A Comparison of Characteristic Features of Coherent Turbulent Structures Found Using the Variable Interval Time Average (VITA) Technique and Using the Pattern Recognition Technique

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Abstract

A quantitative comparison is made of some features of coherent structures called "bursts" found in wall bounded turbulent shear flows. The features have been educted using two entirely different methods: the variable integral time average (VITA) technique of Blackwelder and Kaplan (1976) and the pattern recognition technique of Wallace, Brodkey and Eckelmann (1977). It is found that the instantaneous velocity gradient, $\partial U/\partial y$, normal to the wall is caused, during "bursting", by a phase shift in the velocity perturbations between two neighboring positions separated in the normal direction. This velocity gradient can be determined from the time derivative of the streamwise velocity and a perturbation convection velocity normal to the wall. Finally a qualitative comparison is made between the time-varying ensemble averaged Reynolds stress educted during "bursting" by the two methods and the method of Lu and Willmarth (1973).

Introduction

The existence of coherent structures in turbulent shear flows is today accepted as certain. Although some of their characteristics are reasonably well known now, it is still not possible to conceptualize a complete kinematical picture of these structures in wall bounded flows; even less is held as certain about their dynamics. The methods used to investigate such structures have been quite different, but the existence of particular structure elements (bursts, sweeps, ejections, longitudinal vortices) have been, for the most part, well established. It is striking to us that two completely different methods, namely the VITA technique of Blackwelder and Kaplan (1976) and the pattern recognition technique of Wallace, Brodkey and Eckelmann (1977) obtained both qualitatively and quantitatively good agreement about some of these structural characteristics. Before these are discussed, features of the methods will be briefly described below. Additionally a qualitative comparison with results of Lu and Willmarth (1973) will be made at the end of the paper.

The variable integral time average (VITA) technique uses a detector probe at a distance from the wall of $y^+ = yu_\tau/\nu = 15$. The VITA average of the streamwise velocity $U(x_0,y_0,z_0,t)$ is defined as

$$\hat{U}(x_i,t,T) = \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} U(x_i,t)\,dt \tag{1}$$

where T is the averaging time. If T is large the long-time average is obtained which is independent of t. Blackwelder and Kaplan used the VITA average of the square of the streamwise velocity minus the localized squared mean value which they called the localized variance

$$\widehat{var}\,(x_i,t,T) = \widehat{U^2}(x_i,t,T) - (\hat{U}(x_i,t,T))^2 \tag{2}$$

as a measure of the local turbulent kinetic energy. The velocity signals were always ensembled averaged when the following detection function of the detecting probe had the value of unity.

$$D(t) = \begin{cases} 1 \text{ if } \widehat{var} > k \cdot u^2_{rms} \\ 0 \text{ otherwise} \end{cases}$$

where

$$u^2_{rms} = \lim_{T \to \infty} \widehat{var}\,. \tag{3}$$

In their investigation k was always taken as 1.2, but they show how the conditional averages can be made independent of k for a range of $0.9 < k < 2.5$. Since this criterion is fulfilled over short time periods, the velocity signals are also averaged over a period of time before and after it is fulfilled (which is easily done with a digital computer). The ensemble averaged time function of the streamwise velocity component at $y^+ = 15$ that they obtain with this method is shown in the lower part of Figure 1. This time function clearly shows a large slope when the criterion of equation (3) is fulfilled ($\tau = 0$).

The pattern recognition technique of Wallace et al. searches for a pattern in the time function of the streamwise velocity component, U, which is characterized by a relatively weak deceleration immediately followed by a strong acceleration. Such patterns were observed to have a wide range of time scales (1:25). To obtain meaningful ensemble averages, they are therefore normalized to an arbitrary common length by forcing their points of minimum and maximum slope to be located at the same locations along the time axis and expanding or contracting the lengths of the patterns before the averaging was done. In the near wall region at $y^+ = 15$ where turbulence production is a maximum, the average pattern shown in the lower part of Figure 2 was obtained from recognized patterns which accounted for more than 65 % of the total data sample. We believe that this ensembled averaged time function shows the characteristic U-signal during the occurrence of "bursts".

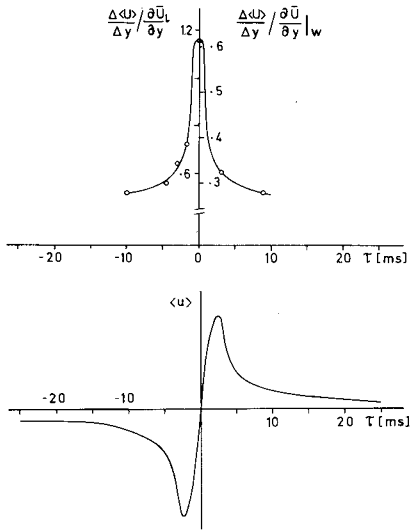

Figure 1: Conditionally averaged streamwise velocity at $y^+ = 15$ from Blackwelder and Kaplan (1976) (bottom). Conditionally averaged velocity gradient obtained from Figure 3 normalized with local mean gradient and gradient at the wall (top).

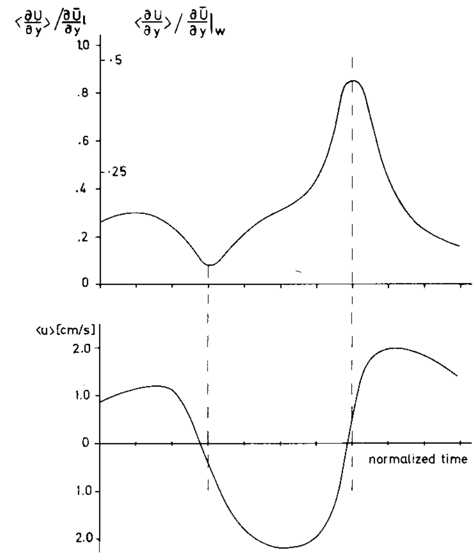

Figure 2: Pattern recognized < u > (bottom). Pattern recognized < ∂u/∂y > normalized with local mean gradient and gradient at the wall (top) from Eckelmann *et al.* (1977).

Similarly, Blackwelder and Kaplan believe their detection criterion (equation 3) is fulfilled during the occurrence of "bursts". If it is true that both techniques are observing the same process, then similar properties of these processes should certainly be observed by both methods. One such characteristic is the average "bursts" duration. Blackwelder and Kaplan found in a turbulent boundary layer that an ensemble average of over 300 "bursts" gave an average "burst" duration of $T \cdot U_\infty/\delta = 2.8$; Wallace et al. obtained an average pattern duration of $T \cdot U_{CL}/b = 2.4$ in a turbulent channel flow. This striking agreement led us to look for further common characteristics obtained by the two methods.

Results

In Figure 3 conditionally averaged velocity profiles are shown which were measured by Blackwelder and Kaplan during the occurrence of "bursts". At time $\tau = 0$ the detection criterion (equation 3) is fulfilled. The variation of the long-time averaged velocity profiles (the dashed curves in the figure) is the ensembled averaged time function shown in the lower part of Figure 1. By differentiating these profiles in the direction normal to the wall at $y^+ = 15$ and normalizing with the average value of the wall gradient, the local normalized averaged gradient shown in the upper part of Figure 1 can be obtained. One sees that the spatial gradient $\Delta < U >/\Delta y$ has a maximum at exactly

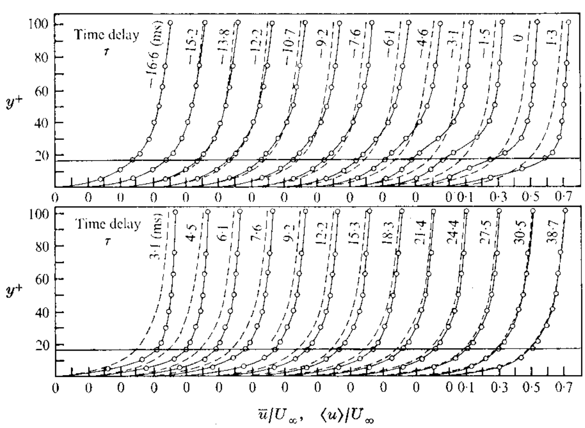

Figure 3: Conditionally averaged and mean velocity profiles with positive and negative time delay τ from Blackwelder and Kaplan (1976).

the same point where the time derivative $\Delta < U >/\Delta t$ shown in the lower part of Figure 1 has its maximum. Eckelmann, Nychas, Brodkey and Wallace (1977) have measured the ensemble averaged spatial gradient $< \partial U/\partial y >$ at various distances from the wall during the occurrence of the "pattern" described above. These are shown in Figure 4. The curve for $y^+ = 15$ is shown again in the upper part of Figure 2 where it is normalized with the averaged wall gradient. Here again it is seen that the maximum of the ensemble averaged gradient occurs at the maximum slope of the time function in the figure below it. Not only is this true; it can also easily be shown that the form of the upper curve can be obtained by time differentiation of the lower curve in Figure 2. This means that during such patterns, Taylor's hypothesis also holds in the direction perpendicular to the wall. This can be expressed as

$$< \frac{\partial u}{\partial y} > = \frac{1}{C_y} \frac{\partial < u >}{\partial t} \tag{4}$$

The convection velocity, C_y, is of the order of u_τ. C_y has been directly measured by Kreplin and Eckelmann (1979) and interpreted as the convection velocity with which a disturbance occurring in a turbulent channel flow is transmitted toward the wall. If one compares the measurements of Blackwelder and Kaplan (Figure 1) with our measurements (Figure 2), it is clear that there is both qualitative and quantitative agreement, i.e. $\frac{\Delta < U >}{\Delta y} / \left.\frac{\partial \bar{U}}{\partial y}\right|_W$ is in both cases of the order of 0.5 where $\partial \bar{U}/\partial y|_W$ is the

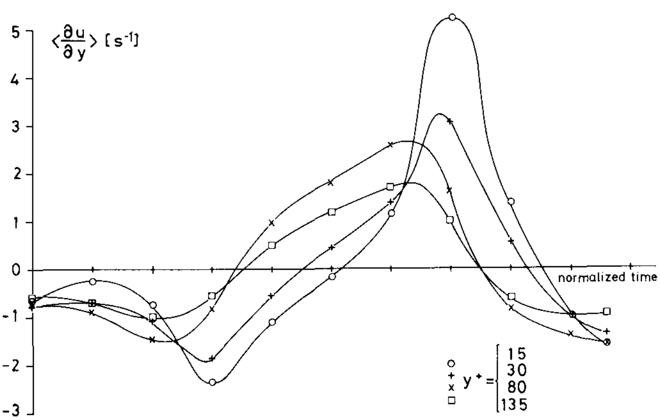

Figure 4: Pattern recognized velocity gradient $< \partial u/\partial y >$ at four different wall distances from Eckelmann *et al*. (1977).

average wall gradient. The gradient measurements of Figure 4 were made by Eckelmann *et al.* with a five-sensor hot-film probe. The fluctuating component of the gradient normal to the wall, $\partial u/\partial y$, was obtained from the two velocity signals at locations (x_0, y_0, z_0) and $(x_0, y_0 + \Delta y, z_0)$. The spatial separation, Δy, of this probe is 1 mm which in viscous length is $\Delta y^+ = 1.7$. The fluctuating component of the velocity gradient in the spanwise direction, $\partial u/\partial z$, has also been measured with the same probe at the locations (x_0, y_0, z_0) and $(x_0, y_0, z_0, + \Delta z)$. In this case the spatial separation, Δz, is twice as large as Δy, i.e. $\Delta z^+ = 3.4$.

Figure 5 shows the pattern obtained with the pattern recognition technique (solid curve) and the same pattern with the gradient pattern $< \partial u/\partial y > \Delta y$ added to it (dashed curve). The patterns are identical in form but are shifted in phase with the dashed curve leading the solid curve. Figures 6-8 show similar curves for $y^+ = 30$, 80 and 135. In addition to the phase shift, it is seen in these figures that the amplitudes of the patterns obtained from the gradients decrease at increased wall distance. Near the wall the pattern obtained at $y_0 + \Delta y$ is very similar to that at y_0 with only a phase difference. This is in good agreement with the measurements of Kreplin and Eckelmann. They observed that a steep front occurs in the near wall region, out to $y^+ = 50$, which has a convection velocity in the streamwise direction of $C_x \approx 12 - 17\ u_\tau$ depending on wall position. Because of the steep slope of this front, disturbances in the velocity further out from the wall are observed at a later time at locations nearer the wall. This fact gives the effective convective velocity perpendicular to the wall, C_y. This similarity in signals is also seen in the time functions of the streamwise velocity of Blackwelder and Kaplan measured at locations between $y^+ = 5 - 100$ in Figure 9. When "bursts" are observed, as indicated along the time axis of Figure 9, their effect is seen over quite a wide region of the wall layer normal to the wall. The signals at adjacent locations appear very similar. The large spatial gradients, $\partial u/\partial y$, can only then occur because of phase shifts in these signals. The decreasing similarity of adjacent signals further from the wall is in good agreement with the patterns of Figures 7 and 8.

The solid curve in Figure 10 shows again the $< u >$ -pattern of Figure 6 for $y^+ = 30$. The dashed curve is obtained by adding the gradient pattern (Figure 11) to the original pattern. In contrast to the patterns of Figure 5-8, no phase shift is seen here; only a reduction of the amplitude of the pattern occurs. This means that in the spanwise direction the correlation of the velocity signals decreases rapidly and that no "frozen" pattern picture can be assumed. A very similar result is seen in Figure 12 where signals at various z^+ locations parallel to the wall at $y^+ = 15$ were measured by Blackwelder and Kaplan.

Although the results shown here emphasize the similarities obtained with the two techniques, there are significant differences remaining. The detection criterion of Blackwelder and Kaplan detected "bursts" during about 18 % of the total data sample and the

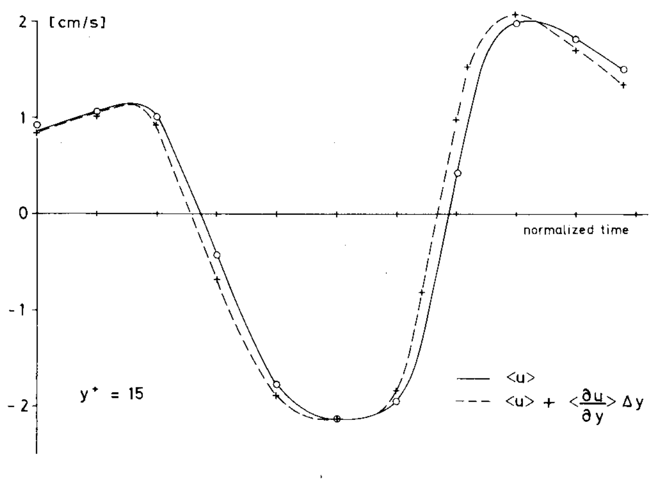

Figure 5: Pattern recognized < u > and added pattern recognized < ∂u/∂y > Δy for $y^+= 15$.

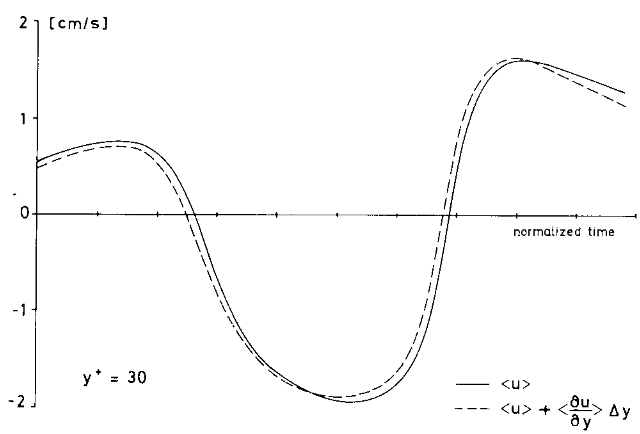

Figure 6: Same as Figure 5 for $y^+ = 30$.

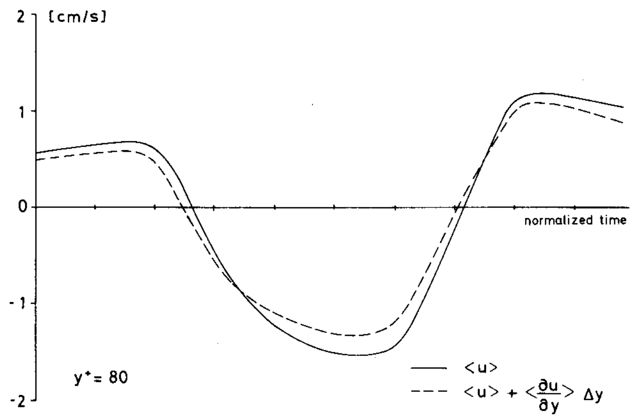

Figure 7: Same as Figure 5 for $y^+ = 80$.

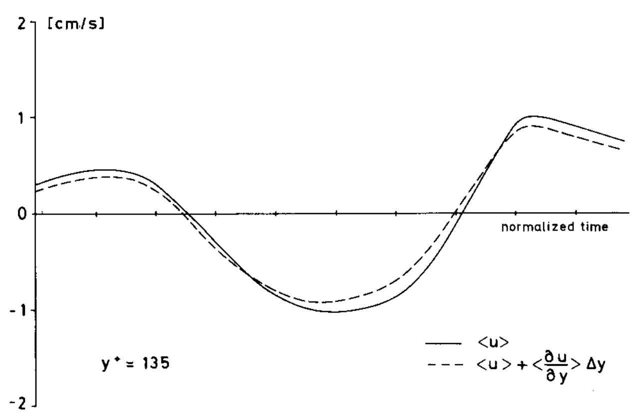

Figure 8: Same as Figure 5 for $y^+ = 135$.

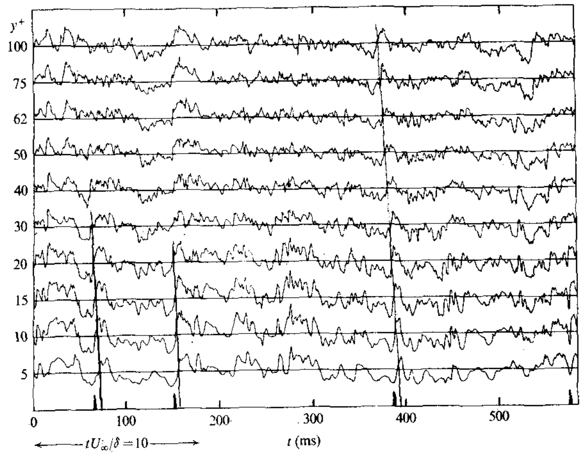

Figure 9: Instantaneous streamwise velocities as a function of the normal wall distance, y^+, from Blackwelder and Kaplan (1976).

maximum of the conditionally averaged Reynolds shear stress is about an order of magnitude greater than the local average at $y^+ = 15$. The pattern recognition technique, on the other hand, found patterns occurring during approximately 65 % of the total data sample but the maximum of the pattern ensemble averaged Reynolds shear stress is only 1.2 times greater than the local average at $y^+ = 15$ and 1.8 times greater at $y^+ = 30$. This would indicate that the VITA technique is a sharper method for detecting Reynolds shear stress producing structures.

The lower level Reynolds stresses obtained by pattern recognition can be explained by the fact that patterns with period lengths ranging over half an order of magnitude were included in the ensemble averages (see Wallace et al.) with the most probable periods being short. The short period, higher frequency fluctuations have lower amplitudes as can be inferred from spectra. Thus the lack of an amplitude criterion in addition to the slope criterion in the pattern recognition technique yields reduced levels of ensembled averaged Reynolds stress. The VITA technique of Blackwelder and Kaplan is basically an amplitude criterion. Either large positive or negative streamwise velocity fluctuations are detected when they occur within the variable interval time averaging window. They, in fact, find that their detection criterion is fulfilled around abrupt accelerations of the streamwise velocity, i.e. regions of large positive slope in the streamwise signal. Thus their amplitude criterion detects periods with

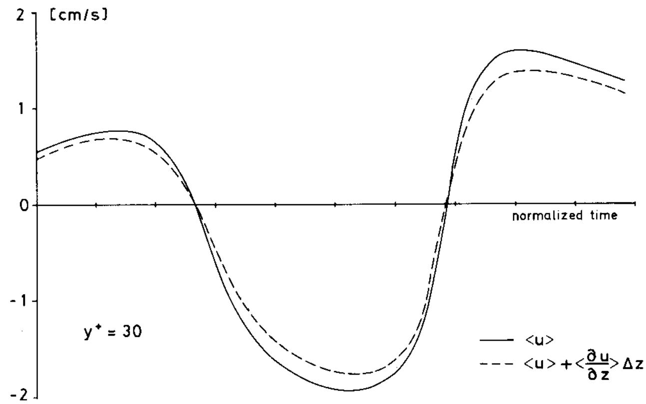

Figure 10: Pattern recognized < u > and added pattern recognized < ∂u/∂z > Δz for y^+ = 30.

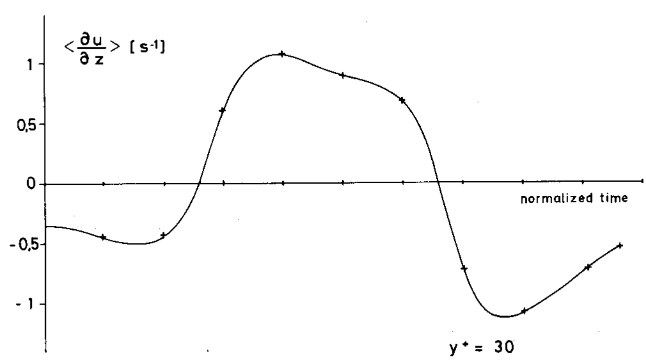

Figure 11: Pattern recognized < ∂u/∂z > at y^+ = 30.

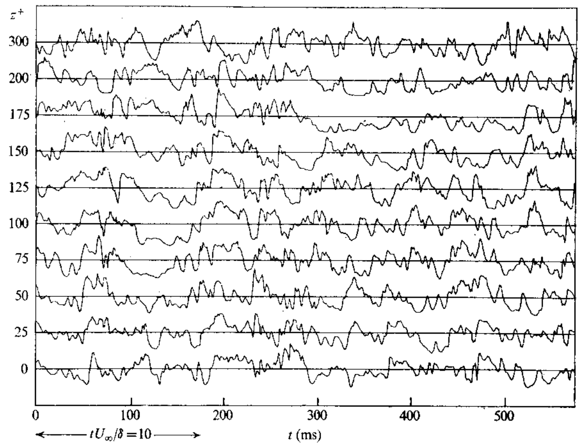

Figure 12: Simultaneous streamwise velocities in the spanwise direction from Blackwelder and Kaplan (1976).

large positive slope, but a slope criterion, as in our case, does not necessarily detect large amplitudes. An improvement in the pattern recognition technique would therefore be to incorporate an amplitude criterion.

Lu and Willmarth (1973) have also measured ensemble averaged Reynolds stresses during "bursting" using a third detection method. "Bursts" are detected at $y^+ = 15$ when the streamwise velocity is decreasing and falls below a preset threshold level. They measured a maximum conditionally averaged Reynolds stress at $y^+ = 30$ of about 2.5 times the local average which is closer to what we find.

Further comparison is planned between these three techniques using a common set of data to see if and when common segments of the signals are detected. Then we will be able to say with certainty whether or not the common characteristics result from the same flow structures being detected.

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