Characteristics of single and clusters of bursting events in the inner layer

Part 1: Vita events

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Abstract A new method of identification of bursting events in a turbulent boundary layer is presented and applied to VITA. The philosophy adopted here is similar to that of Tiederman (1988). It consists of the classification of individual events into groups corresponding to multiple breakups of the same streak (Bogard and Tiederman, 1986). The strategy is however different, in that it uses differences in the signatures of the events belonging to the same cluster. The iterative procedure finds out these differences and classifies events which have similar signatures. It is found that the distribution of the frequency of groups of events identified this way differs from the distribution of the solitary ones. The “multiple shear layer events” (MSLs) have strikingly different signatures compared to “single shear layer events” (SSLs). These differences are mostly present near the wall and disappear progressively at the beginning part of the constant shear layer. The contribution of the MSLs to the Reynolds shear stress is larger. The differences in the conditional averages of the streamwise and wall normal velocities are highly suggestive that the regeneration mechanism of the clusters of events near the wall is dynamically different.

1 Introduction

The bursting process in a turbulent boundary layer includes a multiplicity of complex flow phenomena as revealed by three decades of intensive research. The hierarchy, scale, nature and interaction of the vortical structures (such as quasi-streamwise vortices, arch like vortical structures, transverse vortices, pockets, etc.) responsible of the bursting phenomena have been largely tackled in a number of detailed investigations. One point seems however to not have attracted sufficient attention: the reaction of the near wall turbulence to such periodic lift-ups of the low-momentum fluid from the wall (Corino and Brodkey 1969; Offen and Kline 1974; Talmon et al. 1986; Bogard and Tiederman 1986, 1987; Robinson et al. 1989). In other words, the ejections may intermittently behave like groups of correlated although distinct individual events rather than single structures. According to these observations, the term “bursting” involves a complex regeneration mechanism of clusters of ejections (and related sweeps) rather than a single and eventually multistage process of Kline et al. (1967) and Kim et al. (1971). Extensive studies dealing with comparisons between flow visualizations and single point measurements indicated global characteristics of this process (Bogard and Tiederman, 1986, 1987; Luchik and Tiederman 1987). Such distinctions between single and dual events have also been done in some recent studies dealing with spatio-temporal behavior of the bursting (Lu and Smith 1991).

Several questions remain unanswered however. First of all, it is not clear whether the bursts containing more than one active event are structurally different than the single events. In most of the previous studies, single events have been classified both as the first and the last ejection of the clusters without specifying that they are of a similar nature for all that. Secondly no systematical investigation exists concerning the dynamical importance of the multiple events as for instance the contribution to the Reynolds shear stress compared with the contribution of the single ejections. Even data dealing with the distribution of the time mean frequency of these events in the boundary layer and their scaling (i.e. inner outer or mixing) is missing.

Since every one point detection scheme detects individual events, appropriate identification methods are needed to group them into bursts in order to determine if they emanate from the same low-speed streak. This constitutes the first aim of this study, namely developing a new grouping technique for single point detection schemes. Eulerian detection of the coherent structures have been fairly criticized since these schemes cannot completely catch the three dimensionality of the structures, but methods similar to the one outlined in this study can easily be adapted to the spatio-temporal techniques.

The second aim is to determine the characteristics of the clusters of events and compare them with those of the single events in order to elucidate whether it is legitimated to collect them within the same structure (burst) or not.

The main motivation of this study is based on recent investigations in unsteady turbulent wall layers dealing with the response of the ejection and bursting mechanism to imposed pressure gradient which varies periodically in time. The reaction of the near wall turbulence to such periodic
velocity oscillations is strongly imposed frequency dependent (Tardu et al. 1994a). It was found, nevertheless, that the bursts containing several events follow closely the modulation characteristics of the wall shear stress in a large range of imposed frequency, while the solitary ejections do not (Tardu et al. 1994b). That gave the idea that groups of events are mainly generated in the buffer and viscous region and governed by the wall. One of the objectives of the present study is, therefore, to determine if these two categories of events have different characteristics in steady flow, and this, in order to explain the observed differences in unsteady flow.

This study does not deal with the identification of the individual active events but with their reorganization in their corresponding time series. The originality is therefore not in the detection scheme but in the grouping methodology. The characteristics of clusters of events detected by VITA (Blackwelder and Kaplan 1976) and the corresponding regeneration mechanism will be discussed here. Other Eulerian schemes such as those based on level crossings and quadrant techniques will be discussed in an accompanied paper (Tardu 1995). It has to be recalled here that VITA detects strong shear layers which eventually roll-up to give active structures leading to ejections and bursts. This is why the "word" ejection is no more used in the following.

The paper is divided into two main parts. A new burst identification technique is outlined in Sect. 3. The efficiency of the grouping technique together with the distribution of the frequency of bursting events related to VITA (i.e. strong shear layer events) in the inner layer are discussed in Sect. 4. This is followed by the analysis of the $u'$, $v'$ and $u''v'$ signatures corresponding to different parts of the shear layer events. The link between these characteristics and some existing near wall turbulence models is made in Sect. 5.

2 Experimental set up; data reduction

The experiments were performed both in the closed loop wind tunnel with low turbulence level of Ecole Polytechnique Federale de Lausanne and in the water channel of LEGI. Most of the measurements of the streamwise velocity fluctuations $u'$ and related quantities presented in this study correspond to the wind tunnel experiments and simultaneous measurements of $u'$ and the cross-stream (normal) velocity fluctuations $v'$ are obtained in the water channel.

The working section of the wind tunnel is a two dimensional channel, 2 m long with two fixed transparent side walls and 2 aluminium flat plates. The centerline velocity was set $U_c = 15$ m/s during the experiments and this corresponds to a Reynolds number of $Re_o = 4300$. A subminiature TSI 1260-10 hot-film probe is used and the small sizes of the probe allowed us to perform measurements very near the wall as close as $y^+=4$. The spanwise length of the probe is $\Delta z^+ = 19$ in wall units; although it is somewhat large, it may be assumed that it is in the acceptable limit to avoid the spanwise averaging of the detected structures (Blackwelder and Haritonidis 1983).

The water channel of LEGI is 100 mm wide 2600 mm long. The centerline velocity was $U_w = 17$ cm/s corresponding to $Re_o = 800$. Simultaneous measurements of $u(t)$ and $v(t)$ were performed by means of a TSI 2148-10w x-hot film probe. The probe was calibrated versus velocity and angle and $u(t)$ and $v(t)$ were obtained from the hot-film signals by use of the look-up table technique (Lueptow et al. 1988). Data acquisition was performed on a MASSCOMP computer with a 16 bit accuracy. The data was also compared with the measurements performed by means of a DISA 55 R11 hot film with $\Delta x^+ = 12$.

The sampling frequency varied between $f_s = 1-4 u^+ / v$. The data was transferred to the host computer and analyzed in several ways. The total duration of each record was $T_e = 2500-3200$ h/$U_w$ ($h$ is the half height of the channel) and was long enough to ensure the convergence of statistics up to 4th order moments and of the ejection and bursting frequency.

The classical VITA technique (Blackwelder and Kaplan 1976) is used in order to identify the individual shear layer events. The detector function $D(t)$ of this scheme is

$$D(t) = \begin{cases} 1 & \text{if } \sigma_v > \kappa u' u' \text{ and } du'/dt > 0 \text{ (or } du'/dt < 0) \\ 0 & \text{otherwise} \end{cases}$$

where

$$\sigma_v = (u^2)^{\prime} - (u'_v)^2.$$  

The detection parameters used in this study are those which were obtained by calibration of the detection schemes via flow visualizations (Bogard and Tiederman 1986, 1987; Luchik and Tiederman 1987). They were set as $k = 0.4$ and $T^+_e = 13$. The profiles of the Reynolds shear stresses $u'u'$, $v'v'$ and $-u'v'$, of the skewness and flatness of $u'$ together with high order statistics of the velocity time derivative correspond quite well to the previously published data and are not discussed here. The reader may consult Tardu et al. (1993) for the wind tunnel data, and Tardu et al. (1994a) and Feng et al. (1993) for the measurements obtained in the water channel. The two-dimensionality of the flow statistics, aspect ratios and steadiness of the test sections and the comparisons of the measured statistics with previously published data are reported in detail in these references.

3 Outline of the new grouping technique

The grouping of the ejections detected by level crossing techniques may be done by the use of cumulative probability distribution of time between ejections $P(t'/t > t)$ (Barlow and Johnston 1985). A break point (i.e. the grouping time) appears in $P(t'/t > t)$ either when the time between the leading edge of the ejections (detected by $u'$-level and quadrant techniques) or the time between the trailing edge of one ejection and the leading edge of the next is computed (modified $u'$-level technique; Tiederman 1989). The grouping of the ejections is subsequently performed by considering that the ejections with inter-arrival times smaller than the grouping time belong to the same bursts. We can therefore identify bursts which contain several ejections (multiple ejection bursts, MEB, or multiple events ME) and bursts with single ejections (SEB, or solitary events SE). An easier way to formulate the method is to

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1 $+$ denotes quantities normalized with wall variables $v$, $u$.