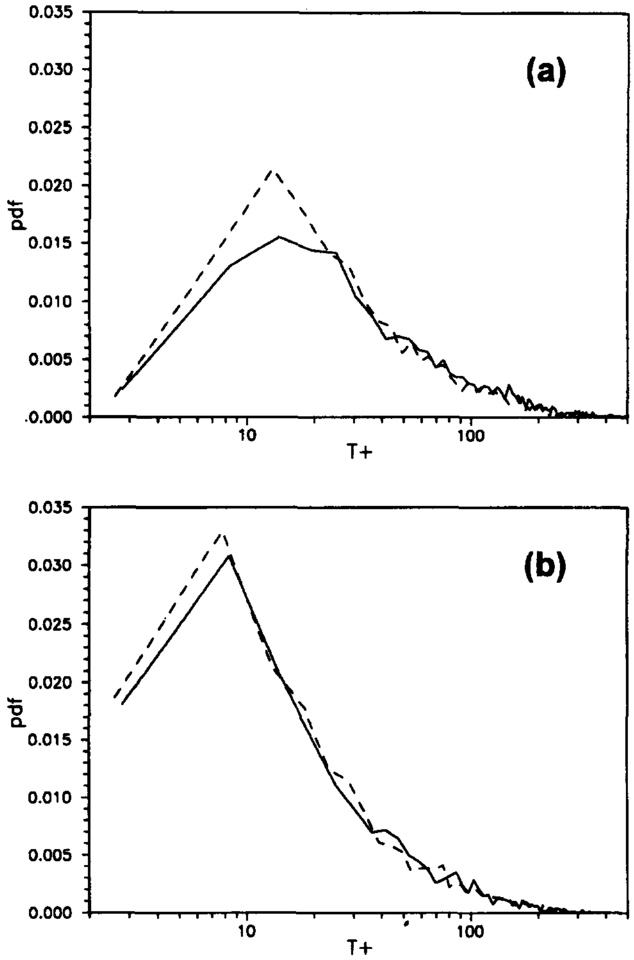

Figure 7 Probability density function for the time interval between the ejections, at 16 (a) and 70 (b) wall units from the wall; solid lines: flat surface; dotted line: riblet surface

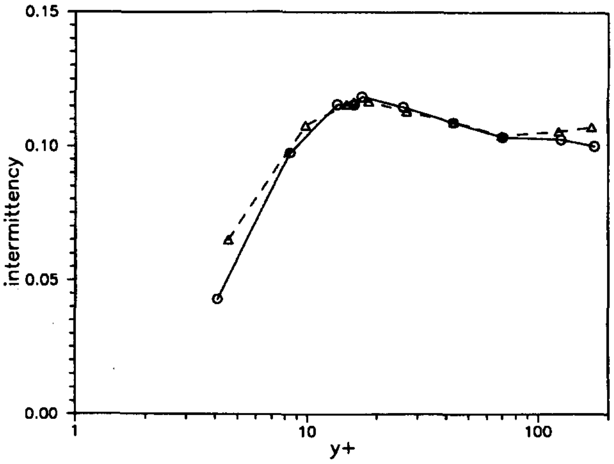

Figure 8 Intermittency factor as a function of the distance from the wall; solid line: flat surface; dotted line: riblet surface

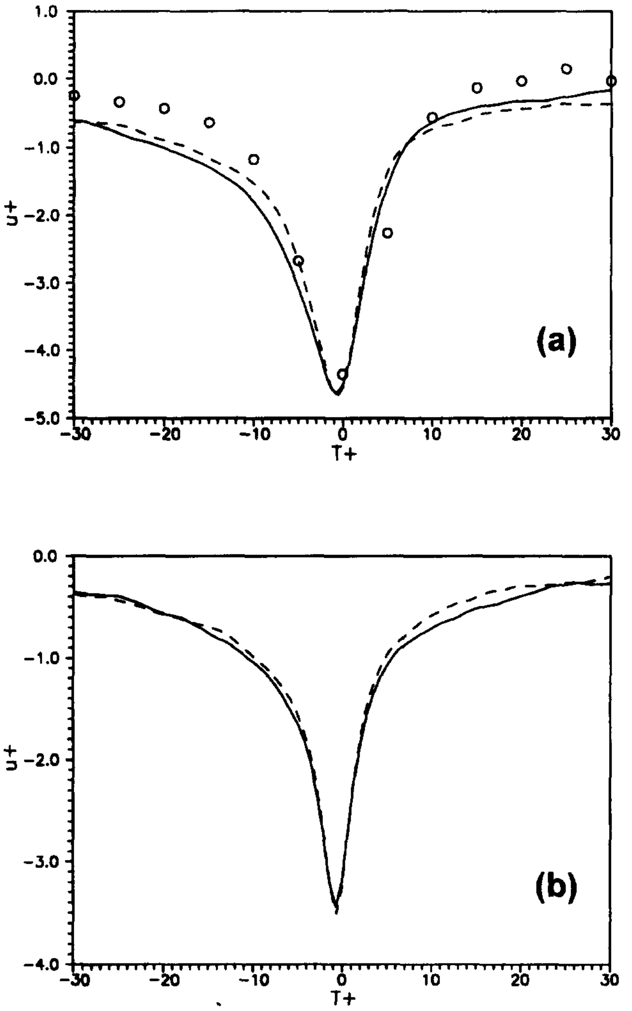

Figure 9 Conditional average of ejection signatures, at 16 (a) and 70 (b) wall units from the wall; solid line: flat surface; dotted line: riblet surface; symbols: data from Luchik and Tiederman (1987)

differences between the two figures, the indication of a slight decrease in the time/space scales of the events in the inner part of the riblet flow, already pointed out in Baron and Quadrio (1993) when discussing results based on VITA technique, is confirmed by Figure 9a. Moreover, again Figure 9b shows that the influence of the riblets almost vanishes beyond the buffer layer.

All of the properties of the ensemble averaged event (duration, amplitude, etc.), examined at various other vertical locations, confirm that the effect of the riblets is likely to persist for up to 30–40 wall units from the solid wall. As an example, the duration of the averaged event is plotted in Figure 10 *versus* the distance from the wall. Note that the definition of *duration* for the averaged event is different from that used for the single realizations: considering the plot of the averaged event, its duration is assumed to be equal to the time interval between the points where $\langle u \rangle$ reaches 0.5 times the minimum value of the averaged velocity pattern.

The grouped events

The concept of grouping (Bogard and Tiederman 1986) is used to determine if the turbulence production cycle over riblets actually shows the tendency to "break-up" the main flow structures into smaller ones. This suggestion can be found, for example, in Choi (1989). In other words, assuming that the main event of the turbulence production cycle (the "burst") is usually formed by a number of ejections, the concept of grouping is used to verify the indication of an increased number of ejections per single burst in the riblet flow.

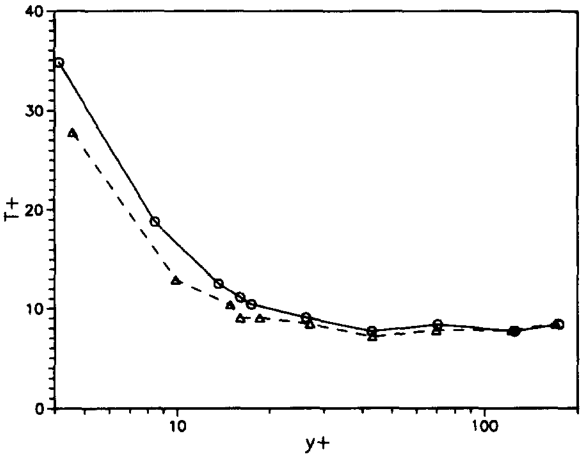

Figure 10 Duration of the average event of ejection as a function of the distance from the wall; solid line: flat surface; dotted line: riblet surface

As already stated in the Conditional analysis techniques section, in the present work the cumulative exponential distribution technique (Luchick and Tiederman 1987) is used for grouping the ejections, together with the U-level technique. In the above-mentioned section, it has also been stressed that the key element that must be accurately determined for a grouping procedure is the time interval τ_e which discriminates if two adjacent ejections belong to the same burst, and that the value of τ_e is strongly dependent on the threshold values adopted in the conditional technique. It is evident, as Luchik and Tiederman themselves clearly point out, that the overall procedure of grouping makes sense if it is possible to define a range of threshold values, for which the results (e.g., the frequency of occurrence of the grouped events f_b) are only negligibly affected by the choice of the threshold value itself.

For a distance from the flat surface of 15 wall units, Figure 11 shows the dependence of the frequency of the grouped events (or bursting frequency f_b) on the threshold L. Even if, strictly speaking, it is not possible to define a range of values of L where f_b is completely independent of L, it can, nevertheless, be assumed that for L greater than 0.5 and smaller than 1.0–1.2, the dependence on L is not such as to blur the substantial trend of the data. In addition, as the figure shows, the comparison with the value computed by Bogard and Tiederman (1986) with the quadrant technique is in very good agreement with the present one for the flat plate case. Figure 11, together with analogous ones computed for the remaining positions over the wall, led to the selection of a value of $L = 0.8$ for all data.

Results in terms of bursting frequency f_b are shown, in comparitive form for the flat and the riblettted surfaces, in Figure 12. It can be educed that, in general f_b shows a weaker dependence on the distance over the wall if compared to the frequency f_e of the single events. In addition, although the interpretation of the plot is not straightforward, it can be stated that, contrary to what has been observed for the ejection frequency, the bursting frequency is slightly reduced over the riblettted surface. This result seems to be compatible with a reduction of the skin friction in the riblet flow.

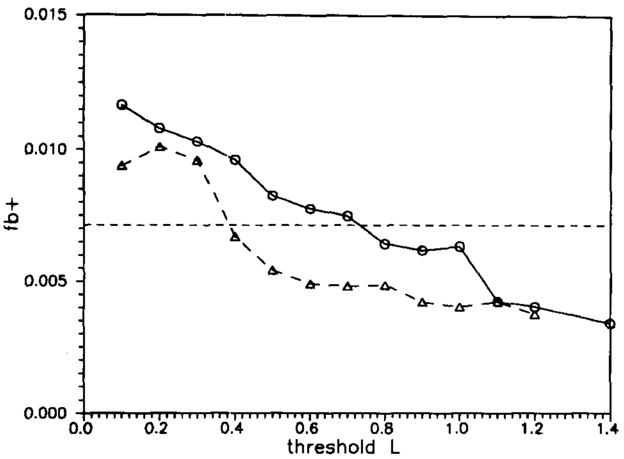

Figure 11 Dependence of the frequency of occurrence of the grouped events, at 15 wall units from the wall, on the threshold value L; circles and solid line: flat surface; triangles and dotted line: riblet surface; reference line: value from Bogard and Tiederman (1987)

Conclusions

Classical statistical methods and time-averaging procedures are not very effective means to the understanding of the origin of the small modifications induced by the riblets in a turbulent boundary layer: the main structural modifications, although dynamically important, are characterized by turbulent timescales, which are so small that any information is likely to be lost in the time-averaging process.

On the contrary, as shown also by the present analysis, a cautious use of conditional techniques proves to support and confirm the observation, reported in various published papers, that the frequency of occurrence of the ejections is increased by the presence of the riblets. This conclusion has been reached by using the U-level technique and by defining as 'ejection' any event detected by the U-level technique itself.

In addition to the detection of the ejections, further essential information is provided by the conditional analysis, pertaining to a number of characteristics of the single realizations. It has been confirmed, for example, that the duration of the ejections tends to be reduced over the riblets and that this reduction compensates for the increased frequency, so that the intermittency factor remains substantially unaltered. As far as the temporal distribution of the ejections is concerned, an indication has been given that these events tend to be more closely grouped over the riblets. Moreover, the application of the grouping procedure confirms that the average number of ejections enclosed in each single burst is larger than that observed for the flat plate flow, thus explaining how an increased ejection frequency can be fully compatible with a reduced bursting frequency.

The overall indication emerging from the present analysis is that in the near-wall region, shorter, smaller, and more grouped ejections occur in the riblet flow. The turbulence cycle is, consequently, subdivided, as already suggested by Choi (1989), into processes that result to be weaker and more fragmented.

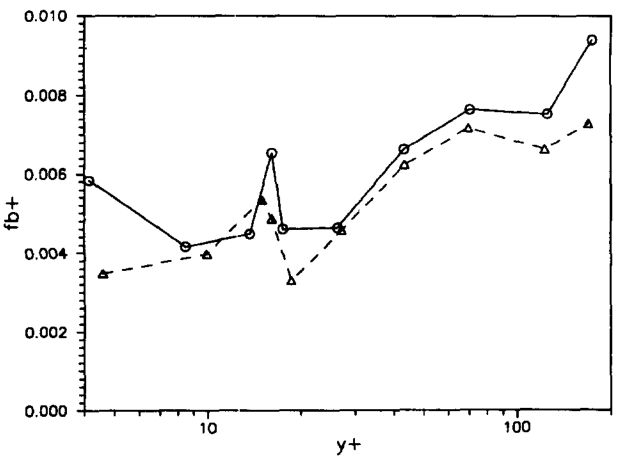

Figure 12 Frequency of occurrence of the grouped events as a function of the distance from the wall; solid line: flat surface; dotted line: riblet surface

Acknowledgments

This work has been partially supported by the Ministero dell'Univeristà e della Ricerca Scientifica e Technologica. The authors gratefully acknowledge the important contribution of Ing Paolo Gherardi in the development and application of the conditional analysis.

References

Baron, A. and Quadrio, M. 1993. Some preliminary results on the influence of riblets on the structure of a turbulent boundary layer. *Int. J. Heat Fluid Flow*, **14**, 223–230

Bechert, D. W. 1993. Paper presented at the VIII European Drag Reduction Meeting, Lausanne, Switzerland

Blackwelder, R. F. 1992. The eddy structure in bounded shear flows. AGARD Rep. 786, VKI special course on skin friction drag reduction

Bogard, D. G. and Tiederman, W. G. 1986. Burst detection with single point velocity measurements. *J. Fluid Mech.*, **162**, 389–413

Bogard, D. G. and Tiederman, W. G. 1987. Characteristics of ejections in turbulent channel flow. *J. Fluid Mech.*, **179**, 1–19

Bushnell, D. M. and Hefner, J. N. (eds.). 1990. *Viscous Drag Reduction in Boundary Layers*, Vol. 123. Progress in Astronautics and Aeronautics, AIAA, New York

Bushnell D. M. 1992. AGARD Rep. 786, VKI special course on skin friction drag reduction

Choi, H., Moin, P. and Kim, J. 1993. Direct numerical simulation of turbulent flow over riblets. *J. Fluid Mech.*, **255**, 503–539

Choi, K.-S. 1989. Near-wall structure of a turbulent boundary layer with riblets. *J. Fluid Mech.* **208**, 417–458

Chu, D. C. and Karniadakis, G. E. 1993. A direct numerical simulation of laminar and turbulent flow over riblet-mounted surfaces. *J. Fluid Mech.*, **250**, 1–42

Comte-Bellot, G., Sabot, J. and Saleh, I. 1978. Detection of intermittent events maintaining Reynolds stresses. *Proc. Dynamic Flow Conference—Dynamic Measurements in Unsteady Flows*, 213

Coustols, E. and Savil, A. M. 1992. Turbulent skin friction drag reduction by passive means. AGARD Rep 86, VKI special course on skin friction drag reduction

Falco, R. E., Klewicki, J. C. and Pan, K. 1989. Production of turbulence in boundary layers and potential for modification in the near wall region. *Proc. 2nd IUTAM Symposium on Structure of Turbulence and Drag Reduction*, Zurich, Switzerland.

Head, M. R. and Bandyopadhyay, P. 1981. New aspects of the boundary layer structure. *J. Fluid Mech.*, **107**, 297–338.

Hoosmand, D., Youngs, R. and Wallace, J. M. 1983. An experimental study of changes in the structure of a turbulent boundary layer due to surface geometry changes. AIAA Paper 83-0230

Kim J., Moin, P. and Moser, R. 1987. Turbulence statistics in fully developed channel flow. *J. Fluid Mech.*, **177**, 133–166

Kline, S. J., Reynolds, W. C. Schraub, F. A. and Runstadler, P. W. 1967. The structure of turbulent boundary layers. *J. Fluid Mech.*, **30**, 741–773

Lu, S. S. and Willmarth, W. W. 1973. Measurements of the structure of the Reynolds stress in a turbulent boundary layer. *J. Fluid Mech.*, **60,** 481–511

Luchik, T. S. and Tiederman, W. G. 1987. Timescale and structure of ejections and bursts in turbulent channel flows. *J. Fluid Mech.*, **174,** 529–552.

Robinson, S. K. 1991. Coherent motions in the turbulent boundary layer. *Ann. Rev. Fluid Mech.*

Schwarz-van Manen, A. D., Hoogsteen, R., Stouthart, J. C., Prasad, K. and Nieuwstadt, F. T. M. 1991. Coherent structures over a smooth and a triangular riblet drag reducing surface. In *Recent Developments in Turbulence Management*, K.-S. Choi (ed.). Kluwer Academic Publishers, The Netherlands, 93–112

Shah, D. A. and Antonia, R. A. 1989. Scaling of the "bursting" period in turbulent boundary layers and duct flows. *Phys. Fluids A*, 318–325

Walsh M. J. 1990. *Riblets,* Vol. 123. Progress in Astronautics and Aeronautics, AIAA, New York

Willmarth, W. W. and Sharma, L. K. 1984. Study of turbulent structures with hot wires smaller than the viscous length. *J. Fluid Mech.*, **142,** 121–149