01 Jan 1973

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ABSTRACT

The concept of organized, spatially coherent large scale structures has been investigated for a variety of turbulent shear flows by a technique called "Conditional Sampling." It can be shown that these structures are related to physically important activities such as, 1) the entrainment of turbulent boundary layers, and 2) the maintenance of turbulence by a wall, 3) the growth of free shear layers, and 4) the structure and noise production of turbulent jets.

The general technique of conditioned sampling is related to visualizations of the flow, and to problems of synchronization of images in the presence of noise. While there are too many different techniques of conditional sampling to include in a short review, several of the important results of various techniques are compared to other visualizations of the flow and are shown to provide more useful quantitative insights into the structure of the turbulence.

PERSPECTIVE

It has become axiomatic that both theories and experiments on turbulent shear flows raise more questions than they resolve. Without entering into a detailed survey of the state of our understanding of the nature of turbulence, it would not be a gross misstatement to confess that it is imcomplete. Indeed, some of our lapses are of a very basic nature.

There are a large number of turbulent shear flows which are well understood from the standpoint of macroscopic average measures, and there are models for these turbulent flows which yield satisfactory engineering predictions for such quantities as skin friction and heat transfer coefficients, as well as some means for guiding the engineer in estimating separation points, mass transfer coefficients, etc. There are, consequently, a wide range of measurements whose aim is to guide in the establishment of a firmer empirical base for engineering prediction.

If we restrict our attention to turbulent shear flows, there is another class of experiments which aims to establish a firmer basis for understanding the mechanics of the turbulence. There are two basic experimental philosophies at play in this area. One school of thought stresses the role of the experimentalist in testing theories that have been proposed, while the second places more emphasis on the role of the experimentalist in cataloging observed phenomena which must be explained, so as to guide a theoretical formulation of the problem.

Obviously there is a need for all three types of experimental approaches. The effectiveness and value of any one approach depends upon the problem at hand, the questions that one has proposed, and the nature of the experimentalist.

In this brief historical framework, the place of Conditional Sampling is more traditional than revolutionary. In brief, the approach is one that stresses a kind of order over disorder, and seems to idealize certain aspects of the nature of turbulence, irrespective of whether or not there is today a theoretician concerned with the phenomena studied. Thankfully, there are very able theoreticians who are directing their attentions to the questions that these observations have raised.

FORMULATION - ERGODICITY

Theoretical formulations of the dynamics of turbulent shear flows address the problem of some deterministic mean field and a random fluctuation field superimposed on the mean. To establish statistical validity (and to define the mean), one conceptually imagines an "ensemble" of physical processes, and defines the necessary statistics to describe the fluctuation field.

Because of the complexity of the problem, one quickly specializes to cases where these statistics are time-independent, and then replaces the "ensemble average" by the time average. This action is referred to as the ergodic hypothesis, and is generally invoked in pragmatic manner (for example, the hypothesis is valid in cases for which it is justified) (1,2).

If we restrict our discussion to isothermal, homogeneous liquids, there is a unique way to perform these averages and the relevant equations of motion for the time-independent quantities are well established. At this level, the crucial issue becomes one of mathematical closure of the system of equations, and of concepts of space-time correlations, spectra, and other tools that in the past have proved fruitful for characterizing the random flow fields in the mathematical treatment of the problem.

It is very difficult to find substantial fault with this method of attack. Theoretically, one notes that the time averages replace the "ensemble mean" in the limit as averaging time goes to infinity. As a practical matter, an infinite wait is not necessary, and one need average only as long as is necessary to make the average meaningful. Implicit in this position, is the further (generally unspoken) understanding that the infinite time equivalent of the independent ensemble is replacable by a set of finite time records, each of which is recorded over enough time to be statistically equivalent (within limits of accuracy) to each other and to the ensemble. Only if the required error in the measures must be zero, must the time go to infinity.

PROCESS TIME - DEFINITION

From the point of view of the experimentalist, there is the concept of some time scale, sufficiently large to permit meaningful statistics to be extracted. This time scale is defined as the process time. In essence, a practical realization of the random process persists for at least one process time. Two realizations separated by the process time are statistically independent, and their statistical measures are equivalent.

Physically, we all know that the process time is related to some velocity scale and some length scale appropriate to the process under study. The exact constant of proportionality is inversely proportional to the permissible accuracy in the statistical measures.

FORMULATION - THE EVENT

While no fault is found with the generalized formulation described previously, there is some reason to believe that it results in an unsolvable problem. Whether this assertion is true or not, it is a fact that the problem has not yet been solved, even for the simplest model cases which some observers have convinced themselves are of interest.

One can mechanistically postulate a model process, which would lead to another entirely different theoretical formulation. This process we can describe in terms of stochastic "Events."

For the sake of illustration, consider a flow field to be constructed of many statistically independent events, with a <u>completely deterministic spatial structure</u> which develops in time after its birth. These structures appear initially at random times, randomly in space, but after their appearance, their development in time is slow, and in some sense Lagrangian.

It is asserted (without proof) that when viewed with an ergodic outlook, this type of model passes all of the tests of randomness, although it is clear that instantaneous spatial correlations will have a form compatable with the structures, if all structures in a given spatial domain are of nearly the same age. It should be stressed that such a process is not turbulence, for it fails the test of randomness in all reference frames.

A LAGRANGIAN INTERPRETATION

Guided by flow visualization, which can often be a useful tool in clarifying one's thinking, the quasi-orderly event described above can be viewed as the passage of some field (which we observe in an Eulerian reference frame) that is mostly Lagrangian in nature. In essence, if the event is truly ordered, it may be regarded as a "steady flow" in some appropriate coordinate system which travels with the structure.

It is too much to expect that the set of all events is ordered. In fact, there must be a degree of disorder or the years spent in the study of turbulence have been wasted. Hopefully, however, the statistics of these events can be better understood if observed in the appropriate reference frame. In fact, it would not be inappropriate to expect the state of the events to be a Markov process. These ideas have been explored for the dispersion of passive contaminants in turbulent shear flows (3), and there is good reason to expect that the process governing "events" is Markovian, which is not a restrictive condition.

However, the event is emphasized because it has an average structure which is definable and hopefully accounts for the physically important phenomena and most of the energy.

THE STATE OF AN EVENT

For studies of turbulent flows in liquids, one is indeed fortunate to have a relatively simple description of the state of a flow. For non-stratified problems, a defining vector field (velocity or vorticity) exists.

There are relative simple flows which are best described by their vorticity fields. (For cases with an initial input of vorticity, this viewpoint is quite appropriate, as for example, in a turbulent mixing layer or jet.)

For boundary layer flows, velocity seems to be the variable most appropriate to define the complete state of the motion, if only that we lack the means to measure the vorticity directly in a simple manner.

In describing the state of an event, it must be remembered that the flow is composed of a sequence of events, so that the state description is at first, more complex. In the absence of a magical transformation which will transform a hard problem into a simple one, one is not surprised at this added complexity. The hope is that the dynamics of an idealized event are more understandable than that of all possible events, hence, it is not too objectionable to accept for each event the added burden of its identification (for example, when in time the event occurred at some point in space).

DETECTION FUNCTION - A REFERENCE FOR AN EVENT

The concept of an event is useless unless the event is identifiable, just as the trace on an oscilloscope is unrecognizable if the sweep is not synchronized with the phenomena. For some signals, an externally provided reference must be supplied. Indeed, one might investigate the pure statistics of television demodulated video amplitudes in the absence of frame synchronization.

Means must exist for identifying events, and synchronizing the sequence of states that exist during the event. In this regard, the detection function is analogous to a trigger which aligns all reference points in the set of events.

A valid test as to whether the detection is significant is that the image is insensitive to trigger level. If we again draw the analogy to the synchronization of an oscilloscope, changing the trigger level may change the number of sweeps, but not the picture shown, if there is anything to show.

CONDITIONAL SAMPLING

With this introduction, one can finally describe the process of conditional sampling as the eduction of information about an event with respect to the time reference defined by its detection function. Conditional Sampling is different from evoked sampling only in that the phenomenon is not stimulated externally.

EXAMPLES

In the following examples, the author does not wish to offend any investigators by omission of their work. The following are examples of the type of work which has been done, and is not meant to be exhaustive or definitive, but merely illustrative, and for that reason, a bias to the author's home institution might be forgiven.

FREE TURBULENCE

The Mixing Layer

The turbulent development of a velocity shear is one of the most basic model problems in turbulence, and has been extensively investigated (4-7). Idealized, the model inviscid problem is that of the Helmholtz instability of a vortex sheet, and for laminar viscous flow, exact solutions which develop either in space or in time exist. These viscous solutions are highly unstable and the character of the shear flow changes to turbulent at quite low values of the Reynolds number.

While some minor discrepancies have been observed for certain measurable quantities, the mixing layer can be regarded as a well studied turbulence phenomenon. One can find in these references mean profiles, spreading rates, fluctuation amplitude distributions, probability densities and even spectra. From these time-averaged measurements the process is described, but not understood.

A recent study by Winant and Browand (8,9) sheds much light on the nature of the turbulent mixing layer, and can be used to explain the behavior of most of the standard statistical observations, such as correlations, spectra, etc. By marking the initial shear layer with dye, Winant and Browand observed the vortex dynamics of the mixing layer, from birth to full turbulence. The sequence briefly involves a laminar instability, non-linear organization of the shear layer into discrete vortices, and then a pairing interaction of this vorticity to form larger and larger agglomerations of vorticity (Figure 1).

It should be stressed that the experimental environment is a completely turbulent shear layer, but since the rate of diffusion of dye and vorticity is of the same order of magnitude, the vorticity is observable. While the vorticity is mixed, more striking is how the observable organization persists for the duration of the experiment. Vortex pairing is an idealization of the motion, and indeed, when it is extracted (Figure 2) by conditional sampling, the energy in the disordered remainder of the flow is significantly reduced.

It should be noted, in connection with this and the following example, that some observers have tried to characterize the structures of these flows in terms of a traveling wave modes. Whatever these results may show, it is clear that such a description must be fundamentally incorrect because of the loss of phase reference as one proceeds with the pairing process (i.e. crests are not conserved as Whitham (10) demands).

The Round Jet

While most of our effort has involved acoustic problem in jet noise, our studies have cast much light on the fluid dynamic structure of the round jet. While the conditionally sampled results (which of course will involve the radiated sound field too) are not complete, we can make definitive statements about the jet structure.

Initially (see Figure 3), the shear layers behave like the previous example, with the important exception that the geometry forces vortex rings. The pairing process forces the linear growth of the shear layers as before, but appears to continue beyond the merging of the shear layers.

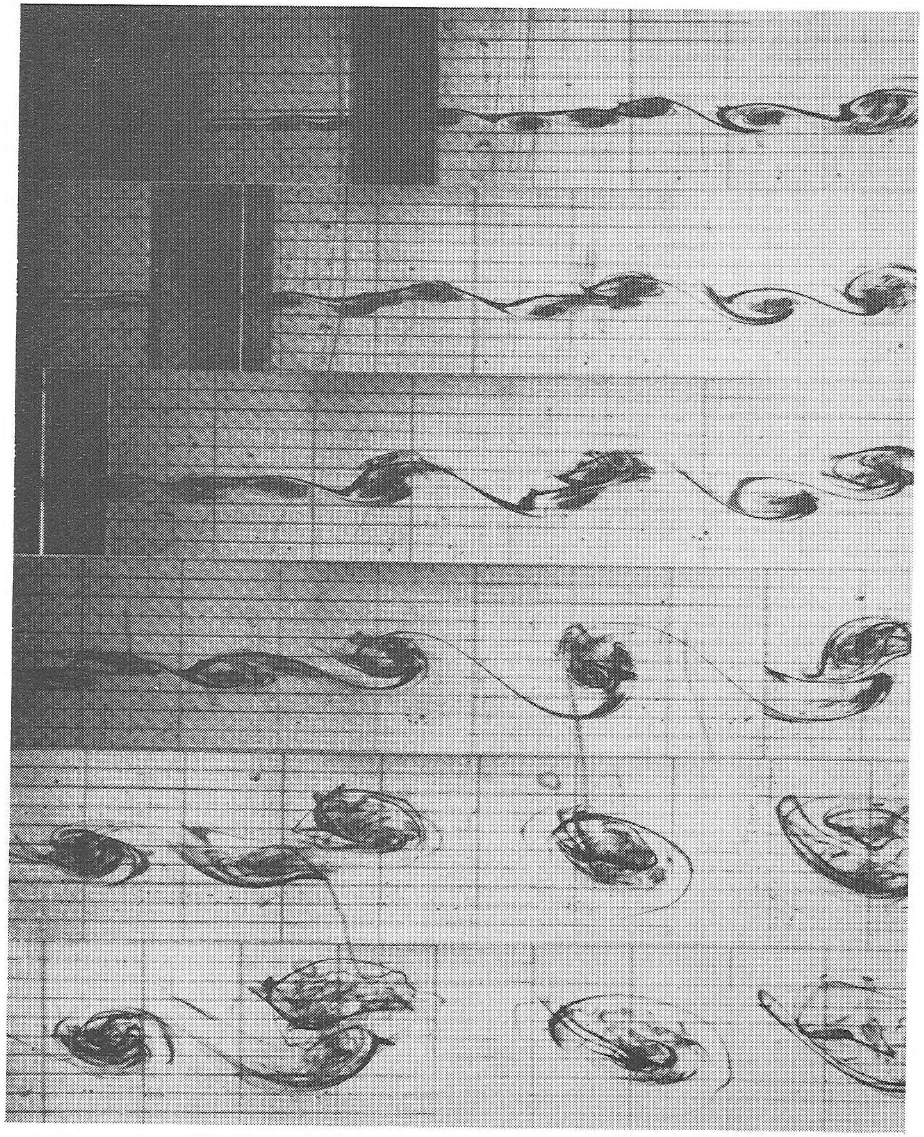

Figure 1. Evolution of Vortex Structures and Vortex Pairing - Turbulent Mixing Layer (Courtesy F. K. Browand).

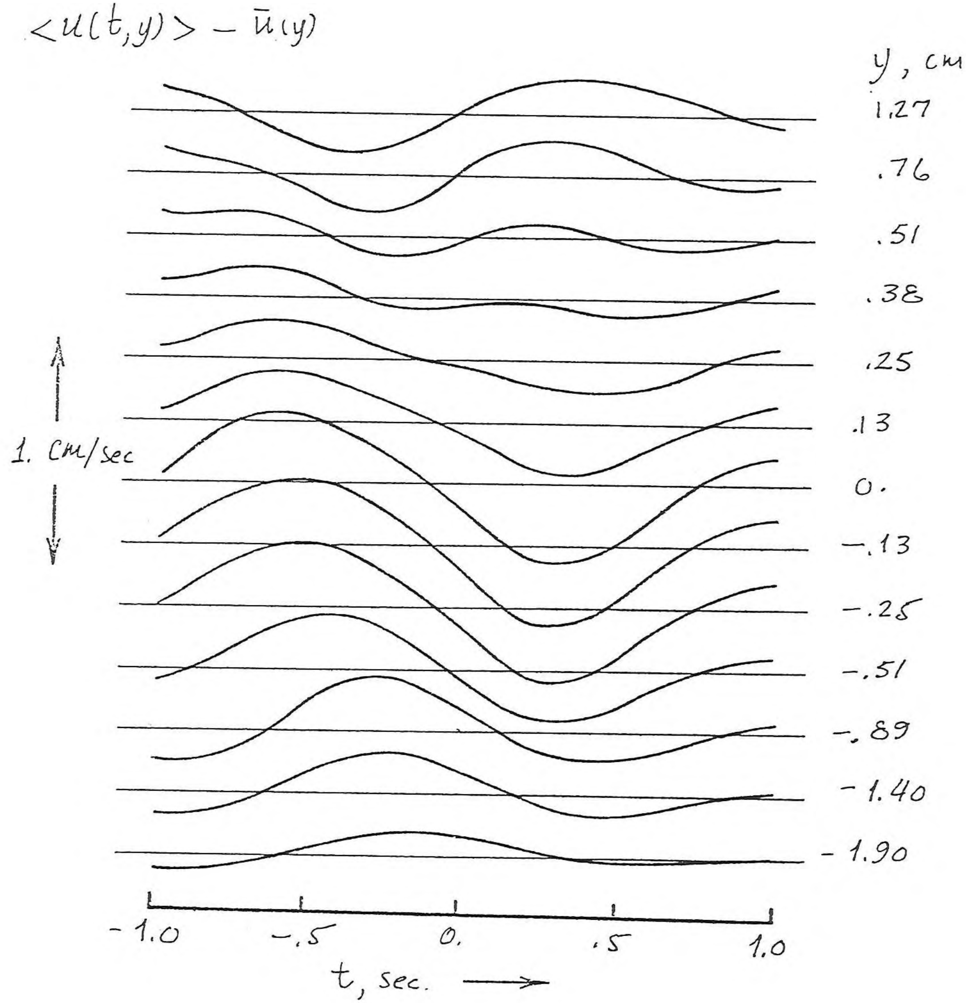

Figure 2. Conditional Averages of u Velocity Fluctuation in a Turbulent Mixing Layer (Courtesy F. K. Browand and C. D. Winant).

At the low Reynolds numbers ($\sim 10^4$) involved in these visualizations, the predominant structure is axisymmetric, again yielding a model that may be idealized to higher Reynolds number where the visualization fails.

While still, non-stereoscopic photographs cannot do justice to the visualization of the vortex dynamics of the jet, a definite intermittent sequence is observed over a factor of 2 in Reynolds numbers.

In brief, the disorder seems to be closely related to the pairing process, in that its ultimate creation is closely related to the existence of the pairing. This disorder is responsible, however, for the ultimate destruction of the ring structure in the far jet regions (past 10 diameters). The entire process in the near jet is always more intermittent at higher Reynolds numbers, but of course is more easily observable in the range of the photograph.

With the bias that some prototype event exists, one is highly motivated to look for it via conditional sampling. It has been pointed out in this case too, that a wave-like description of the motion is inappropriate (11).

WALL TURBULENCE

Transition in a Pipe

A recently published study of pipe flow turbulence by Wygnanski and Champagne (12) used conditional sampling to quantify Reynolds' original observations of pipe flow transition. Using the detection of the passage of the interface between turbulent and non-turbulent regions in the pipe as their reference, they were able to classify the dynamical processes which occur during the transition process. It is clear that for this process, while the ergodic test is valid for long enough times, the process is clearly unstationary, and the turbulent and non-turbulent regions are clearly dynamically different.

Out of the multiplicity of figures which appear in their carefully conceived and documented study, it is appropriate to refer to their Figure 4c and our Figure 4. In this figure we see the concept of conditional sampling graphically analogized as the "triggering of an oscilloscope." It is clear that the structure of what Wygnanski and Champagne call a turbulent "puff" emcompasses a feature which recurs in many realizations.

The Boundary Layer

Studies of the structures of turbulent boundary layer have involved two domains of the flow. The first involves the outer structure and the entrainment problem, while the second is of the inner wall structure, or the shear stress problem. To date, a definitive mechanism connecting the two structures has not been quantitatively observed, although one has been suggested (13).

Study of the outer structures was initiated by observations of Corrsin and Kistler (14), and culminated by Kovasznay, Kibens and Blackwelder (15), Fielder and Head (16), and Laufer and Kaplan (17). By means of a type of conditioned sampling, the structure of flow variables was shown to be fundamentally different across the interface between turbulent and non-turbulent fluid. A sample of typical conditioned averages is shown in Figure 5, taken from Reference 13. Happily, these types of studies have also been related to theoretical formations of the problem (18).

It should be pointed out that many of the techniques used in the investigation of the outer region of the turbulent boundary layer, were used by Coles (19) in his "spiral turbulence" studies. There is still active interest in this aspect of the turbulent boundary, and it is clear that a conditional sampling approach is appropriate to this class of problems.

The applicability of conditional sampling techniques to the sublayer structures is not as obvious. Hama (20) was the first to observe the sublayer structures later thoroughly investigated by the Stanford (21,22) and USC (23) groups and elsewhere. Corino and Brodkey (24) related the sublayer structure to motions which are observed in wide regions of the turbulent boundary layer (but not to the largest scales).

Recently, attempts have been made to characterize these phenomena by means of conditional sampling. Among the active investigators have been

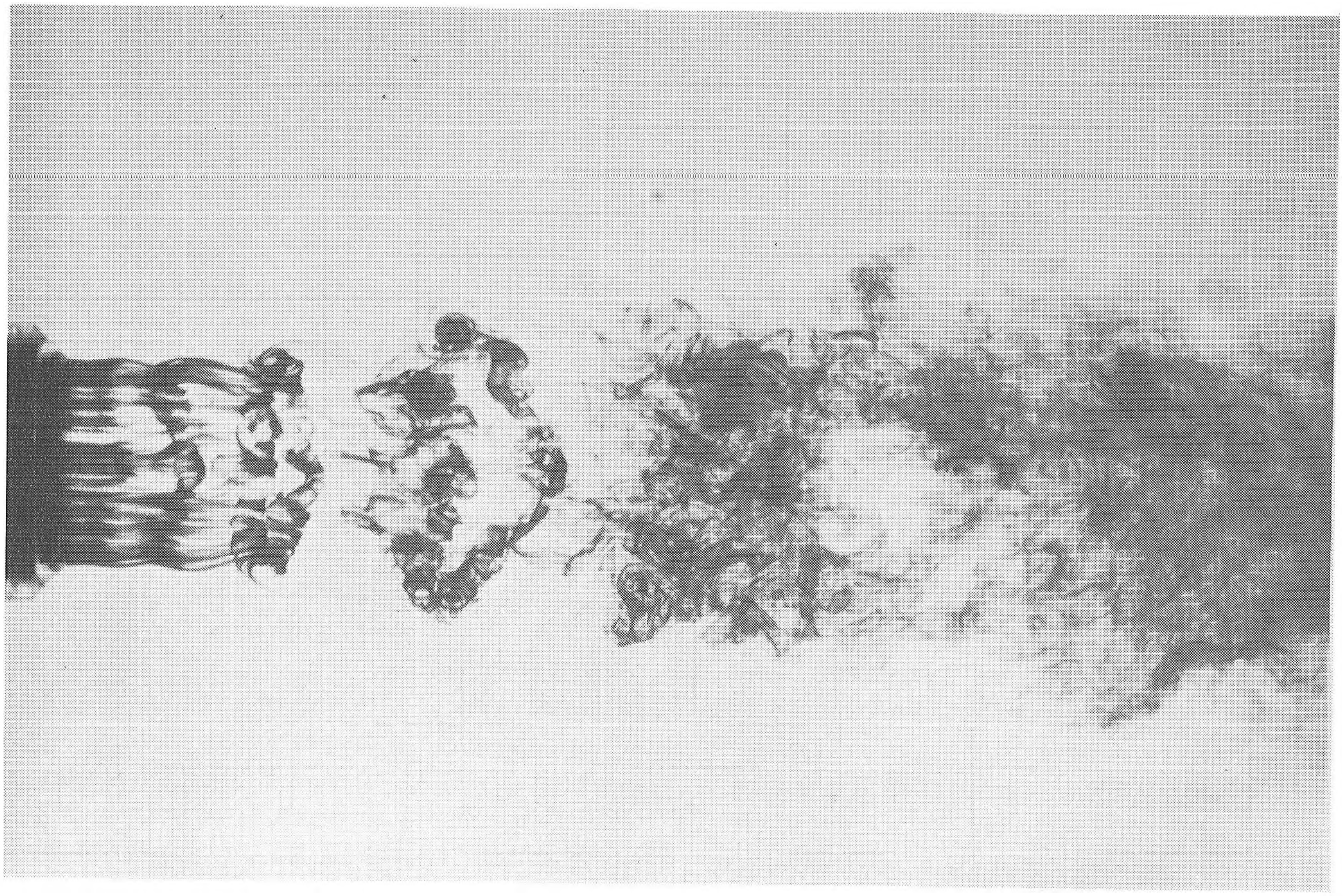

Figure 3. Vortex Ring Structures in Turbulent Jets - Vortex Pairing (Courtesy F. K. Browand).

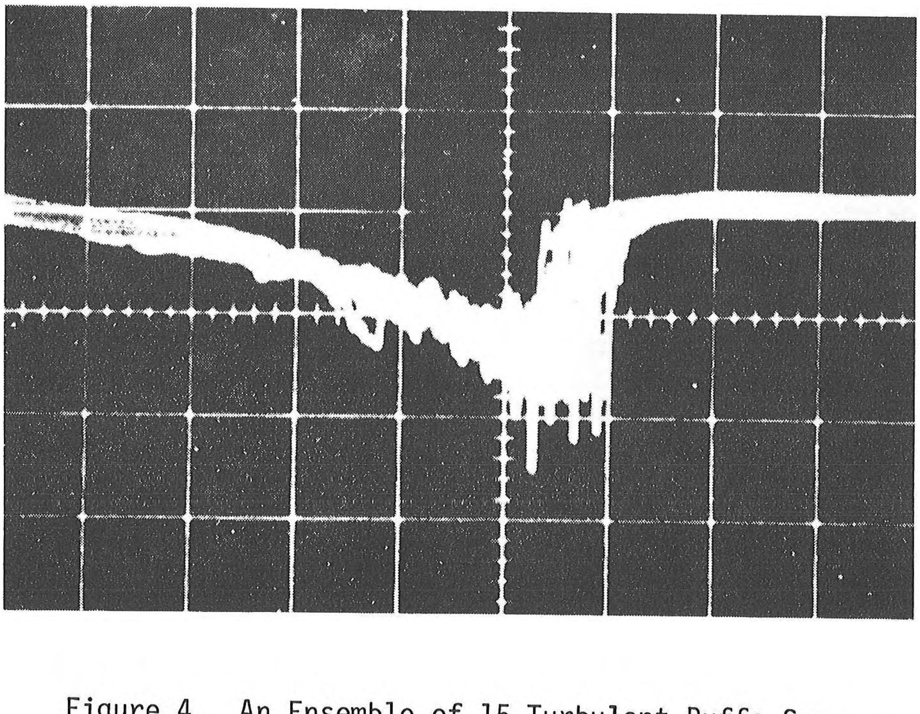

Figure 4. An Ensemble of 15 Turbulent Puffs Synchronized on an Oscilloscope (Courtesy I. Wygnanski).

Willmarth and Lu (25), Wallace et al. (26), and Blackwelder and Kaplan (27,28). In these studies, attempts have been made to quantify further the details of the visual observations.

In the framework of conditional sampling outlined previously, a reference point in the sublayer structure can be easily identified, and the average sequence of states during an event can be measured (Figure 6). Hence the event can be synchronized and studied in detail. It is indisputable that a sequence, significantly different from the time average, does exist. It is still to be established the extent of the physical significance of these events.

Two general statements can be made. First, that the observed event is the largest (in amplitude) feature of the turbulent sublayer and, second, that the structure of the event evidences itself in relatively few (much less than 100) realizations. In fact, the structure becomes visible in as few as 3 averaged events.

There is extensive work now under way to characterize the Reynolds stresses during these events, and their spanwise behavior.

CONCLUSIONS

While it is premature to state that conditional sampling will unravel all the mysteries of turbulent shear flows, it has been an extremely useful tool in helping to characterize the nature of organized turbulent structures. It is one more technique available in the arsenal of the modern experimentalist in turbulence.

ACKNOWLEDGMENT

The author is indebted to his colleagues J. Laufer, R. F. Blackwelder, F. K. Browand, and I. Wygnanski for many fruitful discussions on this and related topics. Much of the author's own research in this area has been supported by the National Science foundation under Grant GK-24578 and the Department of Transportation under Grant DOT-)S-00002.

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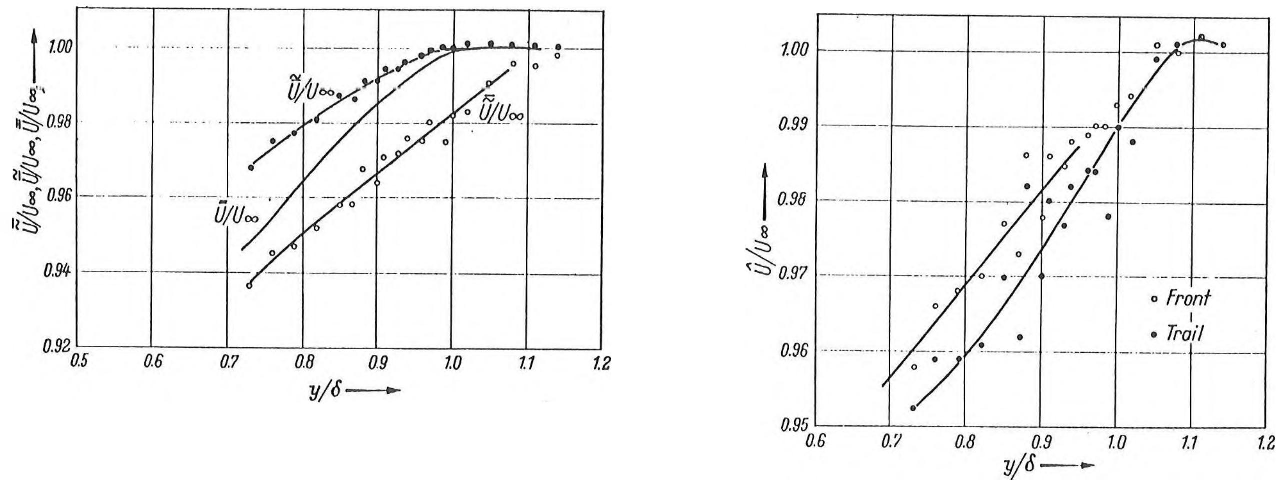

Figure 5. Interfacial Structures of a Turbulent Boundary - Conditioned Point and Zone Averages (Kaplan and Laufer).

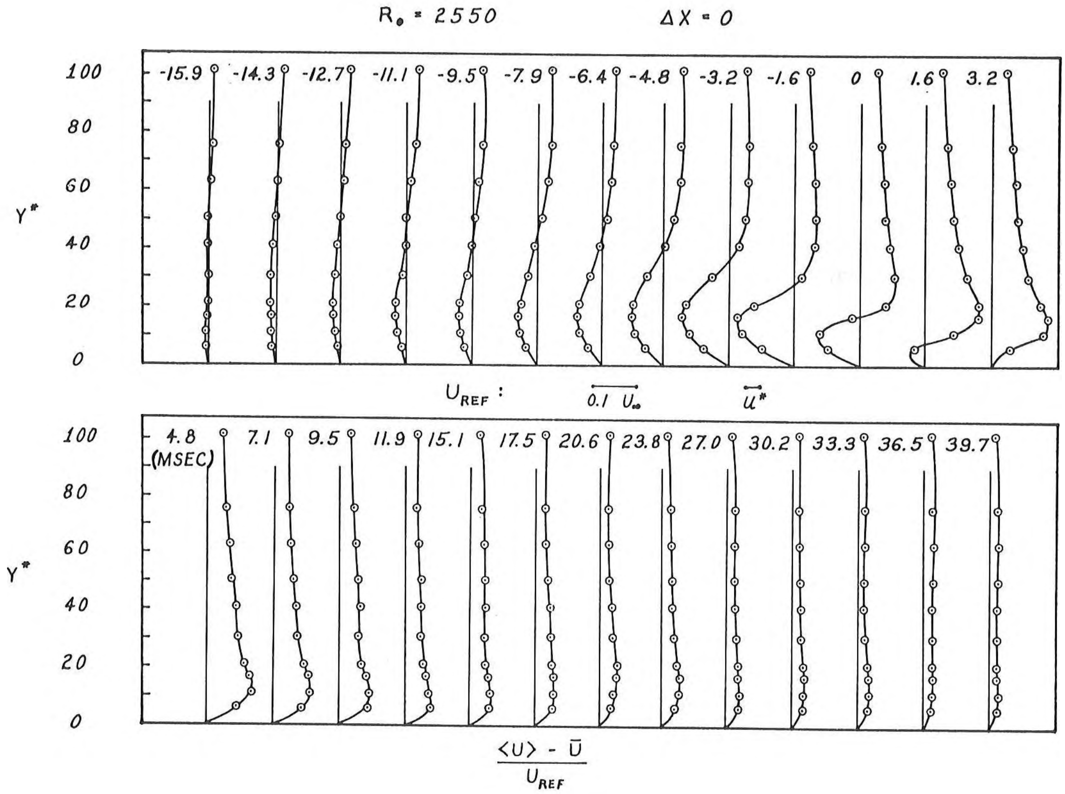

Figure 6. History of Conditionally Sampled Sub-layer Event - (Blackwelder and Kaplan).

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DISCUSSION

I J. Wygnanski, University of Tel-Aviv: It seems that you are postulating a cascade process in reverse, namely smaller eddies becoming larger eddies. And the larger eddies are the ones that generate the new motion.

Kaplan: The big eddies are the mean motion. All the information in the mean motion is there in these little red circles of dye. And that's not just the turbulence, but also the mean field, which is not separated in that picture. It's how the fluctuation field is generated out of the mean motion which interests me. The turbulence and the mean coexist and must be treated together. In the case of the jet, the vorticity is created at a source and it's very hard to destroy. You can mix it up and spread it around in space but you don't kill it off. The velocity field of each of those rings is induced over a large region. You see how I idealize the situation myself, I think of them as perfect rings. They're obviously not, because it's a turbulent flow. The bias towards order helps me sort out my thinking.

Wygnanski: I think quite strongly that we should try hard to condition our sets of results as carefully as possible and thus get better quantitative data. I would like to illustrate this point by showing a few slides from our study in transitional pipe flow. In Figure 1(a) we are looking at a hot-wire signature of a train of turbulent puffs occurring naturally in a pipe at Re = 2200. Time is running from left to right and the vertical scale is proportional to velocity. There is a sharp jump in velocity at the trailing edge of each individual puff (Figure 1a) and yet when these puffs are ensembled together by using conventional analogue techniques for the determination of the trailing interface there is an obvious jitter (Figure 1b). The ensemble averaged velocities (Figure 2) indicate that we have smeared the jump in velocity near the rear interface over a period of time which is equivalent to approximately 15% of the total duration of the puff. More recently, we have repeated the same experiment again using a more refined digital data.

We recorded 1 second of data per event and were able to look at and analyze any portion of this record. In Figure 3 you see a hot-wire trace of a puff and then expanded portion of it near the trailing interface. Figure 4 shows essentially the same ensemble averaged record of velocity as Figure 2 but without the jitter. You can see that the sharp rise in velocity near the trailing edge did not disappear and one can even recognize some large scale structure within the turbulent region. The data represents 100 events, however at the center of the pipe ($r/R = 0$) we have repeated the experiment ensembling 800 events with no visible difference. The message is that careful

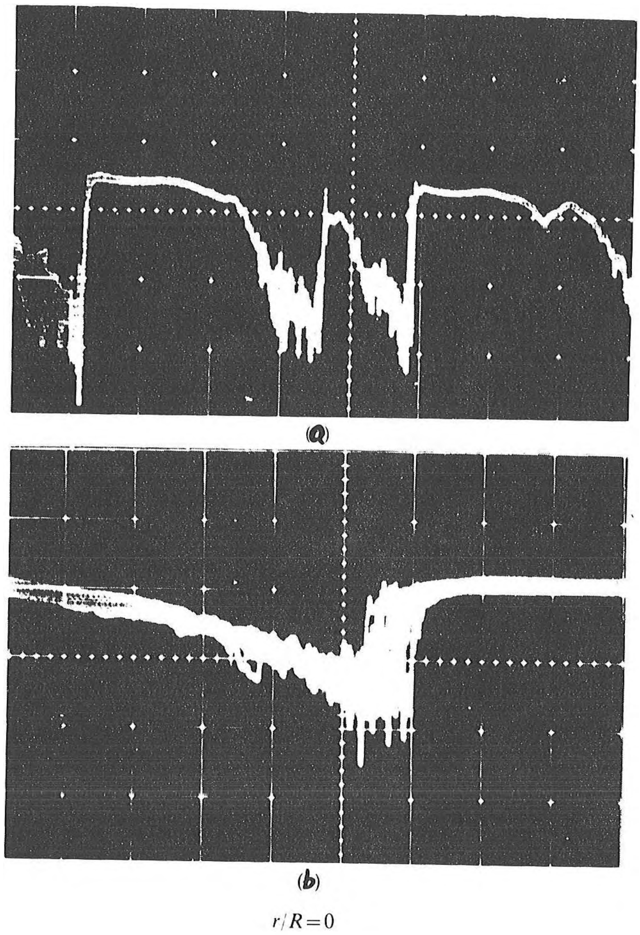


Figure 1. Oscilloscope traces of turbulent puffs - Re = 2200 (Wygnanski)

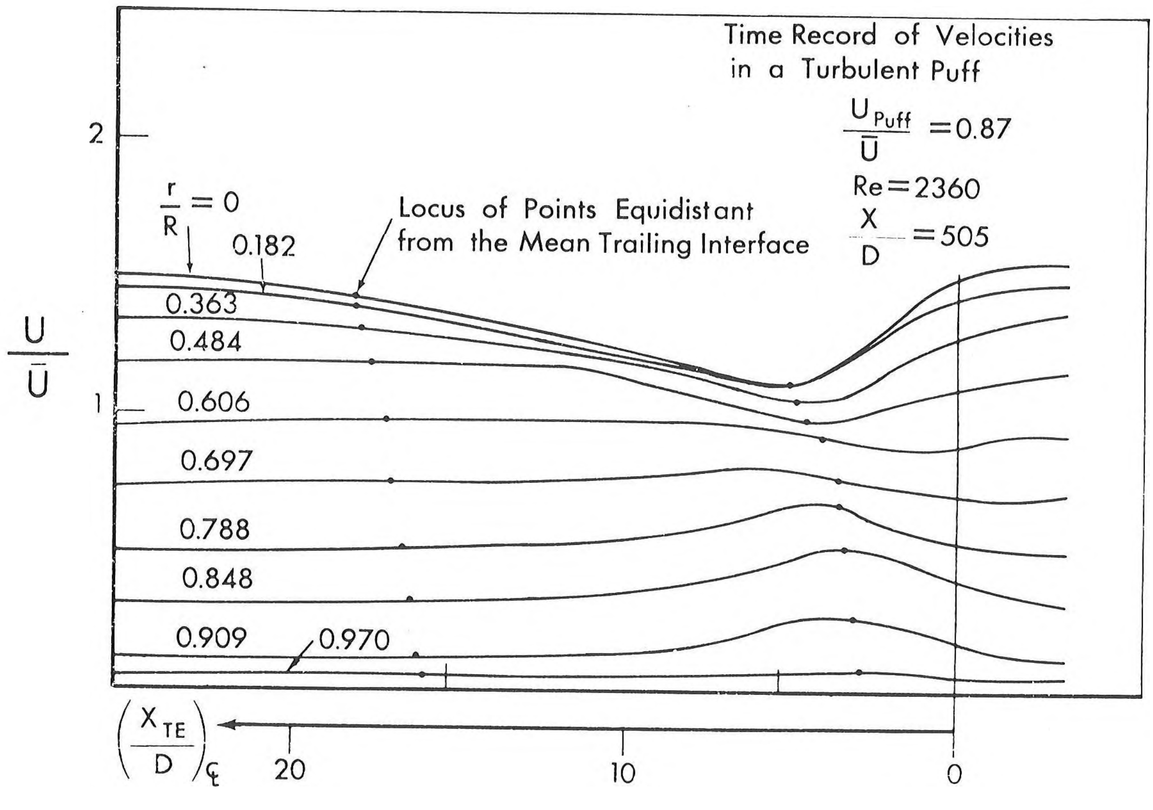
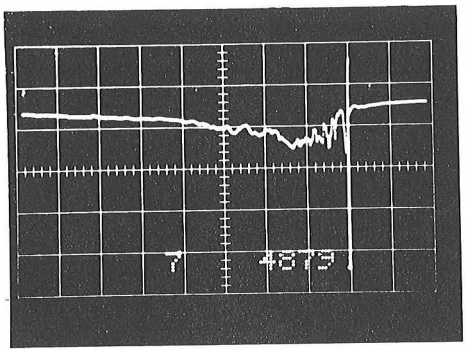


Figure 2. Ensemble-averaged velocities in a turbulent puff (Wygnanski)



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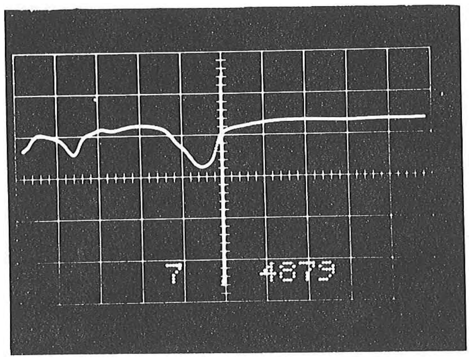

b

Figure 3. The determination of the trailing interface by the cursar program. The first number indicates the number or the puff in the ensemble; the second number indicates the location of the trailing front.

a. An oscilloscope trace of the entire puff.

b. Expanded scale near the trailing edge.

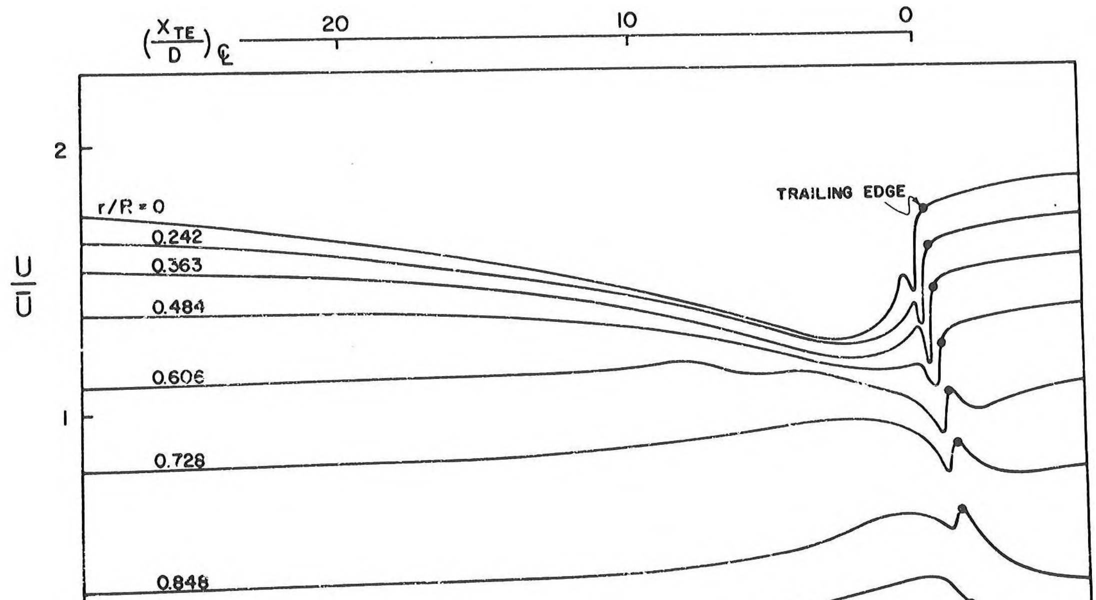

Figure 4. Ensemble-averaged velocities without jitter (Wygnanski)

or precise triggering and ensembling of data can improve our understanding of the mechanism by which turbulence spreads.

V. Kibens, University of Michigan: When you say that the same data was used, does that literally mean that it was recorded on tape and run through different circuits?

Wygnanski: That is not exactly correct because the data shown in Figures 1 and 2 were taken two years earlier. But we have gone through a similar exercise so your statement is precise.

S. J. Kline, Stanford University: I do want to ask one question and make a couple of comments. First of all, I suggested previously that maybe we should get smarter about how we handle triggering and sampling and I didn't expect to hear it already, but that's very nice. Secondly, with respect to your layer, I think we were having an argument yesterday which was a semantic argument which keeps coming up and might be worth clarifying because I agree with what you said today about the shear layers. In Ozzerberg's work, where he's done similar things to what you have, with a two-dimensional jet with three different sets of initial conditions, I think the distinction there is we see also the same kind of organized things that you see. Although we haven't done any conditional sampling there, I'm sure we could get similar results. The initial condition I think ought to be related to the state of the boundary layer coming off the trailing surface and in that sense the first movies you showed were not turbulent, but laminar, and you yourself pointed farther downstream and said it's turbulent down here and I would agree with that but if you go on up to where you have a turbulent layer before it comes off the surface then, in fact, you still see this kind of organization but riding on the organization is more disorganization. There's some similarity but also some differences. I'd like to get your reaction to that.

Further, I want to comment on your inner-layer conditional sampling which is what I was talking about before. I didn't show you the data but I think I should mention that the jitter is very large. It's much larger than what Prof. Wygnanski was just showing and what you were showing for the puffs on the jet, even the turbulent jet. The jitter in that problem is really very big and makes the problem very severe to extract the more organized information.

Kaplan: Let me comment on the second problem in the mixing layer work because we haven't had a chance yet to put trips in the jet. The primary result is a displacement of the transition point measured in units of initial shear layer thickness. The shear layer width is increasing steadily, so its the same as the problem of one amoeba in a bucket which splits every second. After an hour, how long does it take to double the total? It's the initial shift of origin of the shear layer growth by the initial conditions - (the one second) the one pairing displacement. The concept is that a vortex sheet (independent of its fine structure) wants to break up into organized structures. You can see this if you look at vortex puffs, as Maxworthy has done. An isolated laminar ring progresses through space and then transitions - and then causes a turbulent vortex ring. The organized part of the vorticity is very hard to kill. This was attacked for a case of (not rings but) the tip vortices by Steven Crow. In this case, the vortices are destroyed because vorticity of both signs exist.

Kline: I think we're in quite good agreement on that problem. Ozzerberg did do that exactly. He came up with a universal Strouhal number for the two-dimensional case. For a whole mess of data, all we could get our hands on, does exactly what you say. It scales on the shear and as you get a shear layer instability and, that I think is perhaps worth a further comment and that is what Brodkey was saying yesterday and what we think we see is the same thing as you're saying or implying, that there are two parts of it. Let's take them separately, one is the business of cascades which Wygnanski brought up, and I don't see how you can interpret what you're saying except that it's anti-cascade in the conventional sense and I think that idea has been in the literature for about 3 decades or so and everybody sort of accepts it because it was the first theory put forth. But if you look around for data which support the cascade theories, some kind of direct data, not just the assumption that the theory is correct, in fact, you have a very hard time finding any such data which really have to be the ultimate test. That's one aspect of it, another aspect of it is we think we see anti-cascade stuff as implied in the inner-layer the other day and I think Brodkey feels that way about it; he might comment so that there's at least good reasons for at least seriously questioning what's going on in the wave-number space when you begin to get some of these better samples. I think that question is worth mentioning. The other question is the business of the thin shear layer instability, whether one wants to call that Kelvin Helmholz or give it a broader name is perhaps just words, but at any rate if we call it the thin shear layer instability that's exactly what we think we see in the boundary layer problem and I gather Brodkey will agree with that. Perhaps he could comment. That may well be the key that one has to pass on to your receptive theorist. It begins to look more and more that way, and I think that's something perhaps we should be focusing on and trying to sort out and in that sense it's related to exactly what you show in the jets. Maybe you'd like to comment on that.

Kaplan: To support the concept of the anti-cascade we don't need more data. We need a new poem.

R. S. Brodkey, The Ohio State University: One comment first, on the triggering by conditional analysis in a pipe. It is a nice problem because the slug of turbulence fills the region and you're really looking at a front or back edge. Unfortunately, in working close to the wall, we not only have a time randomness but there is also a space randomness. With a fixed probe, you may be hitting an event straight on, hitting a weak event, or just clipping an event; thus, the problem is much more difficult. There is a lot of work to be done in the wall region in eliminating the jitter by a better understanding of conditional sampling techniques.

With regard to shear layer instability, the work that Kline was referring to is the recent Journal of Fluid Mechanics paper by Nychas, Hershey and Brodkey. In the article we called it a Kelvin-Helmholz instability. None of the reviewers suggested calling it anything else, so we left it that way.

What you see in the wall region are thin shear layers where a higher speed fluid is overriding a low speed fluid. The interface between becomes unstable and starts rolling up, but without the regularity one sometimes sees in jets. Often one of these forms and then at times two or three form in a line. The whole structure disappears because it gets mixed as it moves downstream. I would like to emphasize what Kaplan pointed out. It is absolutely essential to move with the flow to see this. You can't identify them from a stationary hot-film trace very easily. The way we finally identified them in signals was to plot point-by-point from our movies the velocity vectors. Then we computed what the velocity should look like when transposed to a stationary probe from the movie. This was done for about 5 such structures that we had identified in the movies. Then with that we went to the anemometry traces and could pick them out. One does not see the organization in the hot-film traces until one knows what to look for. What this is is an effort to tie anemometry work to visual studies. There is a great deal more to be done to help us identify what a fixed probe is seeing. This work is progressing at MPI at Goettingen by the Nychas team (he and she), Wallace, Eckelmann, and myself.

H. M. Nagib, Illinois Institute of Technology: I should comment that if you drive the pairing process, if you imagine a street of vortices all of the same sign, there's no reason to pair. They are in static equilibrium, it's an unstable equilibrium but they are static equilibrated. If you disturb the situation, then two vortices will tend to pair with the strongest neighbor; then once you break up the uniformity, then the pairing process proceeds. So initial irregularities are necessary for the turbulent shear layer to develop. If you drive the initial shear layer by a vibrating ribbon, making all of the vortices of the same strength, the pairing process is inhibited and the shear layer is prevented from growing and then ultimately the growth takes place further downstream. And I think this is easier to do in the shear layer - because you can use the straight vibrating ribbon - than you can with the jet. But we're trying an experiment similar to that in the jet to help prevent the growth. This was also seen in hypersonic flow in the wake of a flow by Jim Kendall.

Wygnanski: I would like to make a comment related to Prof. Brodkey's comment. I am aware that in boundary layer it is very difficult indeed to locate an event. I think that one could precipitate an event by tickling the boundary layer locally by either sparking it or otherwise. We are facing similar problems in studying transition on a flat plate. The turbulent spots occur naturally at random in time and space, however by sparking the laminar boundary layer there is at least the possibility of aligning the spots. There is however a question that keeps arising, are the artificial spots identical to the ones occurring naturally, or do they depend on the disturbance which generated them? We answered this question for the transitional pipe flow case. The puffs occurring naturally in this flow are identical in every respect to the puffs created artificially. We dared to extrapolate this conclusion to the boundary layer case and it remains to be seen if it holds.

K. J. Bullock, University of Queensland: I too think it is very difficult to find an event deterministic in space, time or amplitude in the boundary layer because I do not really believe that they exist. I think nothing this morning contradicts a stochastic wave like interpretation, and I just wish to add a comment or two about some of the work we have done. I agree that the U-velocity is well coordinated across the whole boundary layer and that the phase shifts in y, as was interpreted from some of the measurements. In fact, if you separate out the transverse wave number of significant components you can get a strong correlation of U over a very extensive range of the Y from the wall layer to about $y^+ = 400$. The correlation coefficient will be greater than 0.7 for most components and as high as 0.9 for the large scale structure. Thus there is a very strong coordination in the Y-direction, as is evident in the traces that you had. Some of the instantaneous traces that you have taken in the velocity profile are just the result of wave combinations which you will expect to get from time to time randomly distributed in space. I was a bit confused in the very last diagram that you showed. You seem to indicate that an ensemble of the velocity profile was different from the time average and perhaps you might just comment on that. Secondly, in one of the earlier diagrams where you had three X-positions, you were saying you had what you thought might have been a wave-like phenomenon. Later on it looked as though some of the peaks were not where they should have been. Is this not an amplitude modulated system where the modulation is stochastic, producing something like a beat phenomenon?

Kaplan: It's not an amplitude modulated system. I should comment that the concept of conditional sampling and conditional correlation is not all that theoretical. It is an acceptable statistical practice although we may hoke up our condition a little more than is the acceptable statistical practice. We are trying to bias the sample so we can look at the structure of what we call "events". We find that when we go very far away from our time origin in the events, we do indeed find the time average again, i.e. (unconditional) the long-time-average.

G. K. Patterson, University of Missouri-Rolla: I was wondering if there were any prognostications on the reasons for the damping of the spreading of the jet or the inclusion of fluid in the jet when you have a stratified fluid.

Kaplan: Well, it is stably stratified and the mixed region then would have a lower density. When the fluid is injected from the turbulent region to the non-turbulent region the density is different and since it is stably stratified, the density difference is such that it would tend to present further intrusion. It's quite natural and what one would expect.

Kibens: A very similar thing happens if you have a heated wake coming off a flat plate. You find that it becomes very one-sided because any puffs that go down toward the bottom get pushed back up, and the ones that go up keep on going up.

V. W. Goldschmidt, Purdue University: I wrote a poem -

An Ode to Cascade

First turbulence random was made
And spectra promptly measured
And eddies lovably treasured
All giving an impressive cascade

Suddenly structure was paraded
Spots, bursts and sweeps were sketched
And after conditioning we anti-cascaded
For older models could not be stretched.

Now we wonder if structure was originally made
Or whether the turbulence did come first.
Could it be there's a scale of cascade
And another for the nasty, tricky burst?