Overview of Research by the Turbulence Structure Group

Unlike the other groups, the people in the Turbulence Structure group were primarily experimentalists with the exception of Landahl. The Summer Program thus provided a unique opportunity for these experimentalists to assess the numerical data in comparison with their own experimental data, and to extend their previous work using full 3D turbulence fields. The Group expressed a particular interest in investigating temporal evolutions in addition to the spatial variations of the organized turbulence structures.

The invited participants were:

Dr. Henrik Alfredsson (K. T. H., Sweden)
Dr. Arne Johansson (K. T. H., Sweden)
Professor Ron Blackwelder (U. S. C.)
Dr. Jerry Swearingen (U. S. C.)
Professor Yann Guezennec (O. S. U.)
Mr. Dan Henningson (F. F. A., Sweden)
Professor Fazle Hussain (U. Houston)
Mr. Jinhee Jeong (U. Houston)
Professor Marten Landahl (M. I. T.)
Mr. Kenny Breuer (M. I. T.)

The local participants were:

J. Kim (NASA Ames)
P. Spalart (NASA Ames)
G. Coleman (Stanford University and NASA Ames)
U. Piomelli (Stanford University and NASA Ames)
S. Robinson (Stanford University and NASA Ames)

During the first two days of the Summer Program, the following items were identified as unifying themes for the group:

- Detect significant structures
- Compare with experimental results
- Observe space-time evolutions
- Implement improved averaging schemes
- Investigate flow instability

With these unifying themes in mind, the Group was divited into several teams and each team proceeded to investigate the organized structures in wall-bounded shear flows using the databases generated by Kim, Moin & Moser (channel) and by Spalart (boundary layer). Data were prepared in time intervals short enough ($\Delta t^+ = 3$) to accomodate the study of the temporal evolution.

The most significant result from the Turbulence Structure Group as a whole concerned the temporal evolution of the organized structures in wall-bounded shear flows. Several different detection schemes, ranging from a simple visual method to rather sophisticated iteration procedures, were used to detect the organized structures. The resulting structures were slightly different from each other, since each scheme emphasized different aspects of the structures; however, these structures were also related to each other in many respects. For example, the internal shear layer investigated by Alfredsson and Johansson was generally observed between the structures associated with fourth- and second-quadrant events investigated by Guezennec (see Fig. 1). In all cases, the structures retained their coherence for much longer time than expected, and consequently, they could be tracked over a long streamwise extent. Typically, the organized structures persisted over a period on the order of $t^+ \approx 100$, and they could be tracked in space on the order of $x^+ \approx 1000$. The pictures emerging from these investigations suggest that the organized structures do not go through violent break-up processes, as perceived from previous studies, but rather diffuse slowly into incoherent motions. The spatial structure, however, was highly localized in space with small-scale motions within the structure. When such a structure passes a fixed probe in space, it can leave signatures that might look like a violent break-up process. To confirm this conjecture, it would be worthwhile in a future study to perform *in situ* comparison between the spatial distribution of a detected structure and the temporal signature at a fixed point when the structure passes by.

Brief summaries of each team effort are given in the following:

Johansson, Alfredsson and Kim studied the formation and evolution of shear-layer-like flow structures in the buffer region of wall-bounded turbulent shear flow that were associated with turbulence production. The structures were found to retain their coherence over streamwise distances on the order of 1000 viscous length units, and propagated with a constant velocity of about 10.5 u_τ throughout the near wall region. The shear-layer structures were found to be important contributors to the turbulence production: the conditionally averaged production at the center of the structure was almost twice as large as the long-time mean value. Individual shear layers often showed a strong spanwise asymmetry which was lost in conventional conditional averaging procedures.

Breuer, Landahl and Spalart performed numerical simulations, in which structures similar to those described by Alfredsson and Johansson were used as initial velocity fields, surrounded by a laminar boundary layer. The objective of this study was to investigate the dynamics of such structures in isolation, which made them easier to detect and follow in time. It was found that the structure associated with a fourth-quadrant event upstream of a second-quadrant event grew much more rapidly than that associated with a second-quadrant event upstream

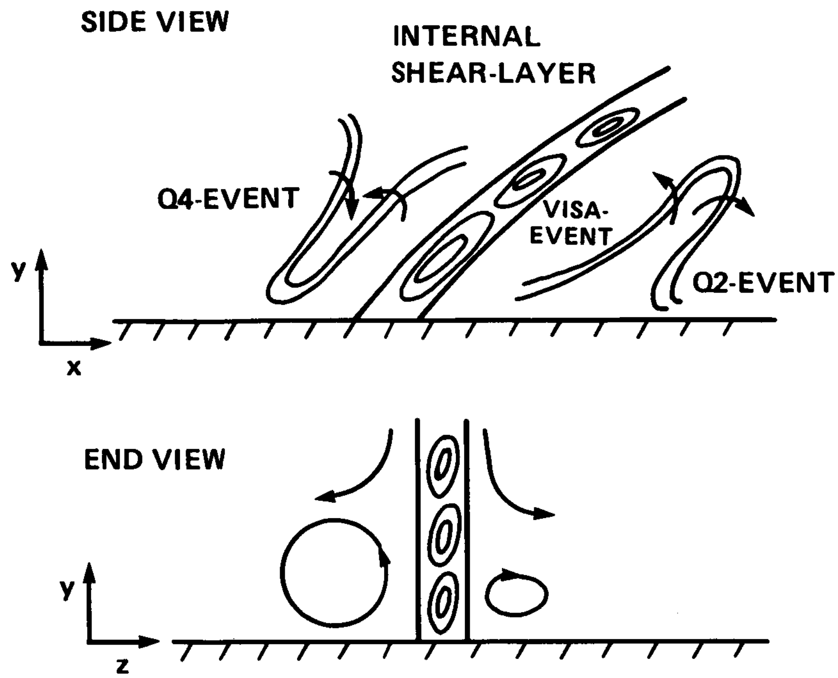

FIGURE 1. Coordinator's view on the organized structures in the wall-bounded shear flow.

of a fourth-quadrant event. This is consistent with the fact that one finds more energetic events of the former type than of the latter in turbulent flows.

Guezennec, Piomelli and Kim implemented several ensemble-averaging techniques (VITA, quadrant technique, techniques based on wall shear, etc) to determine organized structures in the wall-bounded flows. The results were in good agreement with his experimental results. It was found that the size of the detected structures in wall units was a function Reynolds number, and approximately scaled with the boundary layer thickness. Since detected instantaneous structures responsible for turbulence producing events were mostly asymetric, the ensemble-averaging process was improved by taking the asymmetry of the turbulence structures into consideration. The resulting structures were strongly asymmetric, suggesting that conventional ensemble-averaging schemes are misleading in that respect. It was also observed that these structures were persistent over a time on the order of 50 viscous time units.

Hussain, Jeong and Kim applied a conditional sampling technique designed to detect coherent vorticity through an iteration procedure to the above mentioned databases, as well as to a homogeneous shear flow field, to educe coherent structures from each flow. Many characteristics of the detected structures were quite similar to those of the mixing layer observed experimentally by Hussain and his colleagues: the topology consisted of saddles and centers, the saddle region being the location of maximum incoherent Reynolds shear stress and maximum shear production. The effect of shear on the coherent structure was also investigated by comparing the structure obtained in the wall region (high shear) with that obtained in the outer layer (low shear).

Hussain (in collaboration with Kim and Spalart) also studied the propagation speeds of the velocity, pressure and vorticity by examining cross-correlations between two fields at different times. It was found that the propagation speeds for velocity and vorticity were almost the same throughout the channel and boundary layer. The propagation speeds were constant (0.55 U_c) in the wall region ($y^+ < 15$) and slightly less than the local mean outside this region. The value 0.55 U_c is very close to the value obtained visually by Alfredsson and Johansson. The propagation speed for the pressure was also constant in the wall region but much higher than the others (0.75 U_c), whereas in the outer layer it was almost the same as the others.

Hussain (in collaboration with Kim and Coleman) investigated the Taylor hypothesis of frozen turbulence by directly evaluating the terms involved. Three different propagation speeds — mean velocity, local velocity and filtered local velocity — were used for the evaluation. It was found that the hypothesis was surprisingly good except very close to the wall region. It was also found that the departure from the hypothesis was not directly associated with large-scale structures. It should be an worthwhile effort to pursue further to examine which neglected terms contribute most to the departure from the hypothesis in the wall region.

Swearingen, Blackwelder and Spalart investigated flow instabilities associated with shear layers by examining the structure of the normal shear layer ($\partial u/\partial y$) and the spanwise shear layer ($\partial u/\partial z$). They found that a strong shear and an inflectional velocity profile existed surrounding the low speed region, and more importantly, they persisted up to 60 ν/u_τ^2 indicating sufficient time for an instability to develop. The low-speed streaks developed an oscillatory motion which increased in time (also indicative of instability) and eventually the undulating portion of the streaks appeared to break up into chaotic motion.

Landahl, Kim and Spalart examined the basic hypothesis of his "active-layer" model for wall-bounded turbulence. The model assumes that the non-linear (fluctuation-fluctuation) terms are large only in a thin layer near the wall, and hence, the turbulence in the region outside the active inner layer can be modeled as a linear response driven by the active layer. Preliminary investigation indicated that the non-linear effects were indeed strongest near the wall with a maximum around $y^+ = 20$ and, outside the near-wall region, they involved primarily the cascading mechanism to dissipative scales of motion. This model may lead to a reasonably simple procedure for determining the Reynolds stresses and other statistical quantities through a comparatively simple linear calculation making use of a universal model for the non-linear processes in the near-wall region.

Henningson, Landahl and Kim used a kinematic wave theory to investigate the cause of the rapid growth of waves observed at the wingtip of a turbulent spot in plane Poiseuille flow. It was found that the qualitative behavior of the wave motions was well described by Landahl's breakdown criterion: that is, using the breakdown criterion together with the requirement of exponential growth, the qualitative behavior of normal group velocity was able to select a wave number, wave angle and phase velocity comparable to those observed in the simulation.

J. Kim