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The wall region in turbulent shear flow

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Hot-film measurements in a fully developed channel flow have been made in an attempt to gain more insight into the process of Reynolds stress production. The background for this effort is the observation of a certain sequence of events (deceleration, ejection and sweep) in the wall region of turbulent flows by Corino (1965) and Corino & Brodkey (1969). The instantaneous product signal uv was classified according to the sign of its components u and v, and these classified portions were then averaged to obtain their contributions to the Reynolds stress $-\rho\overline{uv}$. The signal was classified into four categories; the two main ones were that with u negative and v positive, which can be associated with the ejection-type motion of Corino & Brodkey (1969), and that with u positive and v negative, associated with the sweep-type motion. It was found that over the wall region investigated, $3{\cdot}5 \leqslant y \leqslant 100$, these two types of motion give rise to a stress considerably greater than the total Reynolds stress. Two other types of motion, (i) u negative, v negative, corresponding to low-speed fluid deflected towards the wall, and (ii) u positive, v positive, corresponding to high-speed fluid reflected outwards from the wall, were found to account for the 'excess' stress produced by the first two categories, which give contributions of opposite sign.

The autocorrelations of the classified portions of uv were obtained to determine the relative time scales of these four types of motion. The positive stress producing motions ($u < 0$, $v > 0$ and $u > 0$, $v < 0$) were found to have significantly larger time scales than the negative stress producing motions ($u < 0$, $v < 0$ and $u > 0$, $v > 0$). It was further surmised that turbulent energy dissipation is associated with the Reynolds stress producing motions, since these result in localized shear regions in which the dissipation is several orders of magnitude greater than the average dissipation at the wall.

1. Introduction

Over the last decade two independent sets of visual studies have provided new impetus for research on bounded turbulent shear flows and have given fresh insight into the physics of the turbulent processes of such flows. Corino & Brodkey (1969) photographed a very small region of a particle marked pipe flow using a high-speed camera that could be moved with the flow. The dimensions of their field of view, normalized with ν, the kinematic viscosity, and u_τ, the friction

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velocity, were $y^+ \approx 45$, $x^+ \approx 60$ and $z^+ \approx 20$. The main sequence of events they observed began with a local deceleration of the flow over a relatively large extent near the wall. Within the decelerated region, the flow had a very small velocity gradient so that at its edges there were regions of high shear. From further upstream a large-scale fluid mass then entered the field of view; this mass moved at a higher velocity and began to accelerate the decelerated fluid. This phase was thus called acceleration. Immediately after the acceleration began there occurred an ejection of fluid from the decelerated region outwards from the wall, and at times more than one ejection from the same decelerated region occurred. This was then followed by the higher speed fluid mass (moving with a velocity usually greater than the mean and parallel to or at a slight angle towards the wall) sweeping the field of the retarded fluid. This completed the sequence. Corino & Brodkey (1969) state that "of course there were variations of the sequence and all of the steps did not appear all of the time or in the exact fashion described, but on the average it proceeded as (described)." They observed that the ejections were an important contribution to the Reynolds stress and, although the measurement was crude, they estimated that 70 per cent of the Reynolds stress at a Reynolds number of 20000 is a result of ejections. The sweep events were presumed by Corino & Brodkey (1969) to make up the remainder of the Reynolds stress contribution.

Kim, Kline & Reynolds (1971), in the latest of several papers from Stanford University, describe the other set of visual studies that has shed new light on the turbulence processes. Using the hydrogen-bubble technique in a turbulent boundary layer, they photographed a considerably larger field than Corino & Brodkey. They observed that near the wall alternating regions of high and low velocity developed which were very much elongated in their streamwise extent, thus appearing 'streaky' in structure. The low-speed streaks were seen (i) slowly to lift away from the wall, (ii) often to begin a growing oscillation and (iii) finally to break up into more chaotic motion. The whole cycle is termed bursting by Kim *et al.* (1971). From estimates made from the hydrogen-bubble data, they observed that practically all the turbulence production given by $-\rho\overline{uv}\,\partial\overline{U}/\partial y$, occurs during bursting. Since $\partial\overline{U}/\partial y$ in this case is the long-term average and $\overline{uv}$ is averaged separately during bursting and non-bursting periods, the term $-\rho\overline{uv}\,\partial\overline{U}/\partial y$ is equivalent to the Reynolds stress multiplied by a constant during those periods.

The present work is an effort to make more quantitative measurements of the turbulent processes which have been visually observed by making use of a rather novel method of anemometer signal analysis. The general background for this work can be found in the literature survey of Corino & Brodkey (1969). The few recently published results specifically pertinent here will be cited as they are needed.

2. The experimental facility

The facility for the hot-film measurements described herein is an oil channel originally built by Reichardt and is completely described by Eckelmann (1970). The description of the channel, its operation and extensive turbulence

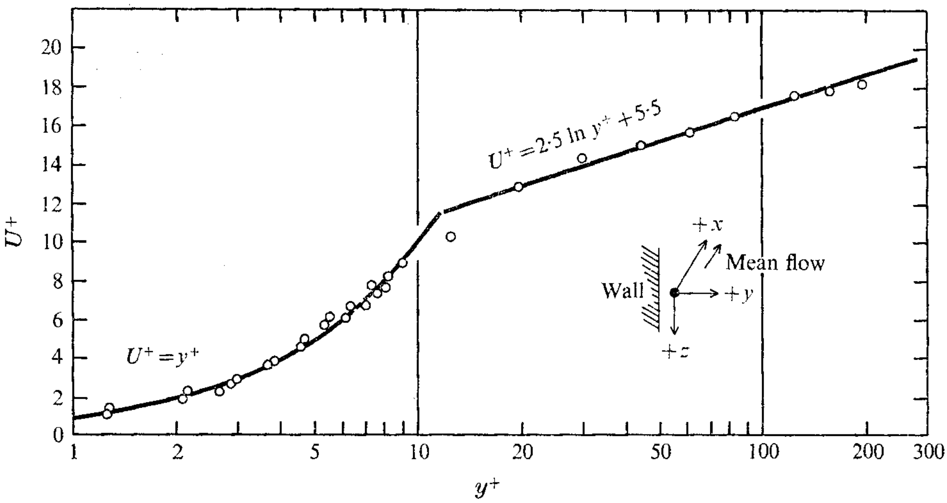

FIGURE 1. Turbulent velocity distribution at $Re = 7150$.

measurements have been published separately by him. Here, we need describe only the unique features of the facility relevant for our measurements. The channel is 22 cm wide and 85 cm deep and is fitted with a top cover to eliminate surface waves. The measurements were made 35 cm below the cover in the fully developed region of the channel flow but outside the boundary layers of the top cover and the bottom of the channel. To demonstrate that the flow was fully turbulent, the velocity profile in dimensionless form is given as figure 1. Also shown is the sign convention used in this paper.

The fluid was an oil of kinematic viscosity $6 \times 10^{-2}\,\mathrm{cm^2/s}$ at 25 °C. This is 6 times that of water and 0·4 times that of air. For the maximum operating velocity of 19·5 cm/s at the centre-line, the Reynolds number based on the width of the channel and the centre-line velocity was 7150. This is equivalent to a pipe Reynolds number of about 11000. For these conditions, a distance of 1 cm from the wall corresponded to $y^+ = 17$. A single hot-film probe could easily be placed as close as $y^+ = 1$ and an X-probe could be placed as close as $y^+ = 3{\cdot}5$. Thus, in this oil channel it was easily possible to take measurements in the area of the interest for a wall region study. The probes were hot-film X-probes, type 1241-20 W, made by Thermo-Systems, Inc., and the electronics for the constant-temperature anemometers were made by DISA, Inc. Special circuitry was used for classifying the signals (u, v and uv). Because of the nature of the oil channel very long run times were desirable to ensure adequate statistical samples. Eckelmann (1970) used 10 min samples, and 100 min samples were used in the present work. This was accomplished by recording the output u and v signals on a four-channel Saba tape recorder at a speed of 0·375 in/s. For data analysis the tape was played back at 37·5 in/s, so that the actual time of analysis for a given statistical quantity took 1 minute but was equivalent to 100 min of actual flow time. Every precaution was taken to minimize errors in the analog circuitry due to d.c. bias, variable gain, etc. by testing the circuit system with a fixed sine wave before processing the turbulence signal. Analog circuits of conventional design were required to form

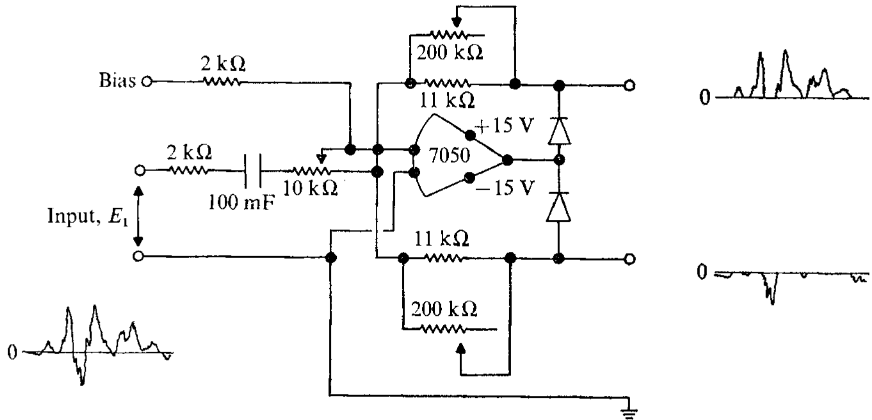

FIGURE 2. Splitter circuit diagram.

the sum and difference of the hot-film signals so that the true u and v signals could be recovered and recorded. Measurements of the cross stress terms were made by analog multiplying and using a digital voltmeter which could integrate for up to 60 s. The key to the entire analysis, however, was the concept of classifying the signal into physically meaningful categories. For this work, classification involved splitting the turbulence signals about zero voltage. It was for this reason that it was important to eliminate any d.c. bias in the analog electronic system and to maintain balanced gains of the split signals. The circuit, shown in figure 2, was designed for this purpose and worked well. Before each set of runs the variable-gain and feed-back resistors were adjusted with the test input sine wave to give the desired gain of unity and balance of the positive and negative parts of the signals.

The analysis involved obtaining $\overline{uv}$ values of the split signal products, i.e. for ($u > 0$, $v < 0$), ($u < 0$, $v > 0$), ($u > 0, v > 0$) and ($u < 0$, $v < 0$), which in the following are called $\overline{uv}_c$, in addition to that of the total signal, $\overline{uv}$. To achieve the split-signal average products, $\overline{uv}_c$ the u and v components were simultaneously rectified in the two equivalent circuits described above, multiplied together and averaged. Autocorrelation coefficients of the total and split product signals were also obtained to estimate the scale of the events.

3. The instantaneous velocity signals

A simultaneous recording of the instantaneous values of u, v and uv, like that shown in figure 3, can offer considerable insight into the meaning of turbulence signals in terms of the sequence of events presented by Corino & Brodkey (1969). Both the u and the v signal look like any other typical turbulence signals when viewed in isolation, but when considered together they are seen to show a high degree of correlation in the wall region. This becomes very clear in the corresponding product or uv trace. The intermittent nature of the uv trace is apparent and is to be expected from the description of the sequence of events by Corino & Brodkey (1969). It has also been observed by Eckelmann (1970) in channel flow and by Gupta (1970) in an air boundary layer. The largest contributions to the uv

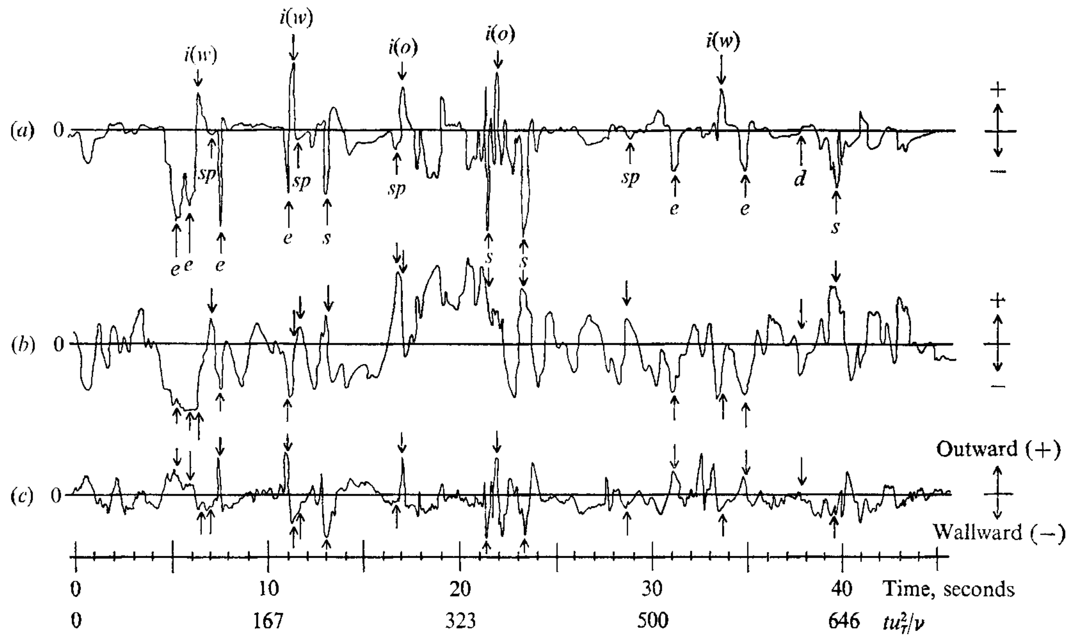

FIGURE 3. Instantaneous (*a*) *uv*, (*b*) *u* and (*c*) *v* traces. *e*, ejection; *s*, sweep; *d*, deceleration; *sp*, sweep parallel to wall; *i*(*o*), interaction (outward); *i*(*w*), interaction (wallward).

product can be easily associated with the description of Corino & Brodkey (1969) either as low-speed fluid moving from the wall (ejection; $u < 0, v > 0$) or as high speed fluid moving towards the wall (sweep; $u > 0$, $v < 0$). Some instances of these contributions are indicated on figure 3. The arrows are intended to point to the areas under the trace between zero crossings of the uv signal. Also indicated are a high-speed fluid element nearly parallel to the wall (corresponding to a sweep with $u > 0$, $v \approx 0$) which will contribute little to the uv product, and a low-speed region nearly parallel to the wall (deceleration; $u < 0$, $v \approx 0$) which also makes little contribution. Smaller excursions can be similarly identified and are probably events that only partially pass the probe at its fixed position; e.g. an ejection starting in the vicinity of $y^+ = 20$ would not appear large to the probe positioned closer to the wall. In addition to these major ejection and sweep events, there occurs an interaction between these events which gives rise to a negative contribution to the Reynolds stress. For example, occasionally one sees at the interface between the decelerated region (giving rise to the ejection) and the sweep an interaction that involves low-speed fluid from the decelerated region being pushed back towards the wall ($u < 0, v < 0$). At these interfaces one also sees high-speed fluid from the sweep being reflected back toward the central region ($u > 0, v > 0$). Some of these regions are also indicated in figure 3. Note that these occur on the slopes of the u trace between minimum and maximum velocities, corresponding to decelerated and higher speed regions (i.e., at the interfaces). Not all the events have been indicated and it should again be emphasized that, as was quoted from Corino & Brodkey (1969) earlier, there are variations of the sequence of events and that all the steps do not appear all the time or in exactly the manner described. Table 1 summarizes the association

Sign of u	Sign of v	Sign of uv	Type of motion
−	+	−	Ejection
+	−	−	Sweep
+	+	+	Interaction (outward)
−	−	+	Interaction (wallward)

TABLE 1

between the u, v and uv turbulent signals and the sequence of events described from the visual observations of Corino & Brodkey (1969).

It is important to recognize at this point that almost all the Reynolds stress $-\rho\overline{uv}$ results from the ejections, sweeps, and their interaction. These and the 'events' (belonging to the sequence) occurring parallel to the wall ($v = 0$) are also seen to account for most of the u and v signals themselves. The observations of the films of Corino show that, within the 'events', the flow appears laminar in nature, not turbulent. The suggestion that the wall turbulence is essentially deterministic and that there is little turbulence other than the events themselves has important implications in the data analysis. It suggests that one should classify the entire signal rather than extract just one type of event from 'background turbulence'.

4. Signal classification and analysis

The total cross-stress correlation coefficient $-\overline{uv}/u'v'$, where primes indicate r.m.s. values, measured in this work compares well with the measurements of Reichardt (1938) and Eckelmann (1970). The present results were obtained from sample lengths about ten times those used by Eckelmann and are considered somewhat more reliable for this reason. In spite of this, however, because of the difficulty in measuring this term in the wall region, the scatter is comparable to that which he observed. The results of Eckelmann and of this work were measured under the same conditions except that the channel was covered in this work.

Figure 4 shows mean values of the four components of the classified uv signal at various positions, from within the sublayer out to the channel centre-line. The values are normalized with $-\rho\overline{uv}$. The main contributions to the stress clearly come from two separate sources, although they are closely connected to one mechanism. The contributions of ejections and sweeps are nearly equal over the generation region; at a $y^+ \simeq 15$, usually associated with the maximum production of turbulent energy, they are each equal at about 70 % of $-\rho\overline{uv}$. At this position, the wallward and outward interactions each make a negative contribution of about 20 %, thus giving the net stress $-\rho\overline{uv}$ as required. The two negative contributions are approximately equal over the entire generation region, suggesting one mechanism. For this reason all the films of Corino (1965)† were reanalyzed

† The short descriptive sound film of the facility and flow is available as noted in Corino & Brodkey (1969). Arrangements for observation of the complete composite of the full-length research films (2400 ft on 2 reels) can be made by contacting R. S. Brodkey (Department of Chemical Engineering, The Ohio State University, Columbus, Ohio 43210) or J. M. Wallace (Max-Planck-Institut für Strömungsforschung, 34 Göttingen, West Germany).

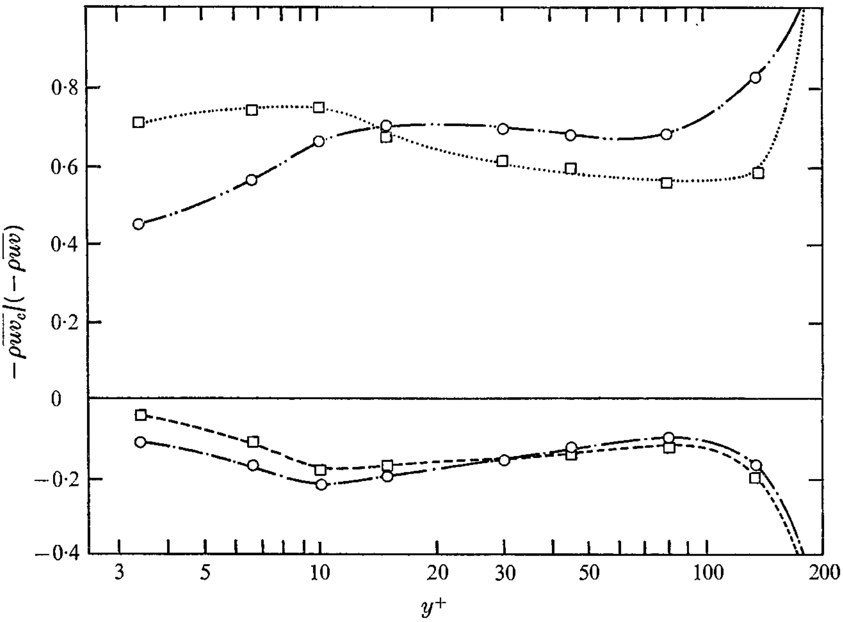

FIGURE 4. The classified Reynolds stress. -·-·-·-, ejection; ·····, sweep; - - - -, interaction (wallward); -·-·-·, interaction (outward).

and it was found that the negative contribution corresponds to an interaction between the ejection and sweep motions. This involves the deflexion of the low velocity decelerated regions back toward the wall and the reflexion of the higher velocity sweeps from the wall.

Away from the balance point, $y^+ \simeq 15$, the sweeps appear to be more important closer to the wall and the ejections more important away from the wall. Also, near the wall, sweeps appear to dominate the interactions as do ejections away from the wall. Near the wall the negative contribution of the outward interaction is greater, implying that accelerated regions are being forced away from the wall; beyond $y^+ = 15$ the opposite is true. Outside the wall region, it is not clear from previous work whether or not this sequential picture is still valid, and more visual studies are called for. As the channel centre-line is approached in figure 4, all the absolute values of $-\rho\overline{uv}_c/(-\rho\overline{uv})$ become very large because $-\rho\overline{uv}$ approaches zero.

The ejections contribute about 70 % of the net stress $-\rho\overline{uv}$, in agreement with the rough estimate of Corino & Brodkey (1969). In contrast to their estimate, however, the sweeps give an equal contribution, not just the balance required to make up 100 % as they suggested. Also they did not realize the existence of the negative contributions to the stress. Independently of the measurements reported here, Willmarth & Lu (1971) also measured the contributions to the Reynolds stress of the four components described above. This was done at $y^+ = 30$, and the results are somewhat at variance with ours. The reasons for this are not yet clear, and further study must be made to clarify this discrepancy. In a recent paper, Grass (1971) presented fresh results obtained using the

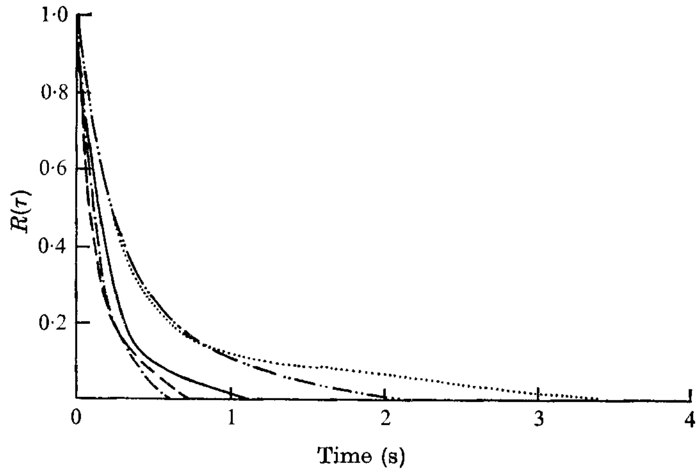

FIGURE 5. Autocorrelation of the classified stress at $y^+ = 15$. —, total stress $-\rho\overline{uv}$; other notation as in figure 4. $\nu/u_\tau^2 = 0{\cdot}06$ s.

	$L(\tau)$, s				
y^+	Total	Ejection	Sweep	Wallward interaction	Outward interaction
3·4	0·4	0·8	0·5	0·4	0·2
15	0·2	0·4	0·5	0·2	0·2
45	0·2	0·3	0·2	0·1	0·1
187	0·1	0·2	0·2	0·1	0·1

TABLE 2. Scales from autocorrelations (channel centre-line at $y^+ = 187$)

hydrogen-bubble technique which are in full agreement with the sequence of events observed by Corino & Brodkey (1969) and with the measurements presented here. He estimates from his films that the sweep-type motion should make about the same contribution to the Reynolds stress as the ejection-type motion for $y^+ \lesssim 60$.

Most of the standard turbulence signal analysis can be done on the split signal. For this work autocorrelations of the split and total signals at four positions were obtained with a PAR 101 correlator. The main purpose was to obtain a rough estimate of the time scale of the different events. As an example of the autocorrelation, figure 5 gives the results at $y^+ = 15$. Here $R(\tau)$ is given by

$$(\overline{uv_c(t)\,uv_c(t+\tau)} - \overline{uv_c}^2)/(\overline{uv_c^2} - \overline{uv_c}^2).$$

At this point the sweeps correlate over a somewhat longer time than the ejections. Here also, both the ejections and the sweeps are larger in their time scale and period of correlation than the interaction events, as was expected. This is seen to be true over most of the flow field investigated, as indicated by the values of the time scale given in table 2. These were estimated from the areas under the correlation curves taken to the first zero crossing.

5. Turbulent energy dissipation

Although no direct measurements are offered in this work, another aspect of wall turbulence has become clearer. It has long been known that the turbulent production is nearly balanced locally by turbulent dissipation (Laufer 1954; Townsend 1956). Turbulent dissipation arises from local viscous dissipation, which for a Newtonian fluid is $\mu\overline{(du_i/dx_j)^2}$ (where overbars indicate time averages), i.e. proportional to local velocity gradients squared. In our reinspection of Corino's films ($y^+ = 0$–40), it became clear that the high shear rate regions and two-layer velocity effects cited by Corino & Brodkey (1969) were the centres for high local dissipation of energy. Because of the close proximity of ejections and sweeps, these dissipative regions exist in the boundary regions between them. Thus the suggested sequential picture could account for the near balance of production and dissipation.

Some specific values taken from the thesis by Corino (1965) can be used to estimate that the square of the radial gradient of the local average velocity at the wall, $(d\bar{u}/dr)^2_{\text{wall}}$, is of the order of $10^3\,\text{s}^{-2}$, whereas the square of the radial gradient of the local velocity, $\overline{(du/dr)^2}$, and the square of the azimuthal gradient of the local velocity, $\overline{(du/d\theta)^2}$, are of the order of 10^6–$10^8\,\text{s}^{-2}$. The latter values are indicative of local dissipation and the former of the average dissipation at the wall.

6. Conclusions

(i) Four distinct classes of motion contribute to the Reynolds stress $-\rho\overline{uv}$ in the wall region of a turbulent shear flow.

(ii) The two classes ($u < 0$, $v > 0$; $u > 0$, $v < 0$) which together contribute a stress more than 100 % of the net value can be associated with the ejection and sweep events observed visually by Corino & Brodkey (1969).

(iii) Two additional classes ($u > 0$, $v > 0$; $u < 0$, $v < 0$) have been identified and their average contributions to Reynolds stress measured. These contributions are of opposite sign to those in (ii) above and account for the surplus stress (over 100 % of the net value) produced by ejection and sweep events. These motions are called interactions.

(iv) The time scale of the four motions has been estimated from autocorrelation of the classified product signals uv_c. The ejection and sweep motions correlate over significantly longer times than the interaction-type motions.

(v) Local turbulent dissipation at the edges of events is several orders of magnitude greater than the average dissipation at the wall.

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