NEW TRENDS IN EXPERIMENTAL TURBULENCE RESEARCH

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John Laufer
Department of Aerospace Engineering, University of Southern California,
Los Angeles, California 90007

1 INTRODUCTION

In the past few years some novel statistical techniques and significant observations have been made in the search for a better understanding of the turbulence problem. These efforts have spearheaded what is believed to be a new trend in turbulence research. In this review an attempt is made to describe this new direction in a qualitative way, to place it in a proper historical perspective, and to assess its significance.

Taking a brief, rather cursory glance at the manner in which experimental techniques have influenced prevailing ideas on treating turbulent flows over the past fifty years, one may recognize several fairly distinct periods of activity. The twenties and thirties were rich in ideas that tried to rationalize the concept of a turbulent viscosity coefficient. Mean velocity measurement was the primary experimental method available at the time and was extensively used to establish the advantage of one theory over another. While no conclusion could be reached on this point, the measurements gave some support to phenomenological approaches, including similarity arguments for helping to solve practical problems, but they served essentially as a passive tool.

By the forties, the hot-wire technique for the measurement of velocity fluctuations was sufficiently developed that the various components of the Reynolds stress could be obtained with confidence. This development made it possible to test the assumptions of the various phenomenological theories more directly. The result was a complete rejection of these theories. On hindsight, this proved to be a rather ironic turn of events: Later results using more sophisticated statistical techniques developed in the early sixties gave some (although not well understood) support to the turbulent viscosity concept; furthermore, it turned many researchers' attention away from shear-flow turbulence to the "simpler" but more academic problem of homogeneous turbulence.

With further improvement of the hot-wire technique and associated electronic instrumentation, subsequent experiments in the fifties concentrated on studying the spectral distribution of the turbulent kinetic energy with a particular emphasis spent on the fine-scale structure of turbulence. Concurrently, the relative importance of the various rate terms occurring in the turbulent energy equation was investigated. A number of instructive results came to light concerning these questions, but unfortunately these modes of inquiry did not help clarify the basic question of how turbulence generates and maintains itself. Nevertheless, attempts to obtain higher- and higher-order correlations and higher moments of the power spectrum continue without a guiding purpose in mind.

In the past ten years two important observations were reported that had significant impact on subsequent turbulence research (Kline & Runstadler 1959, Brown & Roshko 1971). Ironically, these were made not by sophisticated electronics instrumentation, but visually with rather simple optical techniques. The essence of these observations was the discovery that turbulent flows of simple geometry are not as chaotic as has been previously assumed: There is some order in the motion with an observable chain of events reoccurring randomly with a statistically definable mean period. This surprising result encouraged researchers to reexamine the line of inquiry for designing their experiment, and they began seriously questioning the relevance of some of the statistical quantities they had been measuring. It was soon realized, for instance, that retaining some phase information in the statistics and obtaining more detailed spatial information are essential for a quantitative explanation of the visual observations. This of course became possible only with the rapidly developing computer techniques of today. Considerable progress has been made, especially in the utilization of digital techniques, which are proving to be most useful in the study of the quasi-ordered motion. While the new information about these structures is rather incomplete, it is most interesting and is responsible for initiating the trend referred to earlier. The main purpose of this review is to describe this new trend by bringing together some of the still fragmentary information about these structures from presently available sources and to speculate about its impact on our continuing search for understanding of turbulent flows.

2 QUASI-ORDERED STRUCTURES

The discovery of a relatively sharp interface between turbulent and nonturbulent fluid (Corrsin 1943) and, in particular, the subsequent study of its spatial behavior (Corrsin & Kistler 1954) with its characteristically long wavelength provided the first indication of the existence of large-scale structures in a turbulent shear layer. However, it was primarily the work of Townsend (1956) that emphasized the important role these structures play in the development of a turbulent flow. His introduction of the double structured nature of turbulence is believed to be still a very useful concept, and his "dynamic equilibrium of the large structures" is considered still a very attractive working hypothesis for fully developed turbulent flows. However, the relatively strong coherence or ordered nature of these structures was not suspected at the time these ideas were formulated. Information about them was very scant and had to be based on available experimental data, in particular on two-point velocity correlation measurements. On hindsight, one realizes now that the interpretation of such measurements in terms of spatially coherent structures can be quite misleading. Since these structures generally have a history of development as they are convected downstream, observations at one or two spatially fixed stations will include realizations of a large number of structures at various stages of their life history. Time and space averages of such observations will tend to "smear out" their essential features. This smearing-out effect was illustrated using more sophisticated statistical measurements in a viscous sublayer by Gupta et al (1971).

It was the Stanford research group that first realized that measurements at a few points fixed in space are insufficient to obtain comprehensive information about turbulent flows. They have successfully combined various visual observations with simultaneous quantitative velocity measurements that enabled them to study the development in time of spatially coherent patterns (Kline et al 1967, Kim et al 1971). Two most important results emerged from their work: first, the realization that certain significant events occur in the flow with a fairly sharp definable statistical mean period; and second, the discovery that these events are but a portion of the temporal development of quasi-ordered structures that move downstream in the boundary layer. The results implied that the notion of a random velocity field simply superimposed on a mean flow had to be reexamined (Offen & Kline 1974).

A second and perhaps more startling discovery was made by Brown & Roshko (1971) who again, by visual observation, noted the presence of large-scale, two-dimensional vortices in a fully turbulent two-dimensional mixing layer (Figure 1). Their result was surprising not only because these structures appeared easily detectable in their shadow photographs, but also because they clearly retained their coherence in the lateral direction, that is, retained their two-dimensionality on the large scale. It should be emphasized that previous investigators had thoroughly studied mixing layers (see, for instance, Liepmann & Laufer 1947), measuring what at the time were believed to be all the relevant statistical quantities, without providing even a hint about the existence of these nearly two-dimensional structures!

Subsequent experimenters have specifically searched for the quasi-ordered

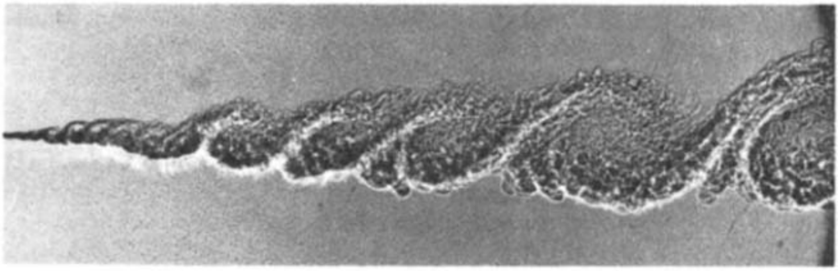


Figure 1 Shadowgraph of a mixing layer produced by helium (upper side) at $U_1 = 1015$ cm/sec and nitrogen at $U_2 = 384$ cm/sec at a pressure of 8 atm. Courtesy of A. Roshko, California Institute of Technology (private communication).

structures. Indeed, observations in the initially developing circular turbulent jets did show the existence of turbulent vortex rings (Laufer 1974, also see Figure 2), and more recently Papailiou & Lykoudis (1974) detected the presence of large-scale vortices in a two-dimensional turbulent wake (Figure 3).

In fact, more and more evidence is accumulating, at least in simple shear flows, that points to the existence of spatially coherent structures and implies that temporal behavior of these structures has a strong bearing on the development of the whole turbulent flow. In the next section a more detailed kinematic description of the quasi-ordered motion in several types of shear layers will be given.

3 KINEMATIC CONSIDERATIONS

As indicated earlier, spectral and correlation measurements gave some indications in the past that large-scale motions do exist in a turbulent flow in addition to the fine-scale turbulence. (See, for instance, Favre et al 1958.) However, the description of these motions was thought of in purely statistical terms (Lumley 1967). Recent observations show, on the other hand, that at least over a certain limited time period they are deterministic; that is, they have a characteristic shape, size, and convective motion that can be determined within a relatively small standard deviation. Of the various detection schemes employed so far, the use of dye technique gives the clearest evidence of the presence and behavior of these

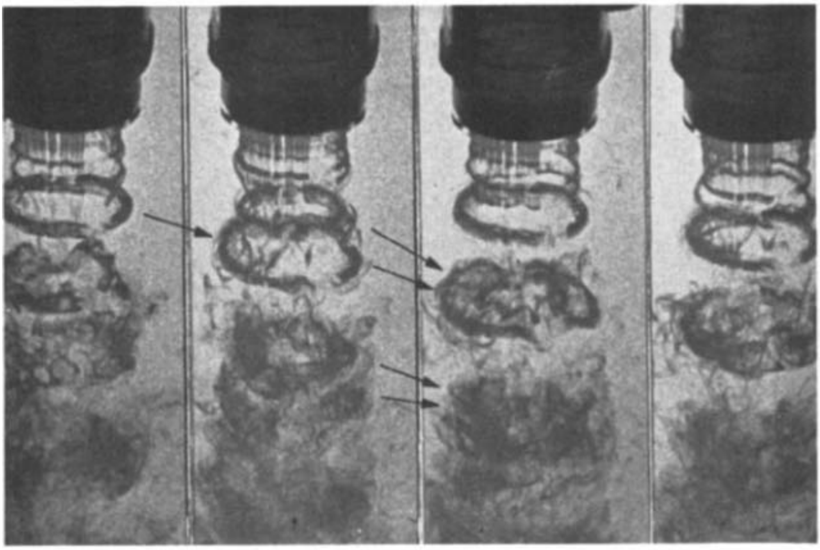


Figure 2 Time-sequence pictures of a circular jet in water. A dye is introduced near the exit of the nozzle. Diameter = 3.75 cm; Re $\approx$ 9000. Arrows indicate coalescing vortex rings. Courtesy of F. Browand, University of Southern California.

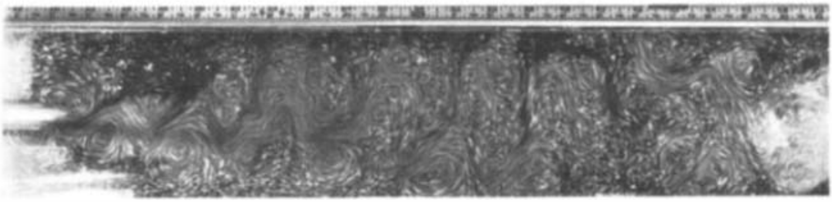


Figure 3 Large-scale structures in a wake behind a cylinder (diameter = 0.953 cm) moving in mercury with a velocity $U = 7.06$ cm/sec (Re = 5850). Exposure time is 1 sec; dimension is one fifth of actual scale. Courtesy of Papailiou & Lykoudis (1974), Cambridge University Press.

structures. Since the interpretation of dye markings may be misleading, vorticity measurements suggest themselves as the most promising method for a quantitative study of the ordered motion. Unfortunately, there are several serious difficulties with this method: 1. direct measurement of vorticity has not yet been successfully accomplished with sufficient accuracy; 2. single-point measurements are inadequate; and 3. following the vorticity-containing fluid in a Lagrangian sense is intrinsically difficult. Nevertheless, considerable progress has been made recently on visual as well as quantitative studies of these structures, especially in a two-dimensional mixing layer and in a boundary layer, using new statistical techniques.

3.1 *The Mixing Layer*

Figure 4, obtained by Winant & Browand (1974), gives an excellent description of the generation and development of the quasi-ordered structures. High-velocity water flow (bottom side of the film strips) mixes with a lower-velocity stream behind a thin splitter plate. The initial vorticity layer is very thin (less than 1 mm); its oscillation is clearly observable on the top strip. The frequency of oscillation corresponds to the most amplified one calculated by the linear stability theory. As the oscillation amplitude increases, the initially uniformly distributed vorticity in the shear layer tends to concentrate into two-dimensional lumps. This tendency toward vorticity concentration is believed to be a typical phenomenon in developing shear flows. The schematic diagram of Figure 5 indicates the successive stages of the initial vortex development taken from Winant & Browand (1974). The strips of films in Figure 4 are arranged in such a way that pictures of the same vortex are exhibited one below the other, emphasizing its time history. In this manner, the two-dimensional vortical lumps are seen to interact: The coalescing of two or occasionally three neighboring vortices becomes clearly visible. Such an interaction between vortices is an essential mechanism responsible for the spreading rate of turbulent mixing layers. This is also evident in the early development of a round jet (Figure 2) and in a two-dimensional jet (Figure 6).

3.1.1 THE DISTRIBUTION OF VORTICITY IN QUASI-ORDERED STRUCTURES

The dye pictures (Figure 4) adequately illustrate the general behavior of these structures, but provide no quantitative information about them. Recently, Browand & Weidman (1973) succeeded in obtaining the vorticity distribution in the flow field with a clever conditional sampling technique. They measured the instantaneous lateral

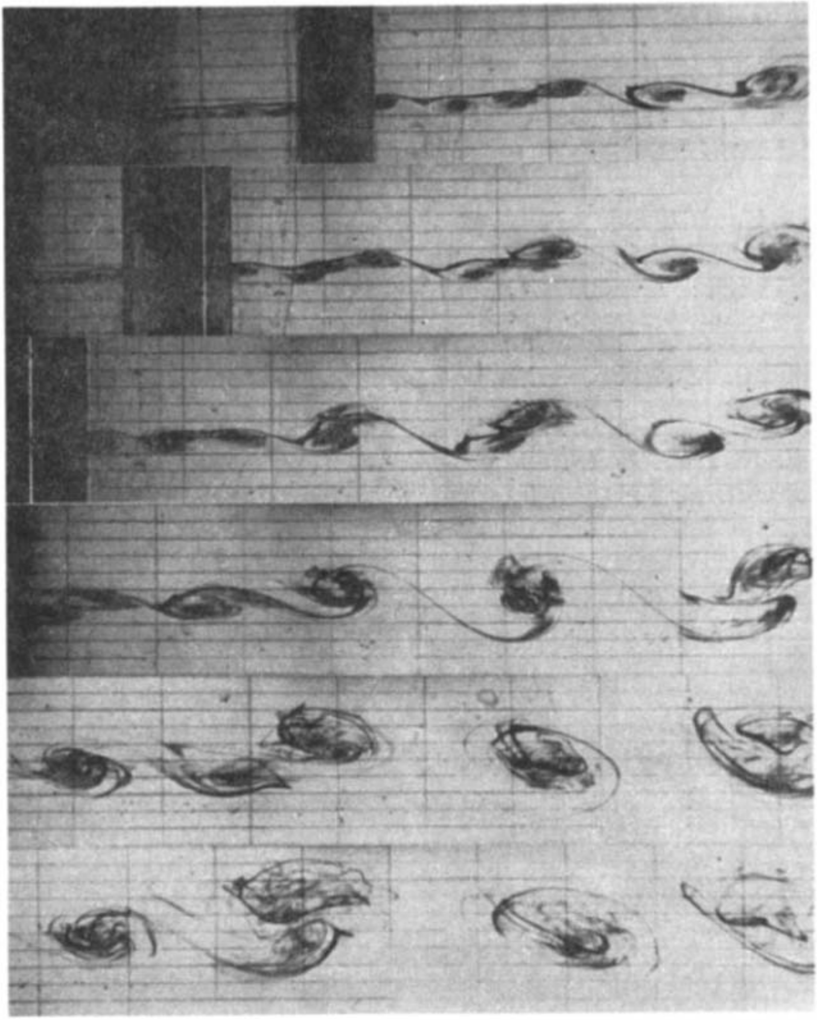


Figure 4 Sequence of photographs showing vortex coalescence. Heavy dye line marks (center of) the shear layer. Upper line is dye injected just above shear layer. The velocity of the upper layer is 1.44 cm/sec and that of the lower layer is 4.06 cm/sec. The camera is moving with the mean velocity, 2.75 cm/sec. Background grid spacing: horizontal lines = 0.5 cm; vertical lines = 2.54 cm. Courtesy of Winant & Browand (1974), Cambridge University Press.

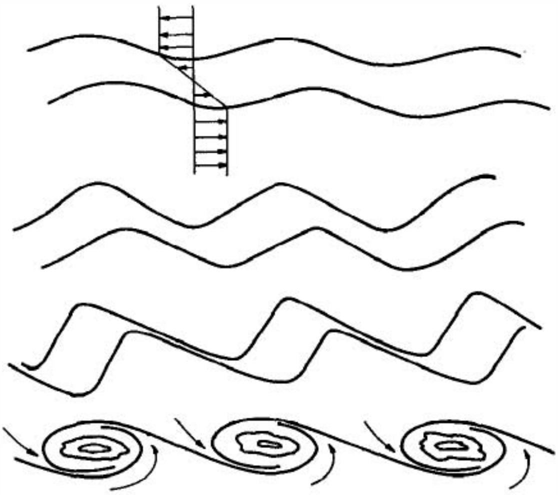


Figure 5 Schematic of the initial instability of the shear layer and the rollup into discrete vortices. Courtesy of Winant & Browand (1974), Cambridge University Press.

vorticity component at a given point only at instants when two neighboring large-scale vortex structures happen to be in a predetermined position with respect to each other, and then formed an ensemble average. Figure 7a shows lines of constant vorticity after a pairing and Figure 7b depicts the vorticity distribution during the pairing process. As expected, the highest vorticity is located in the center region of the large structures.

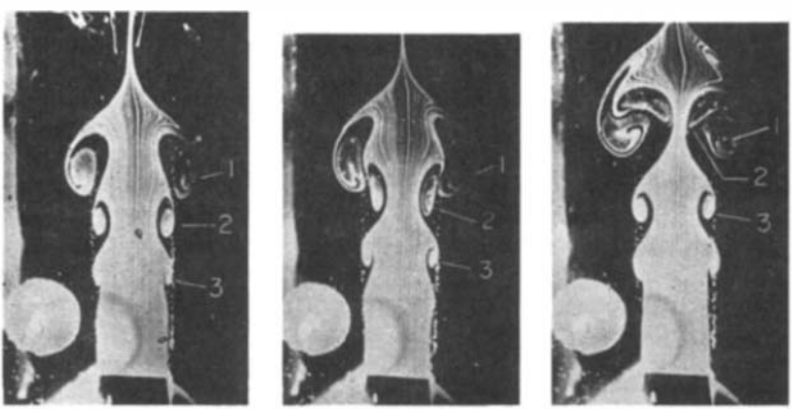


Figure 6 Time-sequence photographs of a two-dimensional jet in water. Nozzle exit width is 2.54 cm with an aspect ratio of 3:1. Re ~ 1860. The coalescence of vortices designated by 1 and 2 is clearly visible. Courtesy of Rockwell & Niccols (1972).

Another characteristic feature of these structures is that they contain surprisingly sharp (unmixed) sheets of vorticity. Figures 7a and 7b do not exhibit these because of the limited spatial resolution and the standard deviation of the averaging process inherent in the measurement. However, the sheets can be effectively recognized using a passive contaminant. For instance, a typical shadowgraph of two neighboring vortices is shown in Figure 8 by using two streams of slightly different density in the facility described by Winant & Browand (1974). The sheets of relatively large density gradients (actually second derivatives of the density) can be easily recognized in spite of the fact that the picture is somewhat distorted because of the spatial averaging along the optical path across the water tank. Brown & Roshko (Figure 1) used nitrogen and helium, which also showed the sharp density fronts.

Sunyach (1971) mixed two streams of slightly different temperatures and used a temperature rake to record the instantaneous temperature variations with time in the mixing zone. Figure 9 shows results with the rake in the center portion of the mixing zone. The presence of unmixed, thin layers with sharp temperature gradients is quite obvious. Knowing the relative lateral position of these layers

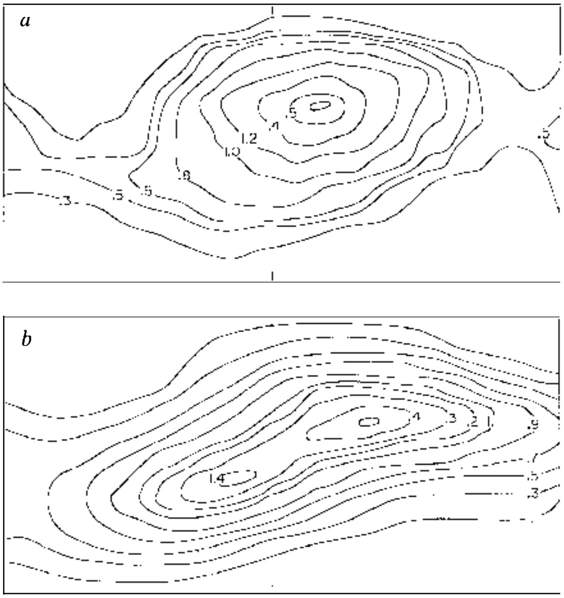


Figure 7a,b Lines of constant vorticity in a mixing layer described in Figure 4. The numbers correspond to the conditionally averaged vorticity normalized by the maximum mean vorticity (−3.2/sec) measured at 15 cm downstream of the origin. Courtesy of Browand & Weidman (1973).

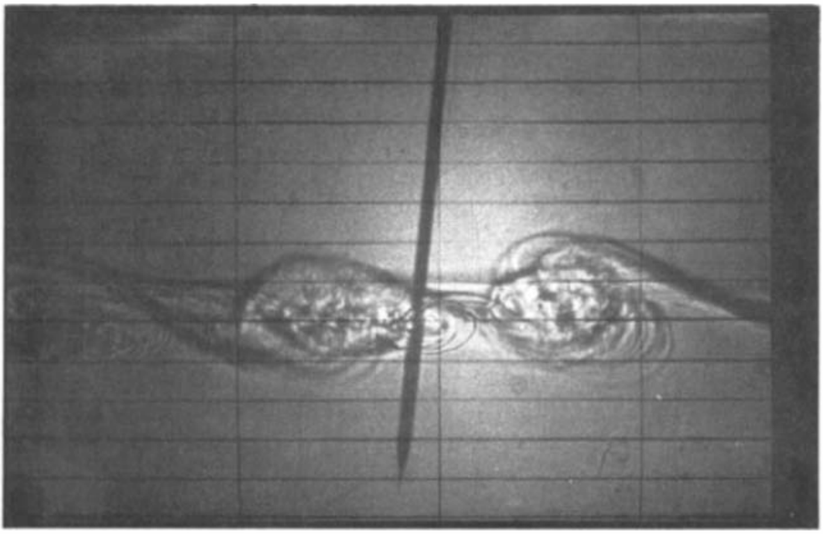


Figure 8 Shadow photograph of the vortex structures in a two-dimensional mixing of two layers with slightly different salinity. The experimental arrangement is the same as that in Figure 4. Courtesy of G. Koop, University of Southern Calif. (private communication).

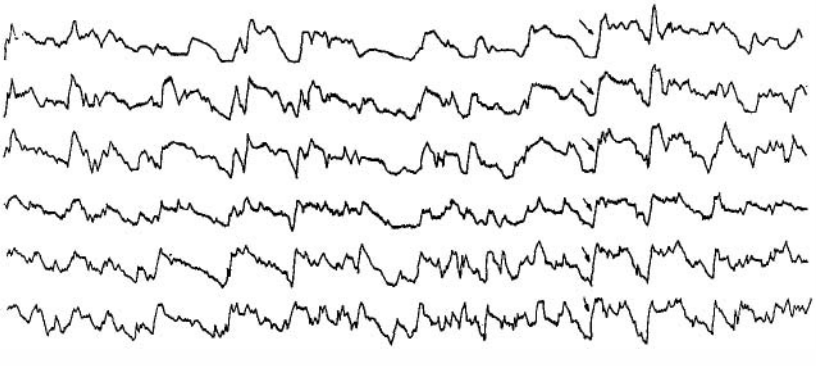


Figure 9 Instantaneous temperature fluctuations in the center region of a two-dimensional mixing layer. The six temperature probes are 1.5 mm apart across the layer and are located 8 cm from the origin. Note the sharp temperature gradients existing across the layer, which are believed to be associated with vorticity layers. (Arrows show one such layer.) The temperature difference between the two streams is 25°C. The high-velocity side corresponds to the lower traces. $U_1 = 1800$ cm/sec; $U_2 = 0$. Time increases from left to right. Horizontal scale: 1 cm = 1/150 sec; vertical scale: 0.1 cm = 2.8°C. Courtesy of Sunyach (1971).

and assuming that they move with the average velocity of the two streams, Sunyach constructed their spatial distribution across the mixing zone. The resulting picture produced layers almost identically shaped to those of Figure 8.

3.1.2 EFFECT OF REYNOLDS NUMBER Since most of the visual observations of the vortex coalescence have been obtained at low Reynolds numbers (Figures 2, 4, 6), one has to raise the question whether this process is also present at high Reynolds numbers. This problem has not been completely resolved, although there is some evidence that the Reynolds similarity hypothesis already applies at the Reynolds number of the experiments in question. In particular, the fact that the geometry of the vorticity sheets described previously is almost identical in the Winant–Browand and Sunyach experiments provides strong evidence. Their Reynolds numbers are two orders of magnitude apart (300 and 30,000). On the other hand, the pairing process in the Brown–Roshko (1971) experiment with a Reynolds number of 250,000 is not as evident (Figure 2), although vortex coalescence is quite discernible in a motion picture they have taken (private communication).

3.1.3 EFFECT OF INITIAL CONDITIONS ON THE DEVELOPMENT OF THE VORTEX STRUCTURES Figure 5 clearly shows that the number of vortices produced in the initial stages (before coalescence) is determined by the frequency of the most amplified wave predicted by the linear stability theory. However, since the vortex pairing process is found to occur randomly both in time and space, the effect of the initial condition is lost after a few pairings. If for instance the initial shear-layer thickness is increased (by increasing the boundary-layer thickness on the splitter plate), the frequency of the initially generated vortices is lowered. However, the rate of vortex interaction, being determined by factors other than the initial frequency, will still produce the same spreading rate, the initial conditions affecting merely the virtual spatial origin x_0 of the mixing layer (Winant & Browand 1974).

The introduction of an artificial periodic disturbance corresponding to the critical frequency (Winant & Browand 1974) also seems to leave the spreading rate unaffected. Observations show that the effect is mostly in delaying the pairing process and consequently changing x_0.

It is to be noted that both of the preceding results are consistent with the classical similarity treatment of the mixing layer. This point is emphasized here, since recently a number of theoretical treatments attempt to analyze the turbulence shear layer from the viewpoint of stability of a periodic disturbance that depends strongly on the initial conditions. (See, for instance, Liu 1974.)

3.2 *The Boundary Layer*

The kinematic description of the quasi-ordered structures in a boundary layer is proving to be much more difficult than that of such structures in a mixing layer. There are several reasons for this: the flow is inherently three-dimensional; there are at least two characteristic length scales in the problem; and the effect of Reynolds number is expected to be more pronounced. Most of the experimental data, visual as well as other types, have been obtained at relatively low Reynolds numbers (in the range $1{,}000 < \mathrm{Re}_\theta < 5{,}000$ approximately) and any conclusions should be viewed with some caution. Furthermore, most of the observations are spatially limited: Visual observations usually cover a cross-sectional surface (Corino & Brodkey 1969, Grass 1971, Nychas et al 1973, Offen & Kline 1974), while velocity measurements at best give simultaneous data along a linear dimension, possibly including one additional spatial point (Blackwelder & Kaplan 1972). There is, in fact, insufficient information available to form a reliable kinematic picture of the flow. Nevertheless, since a large number of publications have appeared in the literature on various aspects of this problem, an attempt is made in this review to suggest a tentative picture consistent with the reported observations. The primary motivation of this exercise is not to come up with a final answer, but rather to point out the least understood phases of the problem and to stimulate further work.

The well-known double-layered nature of the boundary layer is most probably a consequence of the existence of two types of structures: 1. a large-scale vortex-like motion studied in great detail by the Johns Hopkins group (Kovasznay et al 1970, Blackwelder & Kovasznay 1972) and by Kaplan & Laufer (1969); and 2. a wall vortex sheet investigated by a number of groups (Blakewell & Lumley 1967, Corino & Brodkey 1969, Kim et al 1971, Blackwelder & Kaplan 1972, Wallace et al 1972, Offen & Kline 1974, Willmarth & Wooldridge 1962). The two most significant results that first suggested to Laufer & Badri Narayanan (1971) a connection between these two structures are the discovery of certain "significant events" (called bursts) occurring near the wall with a statistically definable mean period (Kim et al 1971), and the finding by Rao et al (1971) that this period scales with the outer flow parameters (that is, the free-stream velocity and boundary-layer thickness) rather than with those of the viscous layer. A possible conceptual

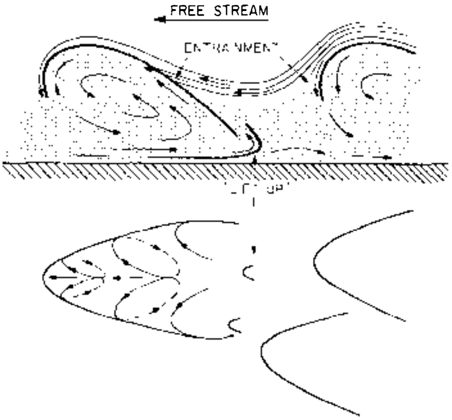


Figure 10 A conceptual picture of a quasi-ordered structure in a turbulent boundary layer in a frame of reference moving with the structure.

picture that presents itself on the basis of these findings may be described roughly as follows: A large-scale, three-dimensional vorticity "lump" is rolling over the wall vortex sheet pulling up with it small-scale vorticity. A schematic view of how this might occur is depicted in Figure 10, drawn in a frame of reference moving with the large structures.

The shape of the large vorticity lumps is suggested by various sources: The conditional sampling experiments of Kovasznay (1970) and Kaplan & Laufer (1969) and the smoke pictures reported by Falco (1974), one of which is shown in Figure 11. The plan view is most speculative and in fact should be used simply as a conceptual guide, as the motion is nonstationary and the small vortex structures near the surface have different time scales from the large ones. The essential points it tries to convey are: 1. the large structures are three-dimensional; and 2. the "lift-up" of the small-scale vorticity, however it may occur and however it may look, has a certain phase relationship with the large scales. This latter point is most noticeable in some recent observations of Chen (private communication) at USC, who used a temperature rake across a slightly heated wall boundary layer and measured instantaneous fluctuations (Figure 12). In order to minimize the effect of the three-dimensionality of the structures as they pass by the rake, a particularly large "bump" recorded by the external-most gauge is selected (see large arrow) under the assumption that this condition provides a higher probability for the rake to produce signals most characteristic of the center region of a bump. The well-documented turbulent-to-laminar interface or vorticity layer can be identified with the steep temperature drop across it on the "back" side of the bump in the outer portion of the boundary layer. The interesting feature to note, however, is that this vorticity layer can be traced deep into the fully turbulent part of the boundary layer where no "intermittency" exists (see downward arrows). The presence and shape of this vorticity layer is clearly seen in the smoke picture

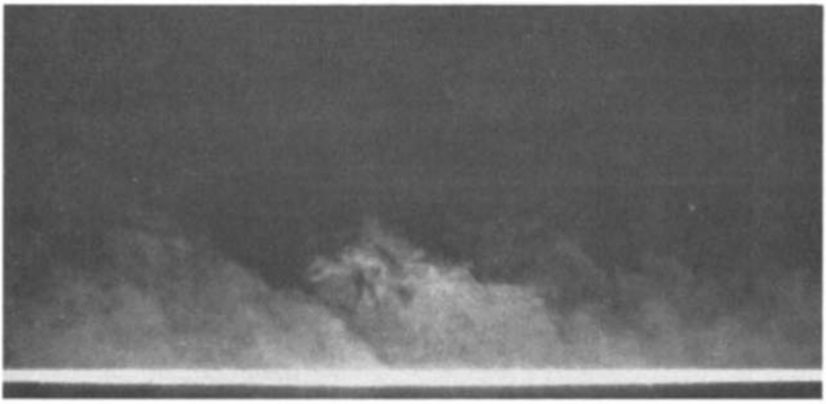


Figure 11 Streamwise slice of the turbulent boundary layer made visible by smoke. Flow is from right to left. $R_\theta \approx 5800$. Courtesy of R. E. Falco (1974).

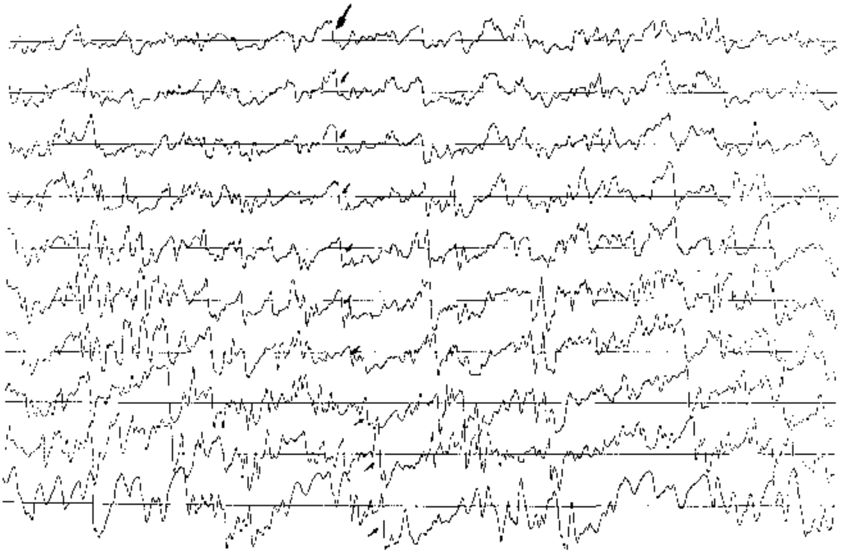


Figure 12 Simultaneous time trace of a ten-wire rake. The wire nearest to the heated plate (bottom trace) is located at a distance of 0.19 cm ($y^* = 25$) from the plate. The wires are approximately 0.64 cm apart. Free-stream velocity is 450 cm/sec; the boundary-layer thickness is 9.4 cm. $R_\theta = 2800$. The plate is 15°C above ambient temperature. Horizontal scale: 1 cm = 47 ms; vertical scale: 1 cm = 5.0°C. Courtesy of P. Chen, University of Southern California (private communication).

of Figure 11 (Falco 1974). Near the wall the vorticity layer is no longer visible, probably because of lateral convective effects. At the same time one detects just downstream (at a later time) another vortex layer originating near the wall (see upward arrows, Figure 12) and extending into the logarithmic region. One identifies this with an uplifted wall vorticity layer (turbulent "burst"). Further, the vorticity layer corresponding to the front of the bumps cannot be traced as far into the boundary layer, presumably because of the three-dimensionality of the large vortex structure.

The important open question in this picture, of course, is why and how the small scale vorticity is "scooped up" by the large structure. Considerable work is in progress on this problem. The most interesting suggestion (as yet unpublished) has recently been made by Kaplan (private communication): The highly strained fluid element in the wall vorticity layer receives additional straining by the large-scale motion. This produces locally a stress condition that the fluid element cannot sustain and a *local* breakdown occurs in a manner that has a peculiar direction determined by the orientation of the principal axes of the prevailing stresses. This idea has been tested on the formation of turbulent spots in the boundary-layer transition process with considerable success. However, Kaplan's work has not been developed sufficiently at this point to warrant further discussion here.

The indication in Figure 10 that a number of "bursts" are occurring under the large vortex lump, first suggested by the author (Laufer 1972), has received some indirect support from a set of novel and most imaginative experiments of Emmerling et al (1973). They were able to obtain simultaneous surface-pressure signatures over an area of about twice the square of the boundary-layer thickness with a fine spatial resolution. They have also identified "significant events" in their measurements and have noted that they occurred intermittently over the surface at an average period consistent with that of other workers. It is hoped that experiments of this type will continue in order to shed further light on the instantaneous behavior of the wall vorticity layer in at least two spatial directions.

3.3 *Jets and Wakes*

As the initial development of two-dimensional and circular jets consists of two parallel and circular mixing layers, respectively, forming around the central potential region, one expects these layers to behave in a fashion similar to that described in Sect. 3.1. Indeed, the vorticity concentration, vortex formation, and vortex coalescence are clearly visible in Figures 2 and 6. However, very little information is available so far concerning the large-scale structures further downstream in the flow.

Even fewer results have appeared in the literature about wakes. The presence

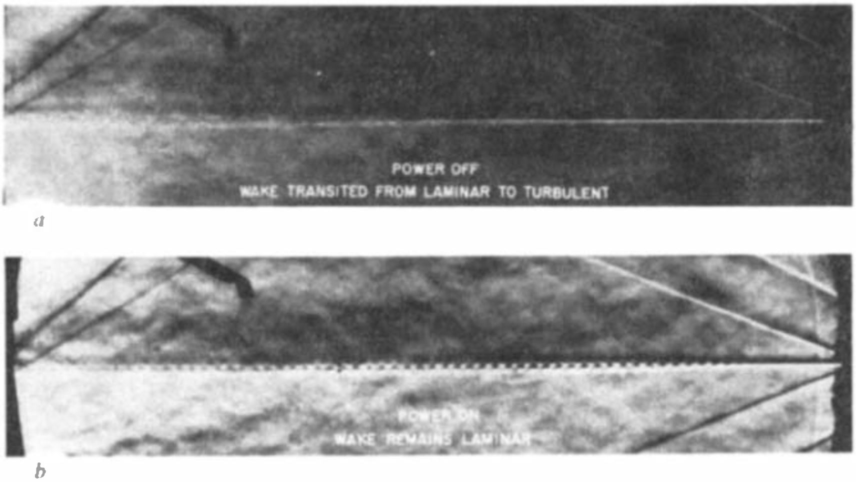


Figure 13a,b Schlieren photograph of the wake behind a flat plate 7.5 cm long, 0.1 cm thick, located on the right just outside of the field of view. (The leading- and trailing-edge shocks are clearly visible.) Free-stream Mach number is 2.4. Stagnation pressure and temperature are 5.4 cm Hg and 288°*K*. Figure 13b shows the effect of an artificial disturbance introduced at the trailing edge of the plate having a frequency of 50 kHz. Dimensions are approximately one quarter of full scale. Courtesy of J. Kendall, Jet Propulsion Laboratory, California Institute of Technology (private communication).

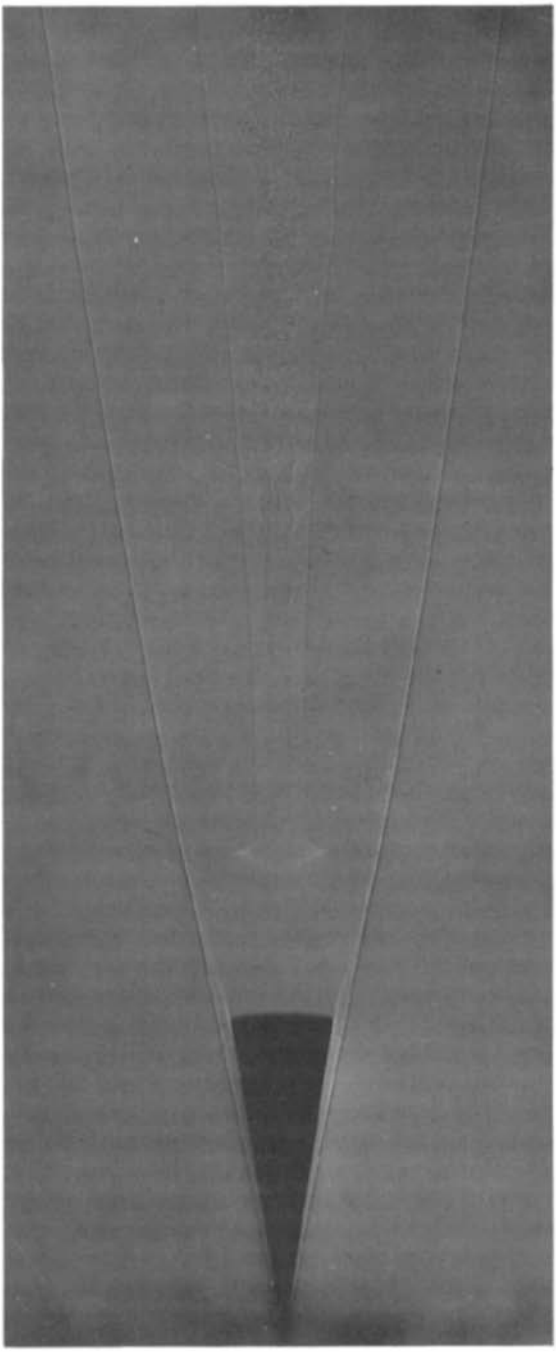
of vortices far downstream of the wake-producing body has already been mentioned (Papailiou & Lykoudis 1974) and the long persistence of large-scale structures has been reported by Oswald & Kibens (1971). There are, however, two most interesting wake observations that are pertinent to this review, each providing additional evidence of the important role the large-scale quasi-ordered structures play in the development of turbulent shear layers.

In an unpublished work, J. Kendall of the Jet Propulsion Laboratory has studied the development of a two-dimensional wake produced by a flat plate in a supersonic wind tunnel (private communication). Figures 13a and 13b show two such wakes under identical tunnel conditions: In Figure 13a the initially laminar wake produced by a thin flat plate grows into a fully developed turbulent one with the expected turbulent spreading rate. A vortex structure in the transitional region is slightly discernible. In Figure 13b a small periodic disturbance (near the most unstable frequency of the layer) is introduced at the trailing edge of the flat plate with a dramatic effect on the wake development. Apparently, by more evenly distributing the vorticity through artificial means in the individual members of the vortex row, their interaction can be minimized and turbulence generation practically eliminated. In a mixing layer with vortices having the same sign, however, this cannot be done (see Sect. 3.1). This is convincing evidence that the development of a wake is basically different from that of a mixing layer (and jet) and is due to the difference in the character of the large-scale structures and in their interaction as already emphasized by Townsend (1956).

The other observation is illustrated by the remarkable shadow pictures (Figures 14a and 14b) made in the ballistic range of the Naval Ordnance Laboratory by Krumins (private communication). In Figure 14a the boundary layer separating from the wake-producing axisymmetric body is a thin laminar one and the development of the turbulent wake is a "conventional" one: The large-scale structures originating from the instability of the laminar wake are visible and are clearly associated with the growth rate of the wake. In contrast to this case, the separating boundary layers and the free shear layers in Figure 14b are turbulent and the wake initially contains fine-scale turbulence only. The generation of the large-scale structures occurs many diameters downstream of the body (not seen in the photograph). Thus, because of the absence of the large-scale structures (evident from the smooth laminar-turbulent interfaces), the turbulent wake has no opportunity to grow in thickness. An attempt to analyze this case has recently been made by Finson (1973).

4 DYNAMIC CONSIDERATIONS

In Townsend's hypothesis, called the dynamic equilibrium of large-scale structures, the large-scale motion plays a central role in the dynamics of the flow development. On the basis of new evidence, this central role seems to be even more pronounced. In fact, there are indications that the large structures dominate the dynamics not only in fully developed, so-called equilibrium turbulent shear layers but also in the



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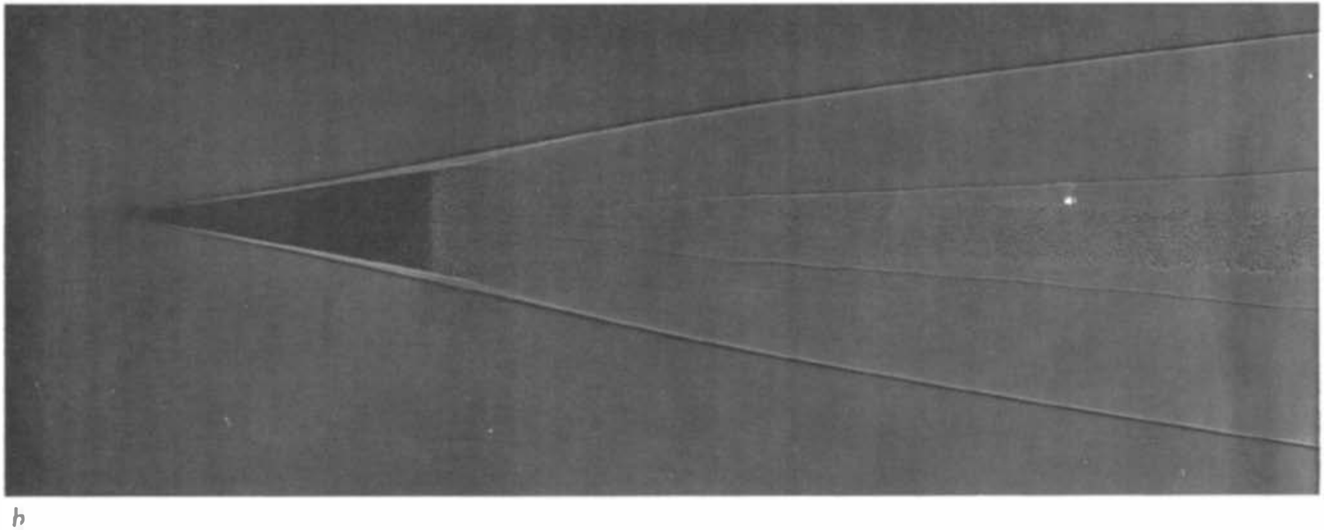

Figure 14a,b Ballistic-range shadowgraphs of wakes produced by a 9° cone (base diameter 2.2 cm) at a Mach number 10. The Reynolds number based on the diameter is 0.63×10^6 for Figure 14a and 4.9×10^6 for Figure 14b. Courtesy of M. V. Krumins, U. S. Naval Ordnance Laboratory (private communication).

early phases of the flow development. This situation is motivating a number of investigators to reexamine the transition problem. A prime example is the beautiful, as yet unpublished experiment of Coles and Barker (private communication) on the flow field and spatial development of a turbulent spot in a transitional laminar boundary layer: Its resemblance to the quasi-ordered structure of Figure 10 is striking and is most likely more than coincidental.

According to Townsend's hypothesis, the flow dynamics is governed by the balance between the rate of energy extraction by the large structures from the mean flow and the rate these structures lose energy to the small-scale turbulence (that is, the rate of turbulent energy production). The new feature that the recently developed experimental techniques bring to focus is the fact that *the turbulence production at a fixed point in the flow is not a continuous process.* The so-called turbulent bursts in the boundary layers and the recent observations of Browand & Weidman (private communication) that turbulent production seems to be phase-related to the pairing process in the mixing layer are two important results to support the above point of view. This is a most important conclusion that will have to be incorporated in any new theoretical formulation of the turbulence problem, as already pointed out in the recent review article by Mollo-Christensen (1973).

At this stage of progress it is too early to speculate in detail about the dynamic aspects of turbulence production and maintenance. However, it is becoming more evident that in formulating the dynamics problem the perturbation of the flow field should not be performed simply on a temporal mean value in the sense of Reynolds, as is usually done in the literature. This inevitably leads to the unproductive closure problem, as important aspects of the dynamics are smeared out in the averaging process. According to the new experimental evidence, the dynamics involves the interaction of a time-dependent, quasi-ordered mode with a small-scale random mode. This, in fact, has been recognized already by Landahl in formulating his "wave-guide" model (Landahl 1972). He gives a wave-like character to the large-scale mode, a point that the author has difficulty in reconciling with observations, especially in the mixing layer. More recently, Kaplan (private communication) is proposing a formulation of the problem in terms of a Langevin type of equation, in which the interaction between a deterministic and a random mode is considered.

5 SUMMARY

This review by necessity is a rather brief and cursory one. It does not attempt to describe in detail the rapidly developing new techniques. Rather, it intends to bring out an inescapable fact rarely evident in the past: Experimental turbulence research of today tends to reflect to a large extent a well-defined specific objective—the study of the nature and dynamics of the so-called quasi-ordered structures. This is undertaken under the assumption that these structures play an essential role in developing turbulent flows. Indeed, more and more evidence is accumulating that justifies this point of view.

The principal difficulty facing this new trend is the development of an adequate measurement technique and statistical method for the study of a nonstationary, convected velocity field. This problem has yet to be solved satisfactorily. One conclusion can, however, be drawn: The measurement of the temporal mean and the standard deviation about that mean of a fluctuating quantity, as well as of conventional correlation or spectral functions, is insufficient for this purpose.

This latter conclusion brings up some interesting questions concerning the present formulation of the turbulence problem. It implies that essential information about the flow dynamics is lost in generating the classical Reynolds equations through a conventional averaging process. It suggests that the formulation will have to reflect more explicitly the double-structured nature of turbulent flows—a time-dependent, lower mode (the quasi-ordered large-scale structure) interacting with a fine-scale randomized motion. It is hoped that the results of the described observations will stimulate further theoretical works along these lines.

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Literature Cited

Blackwelder, R. F., Kaplan, R. E. 1972. XIII IUTAM Meeting, Moscow, *USCAE Rep. 122*

Blackwelder, R. F., Kovasznay, L. S. G. 1972. *Phys. Fluids* 15:1545

Blakewell, H. P., Lumley, J. L. 1967. *Phys. Fluids* 10:1880

Browand, F. K., Weidman, P. 1973. *Bull. Am. Phys. Soc.* 18:1469

Brown, G., Roshko, A. 1971. *AGARD CPP-93* 23:1

Corino, E. R., Brodkey, R. S. 1969. *J. Fluid Mech.* 37:1

Corrsin, S. 1943. *NACA Wartime Rep. W-94*

Corrsin, S., Kistler, A. L. 1954. *NACA Tech. Note No. 3133*

Emmerling, R., Meier, G. E. A., Dinkelacker, A. 1973. *AGARD CPP-131* 24:1

Falco, R. E. 1974. *AIAA Pap. No. 74-99*

Favre, A. J., Gaviglio, J. J., Dumas, R. J. 1958. *J. Fluid Mech.* 3:344

Finson, M. L. 1973. *AIAA J.* 11:1137

Grass, A. J. 1971. *J. Fluid Mech.* 50:233

Gupta, A. K., Laufer, J., Kaplan, R. E. 1971. *J. Fluid Mech.* 50:493

Kaplan, R. E., Laufer, J. 1969. *Proc. Int. Congr. Appl. Mech., 12th, Stanford Univ.* p. 236. New York: Springer

Kim, H. T., Kline, S. J., Reynolds, W. C. 1971. *J. Fluid Mech.* 50:133

Kline, S. J., Reynolds, W. C., Schraub, F. A., Runstadler, P. W. 1967. *J. Fluid Mech.* 30:741

Kline, S. J., Runstadler, P. W. 1959. *J. Appl. Mech.* 26E:166

Kovasznay, L. S. G. 1970. *Ann. Rev. Fluid Mech.* 2:95

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

Landahl, M. 1972. *J. Fluid Mech.* 56:775

Laufer, J. 1972. *Symp. Math.* 9:299

Laufer, J. 1974. *Volume in onore di Carlo Ferrari*, ed. Levrotto & Bella, 435–50

Laufer, J., Badri Narayanan, M. A. 1971. *Phys. Fluids* 14:182

Liepmann, H. W., Laufer, J. 1947. *NACA Tech. Note No. 1257*

Liu, J. T. C. 1974. *J. Fluid Mech.* 62:437

Lumley, J. 1967. *Atmospheric Turbulence and Radio Wave Properties.* Moscow: Nauka

Mollo-Christensen, E. 1973. *Ann. Rev. Fluid Mech.* 5:101

Nychas, S. G., Hershey, H. S., Brodkey, M. P. 1973. *J. Fluid Mech.* 61:513

Offen, G. R., Kline, S. J. 1974. *J. Fluid Mech.* 62:223

Oswald, L. J., Kibens, V. 1971. *Univ. Michigan Tech. Rep. No. 2820*

Papailiou, D. D., Lykoudis, P. S. 1974. *J. Fluid Mech.* 62:11

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

Rockwell, D. O., Niccols, W. O. 1972. *J. Basic Eng.* 94:720

Sunyach, M. 1971. *Contribution à l'étude des frontières d'écoulements turbulents libres.* Ph.D. thesis. École Centrale de Lyon

Townsend, A. A. 1956. *The Structure of Turbulent Shear Flow.* New York: Cambridge Univ. Press

Wallace, J. M., Eckelmann, H., Brodkey, R. S. 1972. *J. Fluid Mech.* 54:39

Willmarth, W. W., Wooldridge, C. E. 1962. *J. Fluid Mech.* 14:187

Willmarth, W. W., Lu, S. S. 1972. *J. Fluid Mech.* 55:65

Winant, C., Browand, F. K. 1974. *J. Fluid Mech.* 63:237