6th Australasian Hydraulics and
Fluid Mechanics Conference
Adelaide, Australia, 5-9 December 1977

Large Structure in a Turbulent Boundary Layer

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1 INTRODUCTION

It is well known that the structure of a turbulent boundary layer, near the wall, is dominated by the phenomenon of "bursting" (Kline et al (1967)). Willmarth reviews the many contributions that have helped clarify the phenomenon. Similarly a large scale structure has been inferred from correlation measurements and conditional sampling techniques (Kovasznay,Kibens and Blackwelder 1970). Rao et al (1971) and Lu and Willmarth (1973) have shown that the rate at which turbulent'bursts'occur scales on outer layer variables and this suggests a connection between the two scales of motion. In the earlier part of this work (Brown and Thomas, 1977, hereafter referred to as I) showed by more direct measurements that an organized large scale structure could be identified within the boundary layer and that the small scale activity near the wall was correlated with the presence of this structure. On the basis of correlation measurements between the wall shear stress and the velocity at various points across the layer they presented a schematic view of the large structure, reproduced in figure 1. The present work is the result of conditionally sampled measurements aimed at clarifying the features of this structure, particularly the relationship between the structure and the Reynolds stress, and more simply the form of the flow field (the stream line pattern) within the structure. Additionally, further experiments have been carried out to try to clarify the relationship between the small scale motion near the wall and the large structure. In particular these experiments were aimed at trying to distinguish between the suggestion by Willmarth (1975) and others that the convected pressure field (specifically $\frac{\partial p}{\partial x}$)of the large structure triggers the small scale response at the wall and the mechanism proposed in I, and independently by Coles at al (1977), in which a rotational instability near the wall plays the important role.

2 EXPERIMENTAL CONDITIONS

Details of the wind-tunnel and instrumentation are discussed briefly in Brown and Thomas (1977) and in detail by Thomas (1977). At the point of measurement the boundary layer thickness was 40 mm, the displacement thickness 5.51 mm, the free stream velocity 36 m/sec and the Reynolds number based on momentum thickness was 10,160. The friction velocity, obtained from Prestion tube measurements, was 1.28 m/sec.

3 DETECTION OF THE LARGE STRUCTURE

The detection of an event which is itself subject to randomness in scale and randomness in its phase with respect to other such events is certainly difficult; subsequent ensemble averaging of such events can be wholly misleading, as many have recognized. To place any weight on the results of such techniques requires at least that the techniques be applied to random noise (or skewed random noise if the turbulent signal is skewed) and that they give zero correlation when none exists. This was the case for the techniques used here. The detection signal used in this work to detect the presence of a large structure was based on the findings in I, that the large structure was characterized by steep velocity gradients on its rearward or upstream surface. As discussed in I these steep gradients were detected by filtering the velocity signal and by then rectifying and smoothing the high frequency component which remained after the low frequency component was substracted from the original signal. The connection between this high frequency (steep gradient) feature and the large scale motion of the large structure is evident in the substantial correlation between the high frequency, rectified and smoothed signal and the remaining low frequency component of the original signal, shown in figures 9 and 10 of I.
The important, in fact crucial, advantage of detecting the large structure by the presence of this steep gradient is that it helps to avoid an overwhelming degradation in the ensemble average (obtained from many structures) due to jitter in the phase of this feature. (A representative ensemble average of step functions of various amplitudes obviously requires detection of the gradient). Thus the presence of the large structure was detected by seeking those times when the high frequency, rectified, and smoothed component of the velocity signal was a local maximum and exceeded some discriminator level. Ensemble averages of the original signal centred about these times were generated. A significant feature of this detection process is that, by virtue of the fact that the high frequency component is rectified, there is no bias towards either steep positive or negative gradients. An ensemble average which has a positive gradient would therefore reflect a genuine feature of the flow. Details of the choice of filter cut-off frequency for the initial splitting of the signal into high and low frequency components and the sensitivity of the ensemble average to this cut-off frequency and to the discrimator level for the smoothed, rectified high frequency signal are discussed by Thomas (1977). The cut-off frequency used was $\frac{w\delta^*}{U} = 0.43$ which is approximately twice the burst frequency of Rao et al (1971). A typical ensemble average for the velocity at $\frac{y}{\delta}=0.05$, obtained by this method, is shown by the lower curve of figure 2.

4 ENHANCEMENT OF ENSEMBLE AVERAGES

The ensemble averages obtained in this way, such as the lower curve of figure 2, had amplitudes

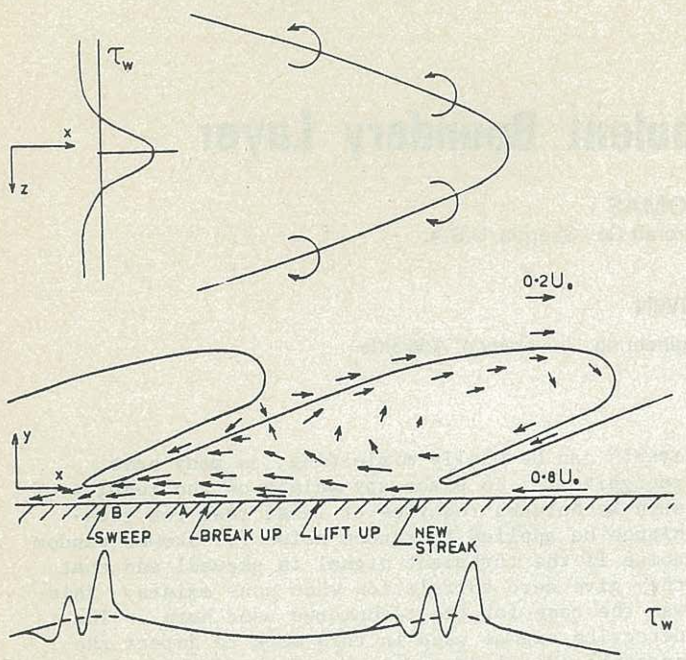

Figure 1 Schematic diagram of the large structure and the wall shear stress (Brown and Thomas,(1977))

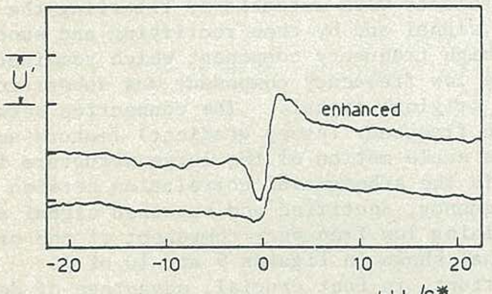

Figure 2 Conditionally sampled ensemble averages of the u component of the velocity at y/δ = .05

which were rather less than those seen in a typical signal. This clearly is a result of the detection scheme not always detecting an, as yet, ill-defined, large structure, as well as being due to 'phase jitter'. These problems were overcome to some extent by the following 'enhancing' technique. The initial ensemble average was used as a first estimate for the characteristic signal of the large structure and then short time correlations between the original detected segments of signal and this ensemble average signal were computed. A negative correlation at zero time delay indicated a 'false' detection and this segment of signal was rejected. If the correlation peaked at a non-zero time delay the origin of time was moved so that the correlation peaked at zero time delay. A new ensemble average of the slightly fewer segments of signal, each centred at a slightly different origin in time was found. The entire process was repeated and rapidly converged. Only 3 iterations were required. When the process was applied to the data shown in the lower curve of figure 2 the upper curve was obtained. The technique is clearly a 'bootstrap' operation in which each iteration sharpens the definition of the detection criterion, reduces the phase jitter between marked events and removes those events which, upon improved definition, are found to be not representative of the intrinsic structure being sought.

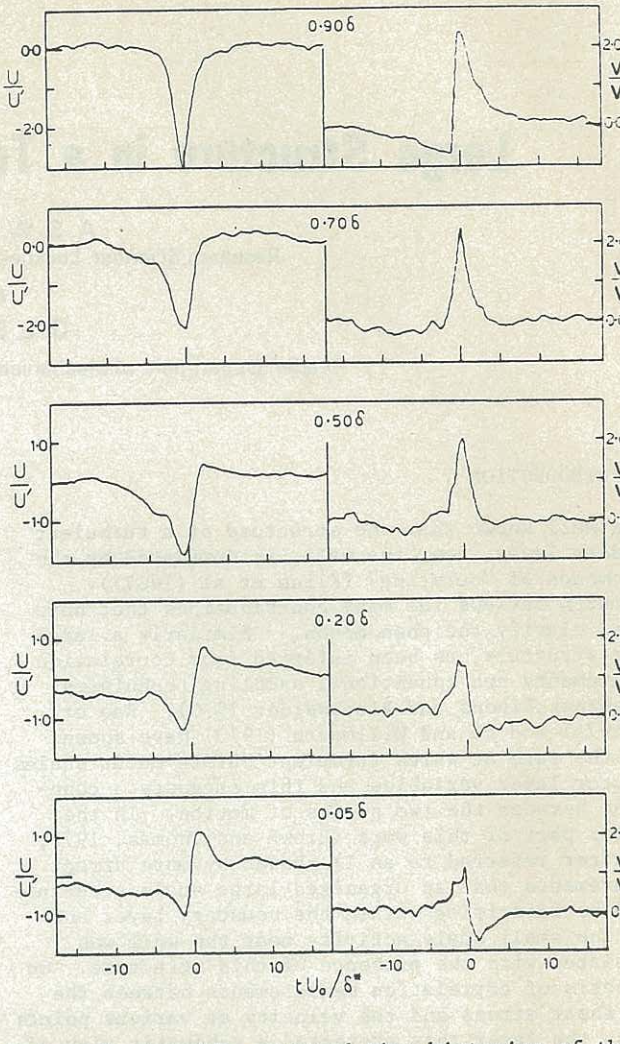

Figure 3 Ensemble averaged time histories of the streamwise component (left) and normal component of velocity (right)

5 ENSEMBLE AVERAGED VELOCITY AND REYNOLDS STRESS

The ensemble averaged variation with time of the stream-wise and normal components of velocity that were obtained using the methods of sections 3 and 4 are shown in figure 3.

Similarly the ensemble averaged Reynolds stress, where the detection point was again based on the u signal (as in section 4) is shown in fig.5. The results for u substantiate the claim in I that an important structural feature of the large structure is a region of rapid velocity change. These results are entirely consistent with the correlations obtained in figure 10 of I. It is this rapid velocity change within the large structure which presumably accounts for the findings of Rao et al (1971) that the rate of 'bursts' scales with outer layer variables. We note that Blackwelder and Kaplan (1976) have identified similar features in the outputs of an array of hot-wires very near the wall and because the acceleration following a region of low velocity was similar to what has been observed in flow visualization studies of the 'bursting' phenomenon, they identified this signal with the bursting process. The present results at much higher Reynolds number, show that this feature can be observed across the entire layer and from the correlations on a large scale(across the whole boundary layer) this feature has been identified here as part of the large structure. (Thomas

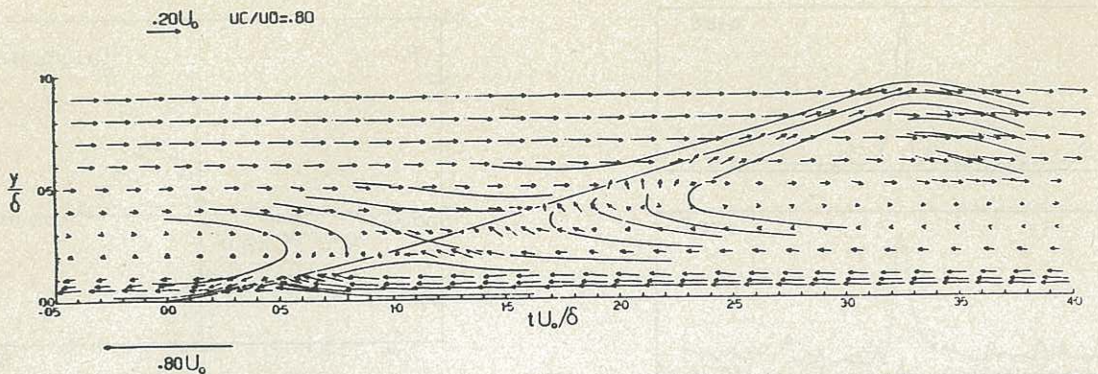

Figure 4 Streamline pattern of the large structure obtained from ensemble averages of the u and v componemts of velocity

(1977) discusses the substantial correlations obtained between the high frequency, smoothed and rectified, component of the velocity signals across the whole boundary layer).

The ensemble-averaged v component of velocity, figure 3, shows that near the wall v goes negative locally, whereas at greater distances from the wall v is positive at positive times and again weakly negative at negative times. These results are not inconsistent with the conclusions drawn by Kovasznay et al (1970) and Antonia (1972).

A much clearer interpretation of these results is obtained by using them to create a stream-line pattern for the large structure. By positioning each averaged time history for the particular $\frac{y}{\delta}$ at a value of time (relative to zero at the wall) corresponding to the time delay where the correlation between the high frequency component of the signal at the wall and at that $\frac{y}{\delta}$ peaks the stream-line pattern shown in figure 4 was obtained. Time has effectively been replaced by x and the result shown in a frame of reference moving with the large structure. Following the results in I the convection speed of the large structure has been taken to be $U_c = .8U_\infty$. The length of each velocity vector is $((\bar{U} + \langle u\rangle - U_c)^2 + \langle u\rangle^2)^{1/2}$ and its direction is arctan $((\bar{U} + \langle u\rangle - U_c)/\langle v\rangle)$ (where <> refers to the ensemble average). The solid lines are not calculated stream-lines but serve as visual approximations to stream-lines.

It is remarkable that the independently measured data from different points in the layer form such a consistent picture of the structure. The dominant feature does appear to be the rearward or upstream surface of the structure where rapid changes in velocity occur; it must be recognized, of course, that it is this region which will be most adequately represented by the ensemble averages. The ensemble average will be degraded (less typical of any one realization) by the variations in the amplitude and time scales of each event (included in the averages) further from this interface. We note that the stream-lines do display a convex curvature near the wall as suggested in I. Further evidence to support the view that this may result in a rotational instability is presented in Section 6.

The behaviour of the ensemble averages for u and v in figure 3 indicate a large correlation between the components of velocity, i.e. a large contribution to the Reynolds stress. The actual ensemble averages of the Reynolds stress are shown in figure 5. In the outer part of the flow the local ensemble averaged Reynolds stress is about sixteen times the mean value; it appears that the organized motion in the large structure dominates the generation of Reynolds stress in this region. We estimate, from the time scales of the large structure that as much as 90% of the stress is contributed by this motion. The magnitude of the ensemble average remains many times larger than the local mean throughout the outer part of the layer. Given the difficulty in obtaining representative ensemble averages the conclusion is evidently that it is the organized large scale motion (including the characteristic rapid changes in velocity on a smaller scale within the structure) which accounts for a major part of the stress. Near the wall the situation changes, the ensemble average is only twice the mean, and we suggest that nearing the wall the stress is increasingly carried by the longitudinal vorticity motions, generated, or at least continually being forced, near the wall by the 'external' large scale motion. Such a view is at this stage no more than a postulate, it obviously does not follow from these measurements but it is not inconsistent with the results. Evidently boundary layers on concave and convex surfaces should help clarify this picture. Detailed comparisons with existing measurements remain to be made.

6 CORRELATION BETWEEN STREAM-LINE CURVATURE AND SMALL SCALE MOTIONS AT THE WALL

It was found in I that the small scale wall shear stress fluctuations were strongly correlated with the low frequency large scale variations in wall shear. This low frequency variation itself was found to be correlated with similar scale variations in velocity throughout the layer. It was suggested, and supported by order of magnitude estimates, that this local generation of small scale acitivy was a result of a rotational instability, that is, an instability due to the large scale angular velocity being of opposite sign to the vorticity. The important implication was that the bursting phenomenon was coupled to the large structure but was not so much related to $\frac{\partial p}{\partial x}$ but, if to the pressure, then more to $\frac{\partial p}{\partial y}$ due to the presence of the large scale rotational motion. Measurements of the wall-pressure, with ensemble averages obtained by the methods of section 4 are discussed in Thomas (1971) and will be published at a later date. On the scale of the large structure however ensemble averages of $\frac{\partial p}{\partial x}$ were found to be small and in fact tended to increase stability so that it seems unlikely that $\frac{\partial p}{\partial x}$ variations on this large structure scale could account for the correlations between high and low frequency components of the wall shear stress (figure 9, I).

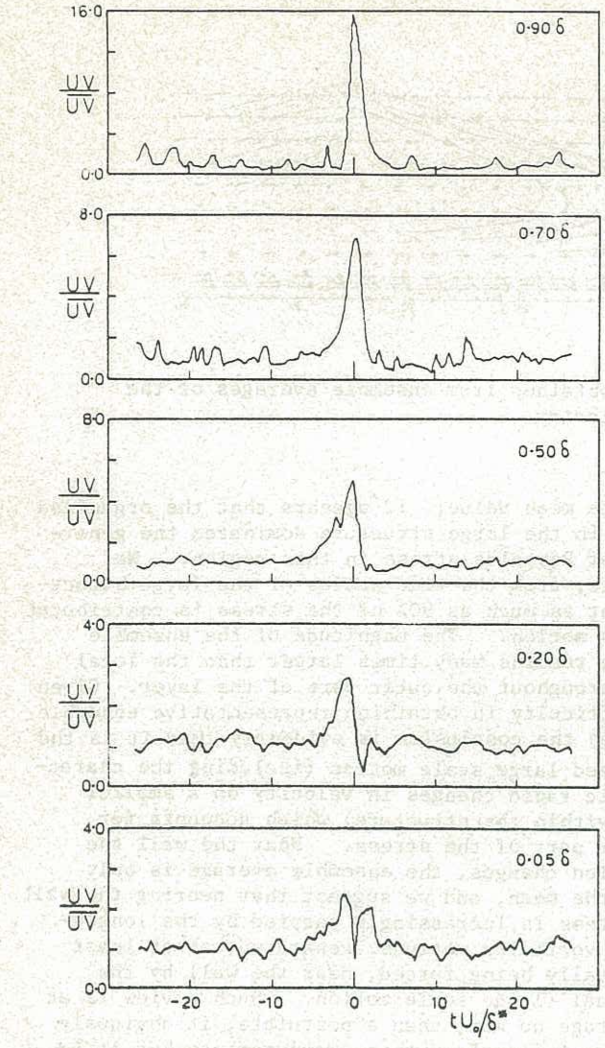

Figure 5 Ensemble averaged time histories of the instantaneous uv product

To test the suggested rotational instability ideas measurements of the stream-line curvature were made at $y^+ = 170$. This was as close to the wall as was readily practical. Measurements of u and v were made and the radius of curvature of the stream-lines was found by the following approximation

$$\frac{1}{R} \simeq \left[-\frac{\partial^2 y}{\partial x^2}\right]_{\psi = \text{constant}} \simeq \left[\frac{1}{U_c}\frac{\partial}{\partial t}\left(\frac{v}{u}\right)\right]_{y^2 = \text{constant}}$$

where u and v are the components of velocity in the appropriate frame of reference. (In this case the convected frame of the large structure). Thus the radius of curvature R was obtained as 1/R(t). Following the techniques described in I the presence of small scale motions near the wall was found by rectifying and smoothing the high frequency component of the wall shear stress. Shown in figure 6 is the correlation between 1/R(t) measured at $y^+ = 170$ and the smoothed, rectified, high frequency component of wall shear stress. The positive correlation shows that the small scale fluctuations are correlated with stream-lines having convex curvature. While quite obviously not proving a causal relationship the result is consistent with a rotational instability being a driving mechanism that continues to maintain and/or generate small transverse scale motions (longitudinal vorticity) near the wall. (The time delay at which the correlation peaks is due to the cross-wires being vertically above the wall-shear probe and is again a reflection of the way the large scale structure is inclined to the wall).

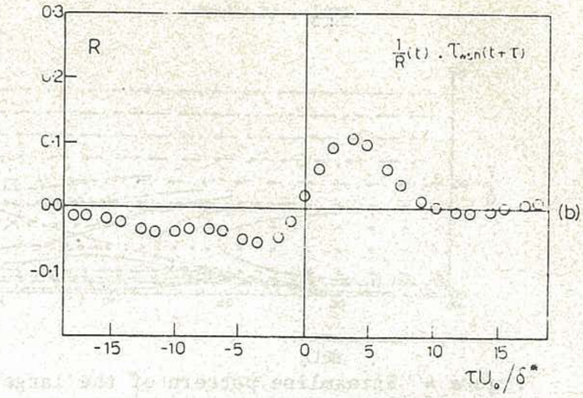

Figure 6 Correlation between the streamline radius of curvature at $y^+ = 170$ and high frequency wall shear stress fluctuations

7 CONCLUSIONS

The experimental results support the conclusion that a large organized structure plays a dominant role in the dynamics of the turbulent boundary layer. A quite remarkably self-consistent picture of this structure has been obtained by plotting the velocity field from ensemble averages of the conditionally sampled velocity at a number of points across the layer. Similarly, ensemble averages of the Reynolds stress show that the large structure accounts for very large contributions to the Reynolds stress. The extent of this contribution cannot be easily quantified at present but appears to exceed 90% of the stress in the outer part of the layer.

Associated with this large scale structure are very much smaller scale motions near the wall which are themselves correlated with the presence of the large structure. The further results presented are not inconsistent with the postulate in I that a rotational instability is the coupling mechanism between the two scales. This work answers far fewer questions than it poses but as a postulate on which to base further experiments it is tempting to view many known effects on turbulent boundary layers, including the quite dramatic effects of small boundary layer curvature in terms of an effect on the large structure itself or on its coupling to the fluctuations generated at the wall by its presence.

8 REFERENCES

Antonia, R.A. 1972, J. Fluid Mech., 56, 1.

Blackwelder, R.F. and Kaplan, R.E. 1976, J. Fluid Mech., 76, 89.

Brown, G.L. and Thomas, A.S.W., 1977, Phys.Fluids. To be published. (October, 1977).

Corino, E.R. and Bodkey, R.S., 1969, J.Fluid Mech., 37, 1.

Kline, S.J., Reynolds W.C., Schraub, F.A., and Rundstadler, P.W., 1967, J. Fluid Mech., 30, 741.

Kovasznay, L.S.G., Kibens, V. and Blackwelder, R.F. 1970, J. Fluid Mech., 41, 283.

Lu, S.S. and Willmarth, W.W. 1973, J.Fluid Mech., 60, 481.

Rao, K.N., Narasimha, R. and Badri Narayanan, M.A., 1971, J. Fluid Mech., 48, 339.

Willmarth, W.W., 1975, Adv.Appl.Mech., 15, 159.

Thomas, A.S.W., 1977, Ph.D. Thesis, Univ. of Adelaide.