Measurements of intermittency of turbulent motion in a boundary layer

By V. A. SANDBORN
Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio

(Received 22 December 1958)

Previous observations of turbulent motion at large wave-numbers have revealed the existence of an uneven distribution of turbulent energy. The spotty distribution of the turbulent motion at high wave-numbers is here studied experimentally for the turbulent boundary layer. The high wave-number intermittency is observed at all locations through and along the boundary layer from near transition to near separation.

The flatness factors for the longitudinal turbulent component at different wave-numbers are measured to give a quantitative value for the intermittency at particular wave-numbers. Upstream of the separation region the flatness factors are found to depend on wave-number and longitudinal distance, but not on the distance from the wall. It appears that the intermittency develops in the transition region and does not diminish very rapidly with distance downstream. Near separation the flatness factors change radically in distribution near the wall, and are there no longer independent of distance from the wall.

Introduction

Turbulence is one of the least understood branches of fluid dynamics. There is still need for a physically consistent model to describe the fluctuations and without such a model there is little hope of solving theoretically the equations of motion. From both the theoretical and experimental point of view a more detailed knowledge of the structure of the turbulent fluctuations is necessary before an adequate model can be constructed.

The foregoing is not meant to imply that nothing is understood of turbulence. A great deal is indeed known of some of the general features of the turbulent fluctuations. In particular, a very detailed study, both theoretical and experimental, may be found in the literature for homogeneous turbulence. Batchelor (1953) has summarized the present state of knowledge of this particular type of idealized turbulence. The state of understanding in turbulent shear flows is by no means as advanced as the theory of homogeneous turbulence, but certain progress is being made (Townsend, 1956; Klebanoff, 1955). However, none of the theoretical or experimental work is devoted at any length to the detailed study of the structure of the turbulent fluctuations. For the most part, knowledge of turbulence is based on the gross effects and not on an understanding of the mechanism.

The observation of the turbulence mechanism in a boundary layer, or for that matter in any turbulent flow, is very difficult. Direct visual observations in a smoke tunnel or a water channel have been somewhat successful (Hama, Long & Hegarty, 1956; Weske, 1957; Kline, 1957), and as the visualization technique and understanding of the phenomena improve, these observations will shed much light on the flow structure. The hot wire has proved a valuable tool in statistical studies of turbulent flows; however, it is quite difficult to visualize the physical picture of turbulence from a hot-wire trace. For a study of the small-scale, high-frequency motion of turbulence, present flow-visualization techniques are inadequate, and the hot wire must be used.

The present paper presents some experimental observations with a hot-wire anemometer that appear to be of interest in the understanding of the turbulent mechanism, particularly the small-scale high-wave-number features. By electronically examining isolated frequency components of the over-all turbulent signal in the turbulent boundary layer, a lump or intermittent character is observed at the high frequencies. Measurements of the flatness factor of the frequency components were made to give an indication of the extent of the intermittency over the complete frequency spectrum. The physical picture of what is being observed is certainly inadequate; however, the measurements are presented at this time with the hope that they may contribute to the over-all picture of the turbulent structure.

Measurement procedure

Test facility

The data reported herein were taken along the test wall (3 in. above the centre line) of the NACA Lewis laboratory 6- by 60-inch boundary-layer channel described by Sandborn (1953). A diagram of the channels is shown in figure 1. The test wall of the channel is a flat Masonite plate 12 ft. long. The opposite wall is constructed of flexible porous bronze. Suction through the porous wall prevents its boundary layer from interfering with the layer on the test wall. Removable sections are also provided so that the distance between the channel inlet contraction and the test wall can be varied. The widths of the channel between test wall and porous wall for the present test condition are listed in table 1. Sketches of the probes used to survey the boundary layer are shown in figure 2.

Electronic equipment

The constant-temperature hot-wire-anemometer equipment is that described in detail by Laurence & Landes (1952). Details of further modifications to the equipment and the method of evaluating the turbulent fluctuations from hot-wire signals are given by Sandborn & Slogar (1955*a*). A 0·0002-inch-diameter by 0·040-inch-long tungsten wire was used for the present measurements. A commercially available true root-mean-square vacuum-tube voltmeter was used for direct measurement of the hot-wire output. The over-all accuracy of the constant-temperature-anemometer system is compared with the conventional constant-current system by Sandborn (1955). It was found that the two systems are equivalent for shear-flow measurements.

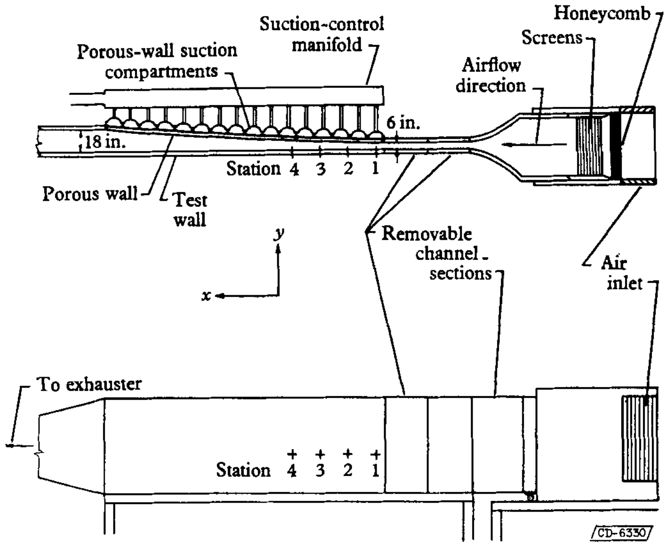


FIGURE 1. Diagram of 6- by 60-inch subsonic boundary-layer channel.

Station	Distance from contraction (in.)	Channel width (in.)	Pressure gradient, lb./sq.ft. / ft.	Boundary-layer thickness (in.)
	0	6·00	—	—
	10	↓		
	20			
	30			
	40			
Start of channel expansion	44	6·00	—	—
1	49·13	6·05	0·0016	0·9
	50	6·05		
	60	6·2		
2	65·63	6·3	0·0256	1·0
	70	6·4		
	80	7·0		
3	83·25	7·3	0·0294	2·0
	90	7·7		
	100	8·6		
4	100·75	8·7	0·0160	3·3
	110	9·5		
	120	10·3		
5	121·38	10·4	0·0112	5·2
	130	11·2		
	140	12·2		

[Channel height, 60 in.]

TABLE 1. Channel geometry

Commercially available variable electronic filters were used to analyse the contribution to the turbulence signal from various frequency bands. Typical band shapes at various frequencies are shown in figure 3.

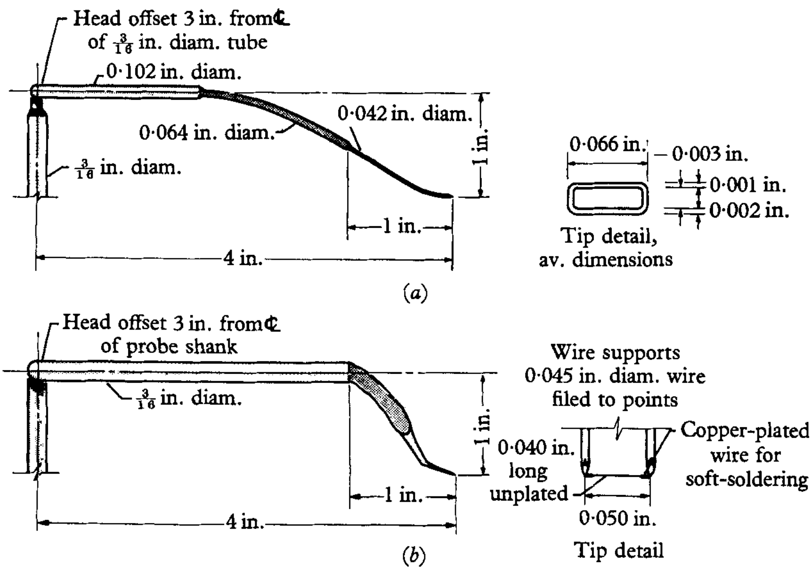


FIGURE 2. Survey probe details. (*a*) Total-pressure probe. (*b*) Hot-wire probe.

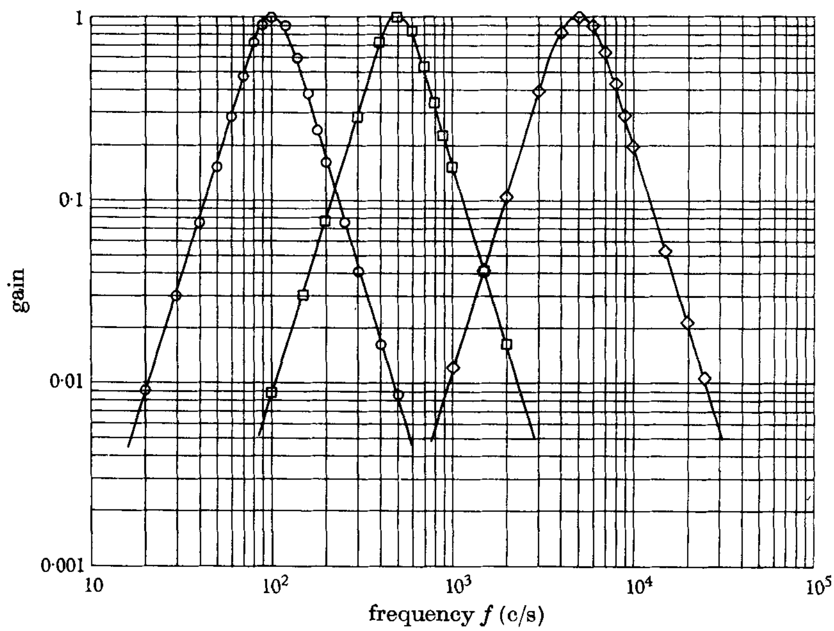


FIGURE 3. Typical bands obtained from band pass filters.

A Philbrick multiplier was employed to obtain the fourth power of the turbulence signal necessary for determining the flatness factor or intermittency. The unit consists of two multipliers, such that the instantaneous squared signal is fed into both sides of the second multiplier. The output of the second multiplier is read directly with a direct-current vacuum-tube voltmeter. A calibration of the multipliers is shown in figure 4. For the turbulence signals encountered in the present analysis it was necessary to operate the multipliers at very low output levels. The low levels are required in order that the very large intermittent bursts of turbulence do not saturate the multipliers. A typical calibration for the low voltage levels made in connexion with evaluating one day's data is shown as an insert on figure 4. The drift of the multiplier is indicated by the two calibrations taken 7 hr apart, as noted on the insert.

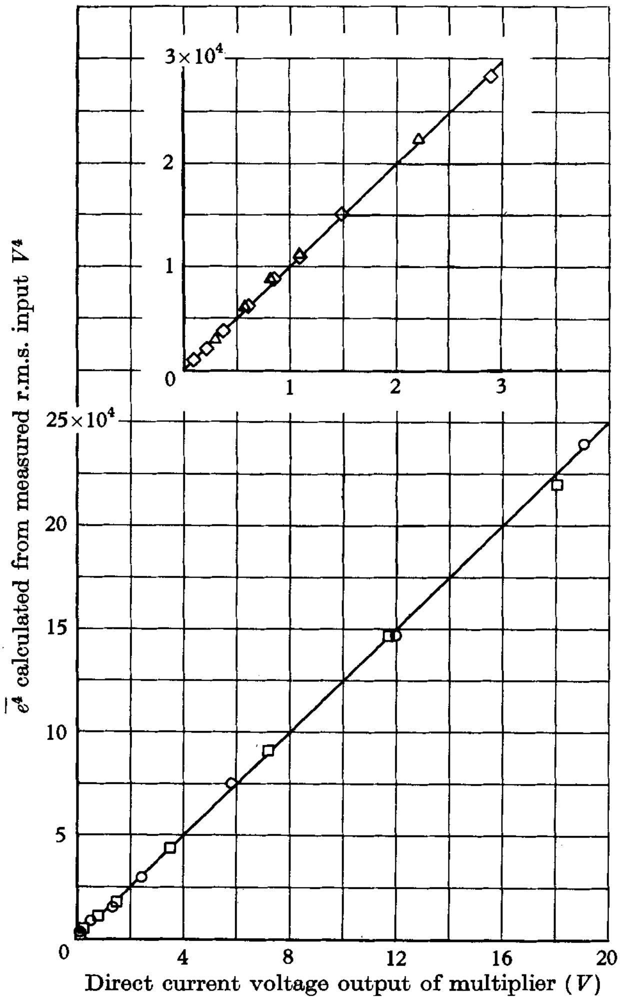


FIGURE 4. Calibration of Philbrick multipliers for obtaining fourth power of hot-wire signal. Typical low-voltage-level calibration: ◇, sine-wave calibration; △, repeat calibration 7 hr apart; ○, sine-wave; □, triangular wave.

With the exception of the values of turbulent intensities, which were obtained from direct readings, all the measurements presented were first recorded on magnetic tape and then analysed from the tape. The tape recorder was accurate for frequencies from 30 to greater than 10,000 c/s (± 2 db from 30 to 15,000 c/s). For the very low frequencies a pen recorder was used to trace the fluctuations.

Results

Intermittency and flatness factor

To study the small-scale features of the turbulent motion with a hot wire, the large-scale, low-frequency components are removed by using an electronic filter. The wave form displayed on an oscillograph screen after the low frequencies are removed is quite different from what is expected. Instead of being uniformly distributed in time (or space) as it flows past the wire, the small-scale turbulence appears to be contained in quite sharply defined lumps or bursts. The lump character of the turbulence is shown in figure 5. For these particular traces, two electronic filters were employed, so that the traces shown are within a narrow frequency band around the frequency noted (figure 5). The traces are for a very low Reynolds number flow, $1\cdot 9 \times 10^5$ per foot at station 1 (since they can then be more clearly photographed), and may not be the truest representation of the phenomenon at higher Reynolds numbers. Also, the traces shown were arbitrarily selected; thus, the number of lumps implied from the figures may not be exactly representative. (Note that the time basis for each trace does not correspond to any other trace.) The particular y-distances shown in figure 5 were chosen to demonstrate the existence of these bursts throughout the layer and should not be compared for stations 1 and 4.

This uneven distribution of turbulent energy is not characteristic of the usual picture of turbulence. However, there is evidence to suggest that it is quite universal for turbulent flow in general. Batchelor & Townsend (1949) indicate evidence of the same type of intermittency for measurements in isotropic turbulence and for turbulence in the wake of a cylinder.

The lump character of the turbulent motion corresponds to a measurable 'intermittency' in the output signal. Batchelor (1953, p. 184) assigns a value γ as the fraction of time a given signal is turbulent. Thus, γ is termed the intermittency factor. For $\gamma = 0$ the flow is laminar, and for $\gamma = 1$ the flow is turbulent all the time. The original definition of the intermittency factor was given by Townsend (1948). Electronically, it is possible to obtain a measure of γ directly from the hot-wire signal, as was done by Klebanoff (1955); however, such a circuit was not immediately available for evaluating the present data. A second indirect method was employed to determine the degree of intermittency in the present study. Instead of counting the bursts directly, the flatness factor, $\overline{u^4}/(\overline{u^2})^2$, of the hot-wire signals was measured. The flatness factor is an approximate indication of the intermittency. Since the flatness factor may be written as

$$\frac{\overline{u^4}}{(\overline{u^2})^2} = \frac{\int_{-\infty}^{\infty} u^4 P(u)\,du}{\left[\int_{-\infty}^{\infty} u^2 P(u)\,du\right]^2}, \tag{1}$$

where $P(u)$ is the probability of a fluctuation velocity of magnitude u in a band du, it may be seen that $\overline{u^4}/(\overline{u^2})^2$ represents a measure of the extent of the skirts of the probability density curve, since the fourth power weights the large values of u heavily. A burst or large-amplitude-type intermittent signal will affect the

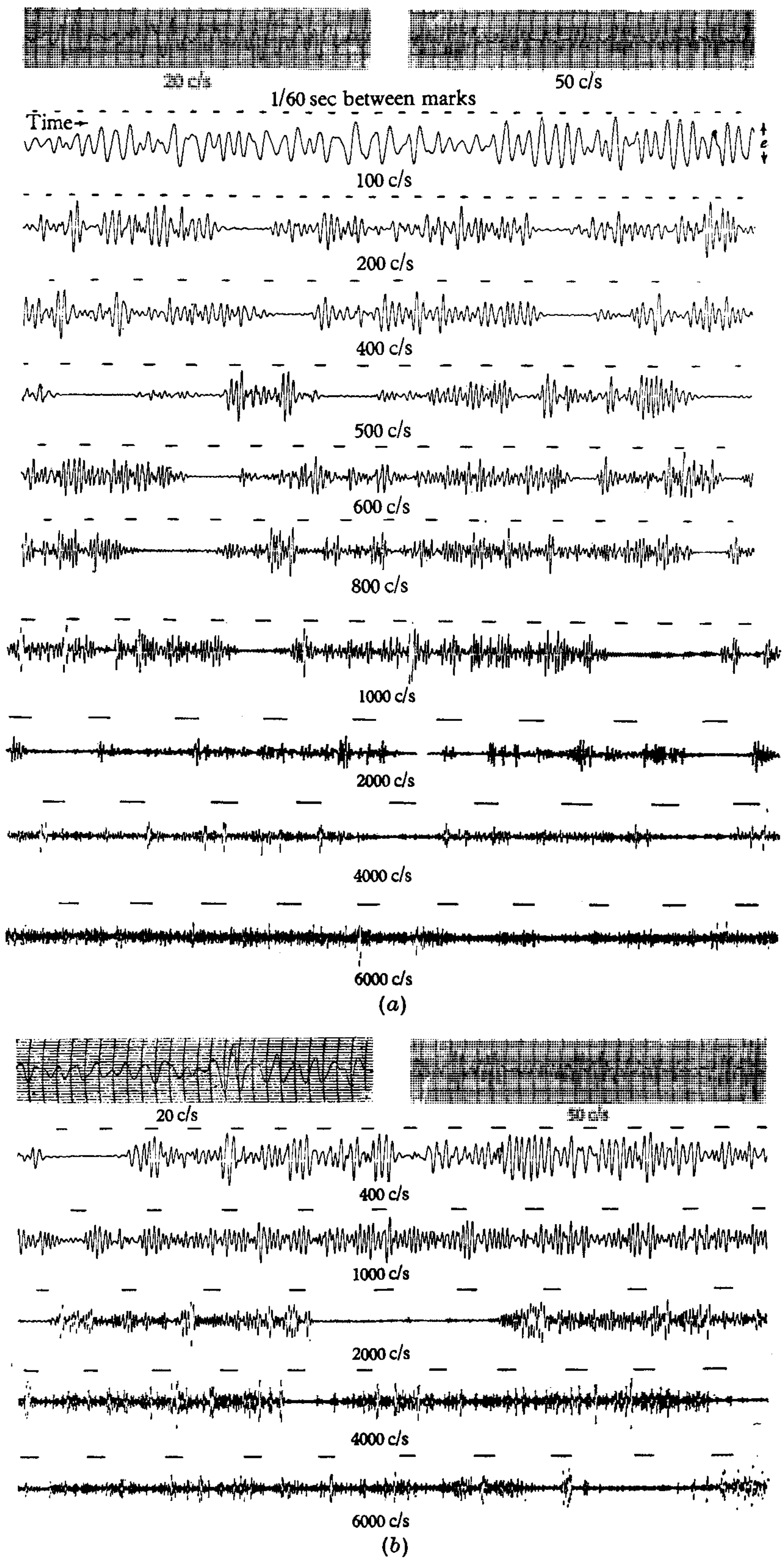
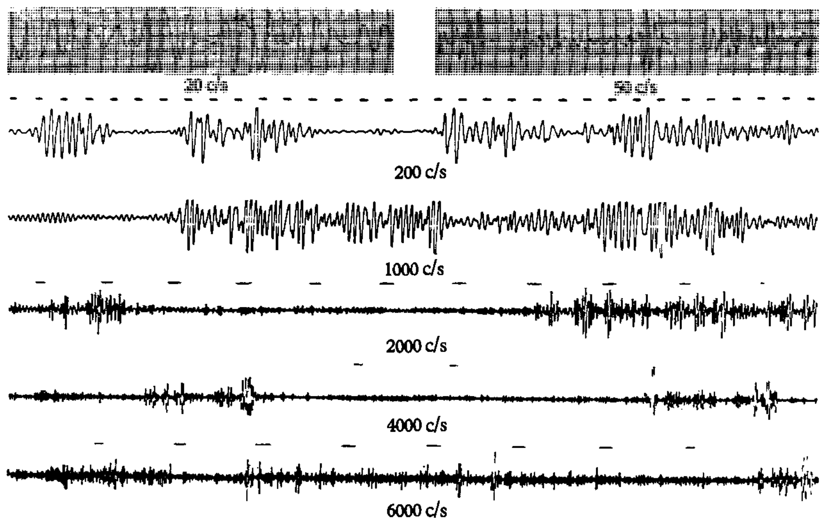


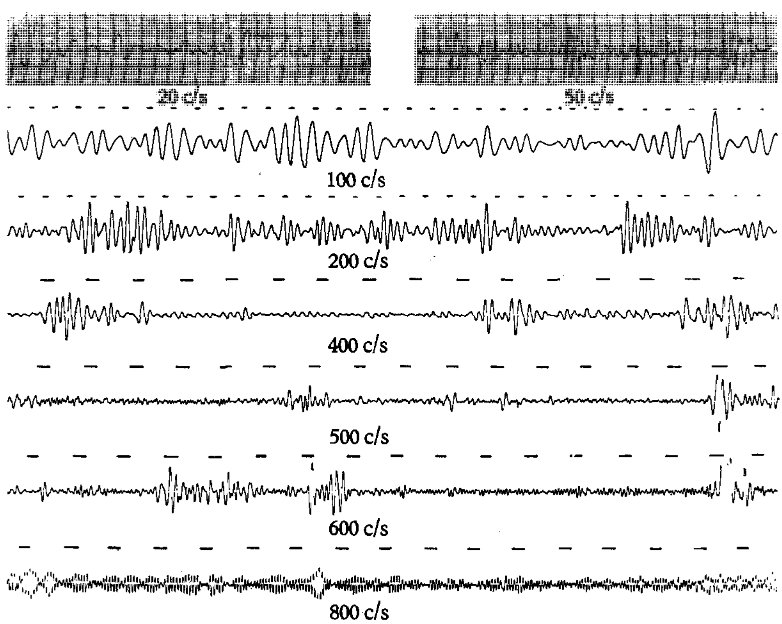
FIGURE 5. For legend see p. 229

skirts of the probability curve greatly; thus, a relation between flatness factor and intermittency is suggested. Batchelor (1953, p. 184) demonstrates that the flatness factor and the intermittency factor may be related for an idealized model of the probability curve. The case considered by Batchelor (a distribution in which the central peak is of infinite height, but encloses a finite area $1-\gamma$), leads to the relation

$$\text{flatness factor} = \frac{3}{\gamma} = \frac{\overline{u^4}}{(\overline{u^2})^2}. \tag{2}$$



(*c*)



(*d*)

FIGURE 5. For legend see p. 229.

This relation comes from the Gaussian distribution values of $\overline{u^4}/(\overline{u^2})^2 = 3$ and $\gamma = 1$. Klebanoff (1955) demonstrated that equation (2) gives reasonable values for the intermittency factor in a boundary layer where the distributions are other than Gaussian.

First observations of the bursts in the high-frequency range were made at the time the measurements by Sandborn & Braun (1956) were carried out. A preliminary set of flatness factors was measured at that time with a simple squaring

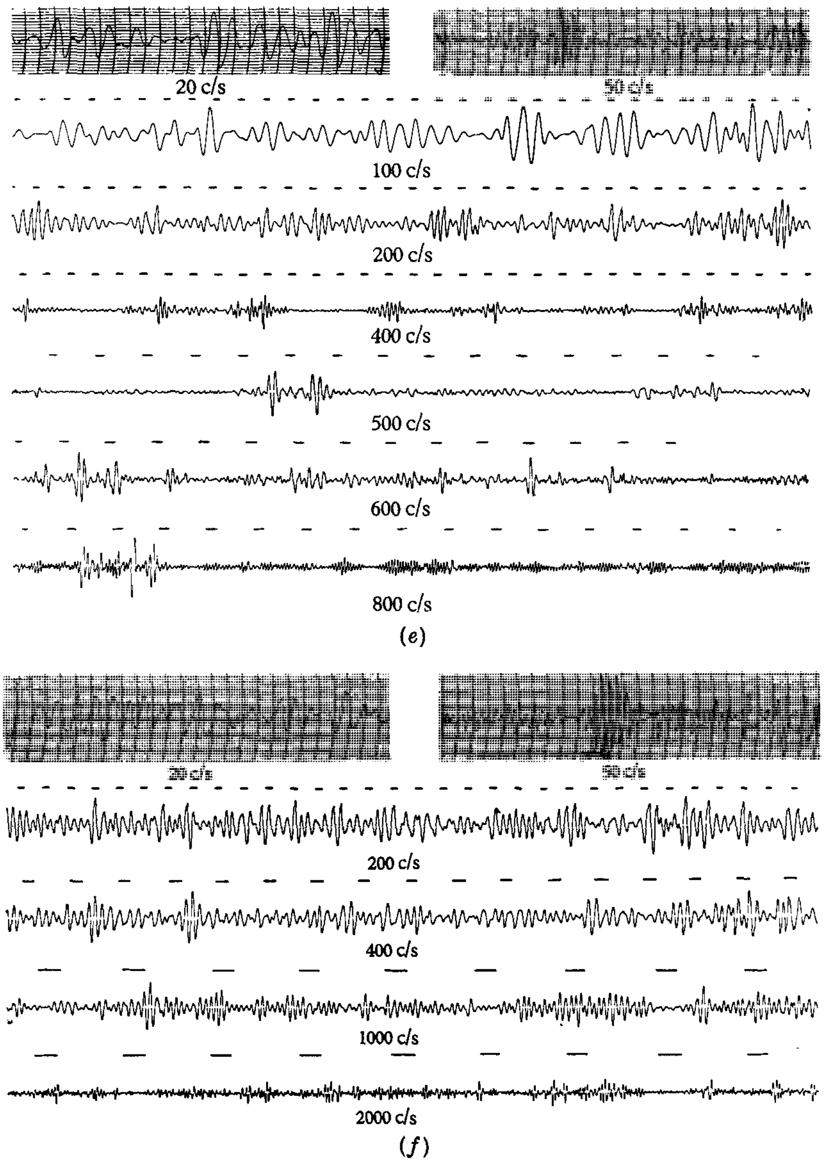


FIGURE 5. Distribution of turbulent fluctuations at various frequencies (amplitude varied between traces). (*a*) Station 1, $y = 0{\cdot}005$ in. (*b*) Station 1, $y = 0{\cdot}100$ in. (*c*) Station 1, $y = 0{\cdot}400$ in. (*d*) Station 4, $y = 0{\cdot}005$ in. (*e*) Station 4, $y = 0{\cdot}010$ in. (*f*) Station 4, $y = 1{\cdot}00$ in.

circuit (similar to one described by Townsend (1947)) and a true r.m.s. voltmeter. The data from these preliminary measurements are shown in figure 6. Only one high-pass filter was employed in the recording of these data. The results confirmed the use of flatness factor to explore the quantitative nature of the bursts, and a more elaborate study was therefore undertaken and is reported in the following sections. The preliminary measurements are included here since they

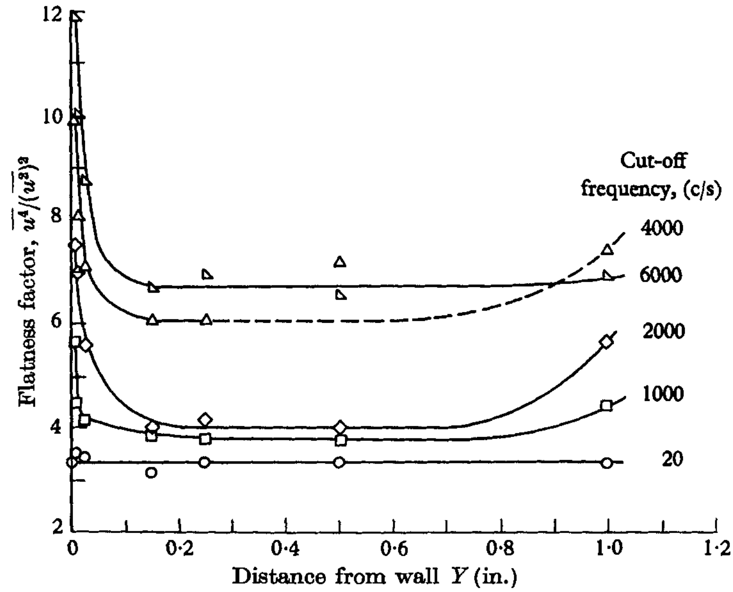


FIGURE 6. Variation of flatness factor with distance from wall and filter cut-off frequency. Data for flow conditions and station 1 of Sandborn & Slogar (1955*b*). (U_1 = 48·6 ft./s., $\partial p/\partial x \approx$ 0·01 lb./sq.ft./ft., temp. = 74° F.; p_{bar} = 29·60 in. Hg.)

are for the rather extensively surveyed flow. (The flow conditions corresponding to figures 6 and 7 must be obtained from Sandborn & Braun (1956) and Sandborn & Slogar (1955*b*), since channel dimensions and flow velocity were changed for the present measurements.) Figure 6 suggests that the sharp rise in flatness factor near the wall might be due in part to the presence of the solid boundary. (Note that the data do not extend out to the intermittent outer edge of the layer, $\delta \approx$ 1·8 in.) However, if the effect of local mean velocity, U, is removed by employing wave number $2\pi f/U$ instead of frequency, f, the flatness factor appears to be nearly independent of distance from the wall (figure 7). (The data beyond 6000 c/s, noted in figure 7 by solid points, departed markedly from the universal curve, but it was thought that the noise level of the electronic circuits caused the deviation.)

Measurements

To obtain a more graphic picture of the intermittency, it was necessary to reduce the flow velocity. The lower velocities in turn lower the frequencies at which the intermittency occurs and thus make it possible to obtain clearer photographs of the phenomenon. Figure 5 shows oscillograph traces for a flow with a Reynolds number per foot of $1\cdot9 \times 10^5$ at station 1 (see table 1). This flow is such that station 1 is just at the end of the transition region, with a very slight amount of bursts observable in the over-all turbulent traces. The flow pressure distribution and boundary-layer development for this Reynolds number are summarized in figure 8. The mean and fluctuating velocity distributions are shown in figures 9 and 10 for stations 1 to 4. The fluctuating velocities are plotted as a ratio of both the local mean velocity U, and the freestream mean velocity U_1. No corrections were made for the high intensities of turbulence encountered.

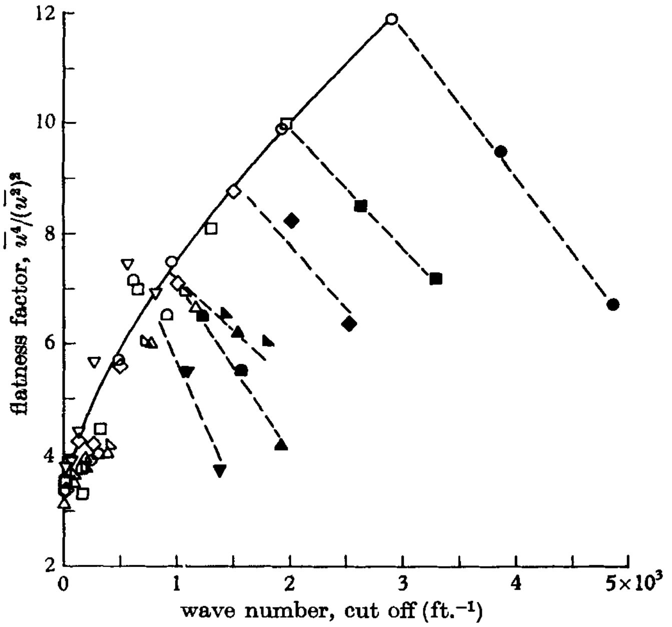


FIGURE 7. Flatness factor at different wave numbers. Data for flow conditions and station 1 of Sandborn & Slogar (1955*b*). ($U_1 = 48\cdot6$ ft./s., $\partial p/\partial x \approx 0\cdot01$ lb./sq.ft./ft., temp. = 74° F.; $p_{\text{bar}} = 29\cdot60$ in. Hg.)

	Distance from wall, Y (in.)	Local mean velocity, U (ft./s.)		Distance from wall, Y (in.)	Local mean velocity, U, (ft./s.)
○	0·005	13	◺	0·250	35
□	0·010	19	▢	0·500	40
◇	0·025	25	▽	1·00	46
△	0·150	33			

Solid symbols for 8000 and 10,000 c/s.

For the very low velocities encountered near the wall there is a question as to how accurately a total-head probe can measure the pressure. Attempts to correct the readings using the correction curve given by Homann (1936) are shown on the mean velocity plots. Comparison of the indicated velocities obtained with a hot wire suggests that a very large error exists in the total-head-probe data near the wall at stations 3 and 4. The values obtained with the hot wire are plotted in figures 9(*b*) to (*d*) and were used in the calculation of wave-number in the analysis. Actually, even the hot-wire measurements may indicate too great a velocity in the region near the wall, since molecular conduction between the wire and the wall causes an excess of heat transfer; however, for the 0·0002-inch-diameter wire this error is small.

The flow conditions are not exactly identical for each station. The complete set of mean velocity profiles and the hot-wire measurements for stations 1 and 4 were recorded during one tunnel run, while the hot-wire surveys at stations 2 and 3 were recorded during another run. A check between the hot-wire data for mean velocity and the total-pressure data at stations 2 and 3 shows a slight

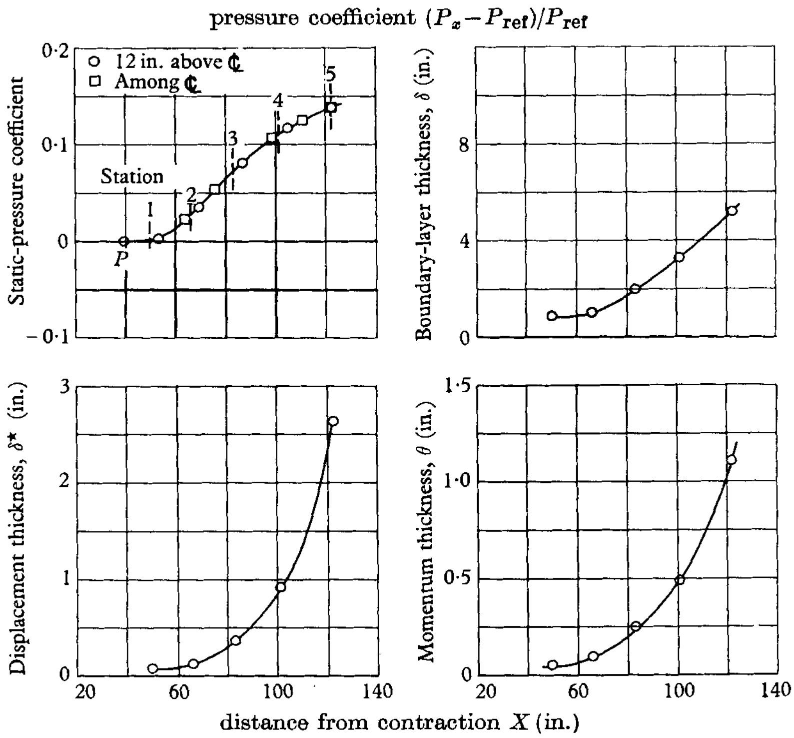


FIGURE 8. Parameters specifying boundary-layer flow. (P_{ref} = 5·42 lb./sq.ft. below atmospheric.)

discrepancy (figures 9*b* and *c*). However, this variation of flow conditions was believed to be too small to affect the flatness-factor measurements. Since the two runs were made within the same 8-hour period, the temperature was nearly constant at 76° F. and the barometric pressure was 29·24 in. of mercury.

The measured values of flatness factor for stations 1 to 4 are plotted in figure 11. Except for the intermittency of the outer edge of the layer, the flatness factors at stations 1 to 3 (figures 11*a* to *c*) are apparently dependent only on wave-number, as found in the earlier preliminary measurements (figure 7). Station 4 (figures 11*d* and *e*), which is near separation, exhibits a very different distribution of flatness factor near the wall, although the outer region of the layer of station 4 again suggests a distribution of intermittency dependent only on wave-number. (Note that the outer region of the layer is the region away from the wall where only the turbulent transport properties are important. The outer edge of the layer is the region where the flatness factor of the over-all turbulence signal becomes greater than 3. The two regions will overlap. The outer-edge intermittency will not be discussed in the present paper; however, some distributions of flatness factor with wave-number for the outer-edge region are noted by the dashed curves on the wave-number plots.)

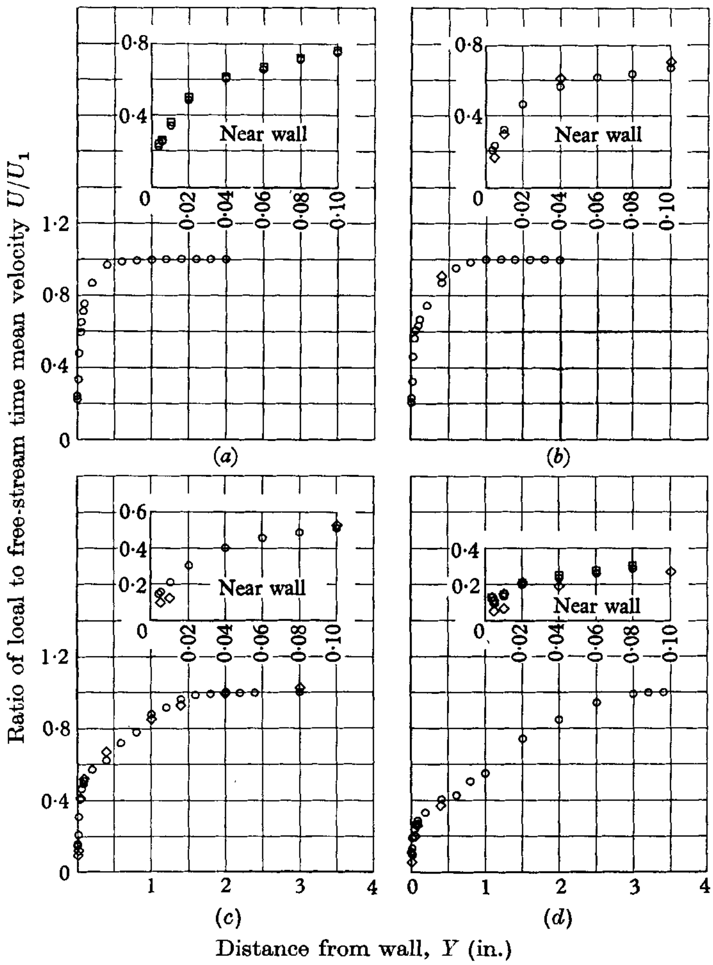


FIGURE 9. Mean velocity distributions. (*a*) Station 1, $U_1 = 32{\cdot}2$ ft./s. (*b*) Station 2, $U_1 = 30{\cdot}2$ ft./s. ○, actual measurement; □, corrected for probe Reynolds number effect; ◇, hot-wire measurement. (*c*) Station 3, $U_1 = 26{\cdot}6$ ft./s. (*d*) Station 4, $U_1 = 23{\cdot}3$ ft./s.

Before proceeding with a general discussion of the observations, a reservation is in order. The hot wire has a finite length (0·040 in.) and does not give a point measurement; therefore, the trace observed and analysed is an integral of the turbulence over the wire length. The turbulence must be a size such that only one burst can on the average strike the wire at a time. If two or more independent bursts can pass over the wire at nearly the same time they would tend to decrease the apparent intermittency. The wire length should also be small compared to the wavelength of the particular frequency being observed if the burst is due to single eddies (or waves). The wire length (0·040 in.) corresponds to a wave-number of 1900 ft.$^{-1}$, which is near the point where most of the flatness factor measurements start to decrease. If, however, the bursts are composed of several eddies or oscillations (as might be implied from figure 5) then the wire length need only be small compared to the over-all size of the burst.

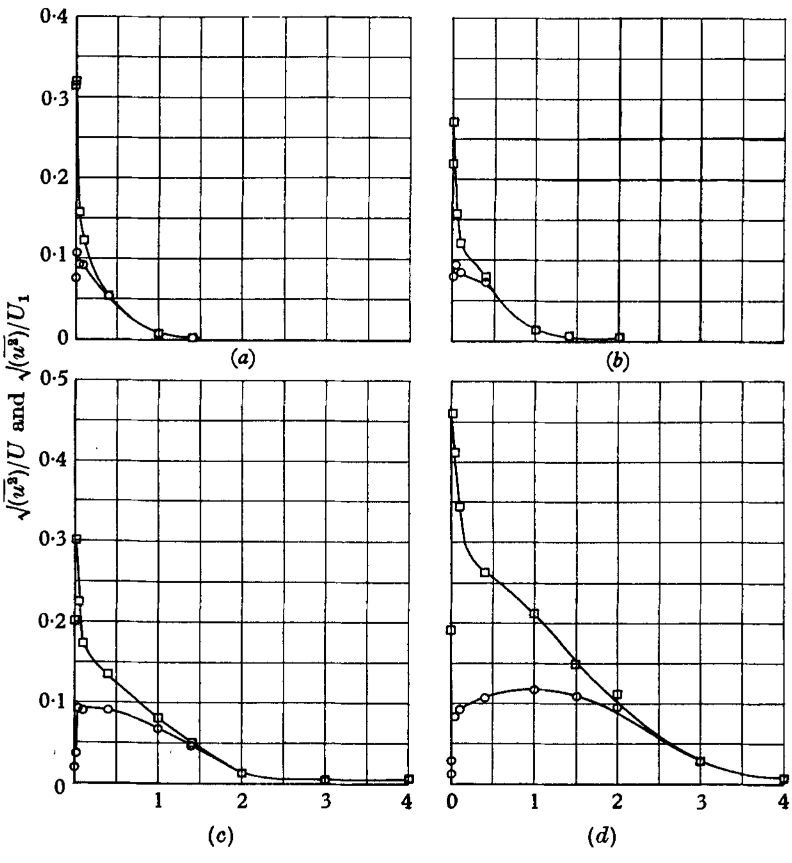


FIGURE 10. Turbulent velocity distributions. (*a*) Turbulent velocity, station 1. (*b*) Turbulent velocity, station 2: □, $\sqrt{(\overline{u^2})}/U_1$; ○, $\sqrt{(\overline{u^2})}/U$. (*c*) Turbulent velocity, station 3. (*d*) Turbulent velocity, station 4.

Discussion

An understanding of the present observations of the small-scale motion is far from complete. Little theoretical information is available for this high-wave-number region, even for isotropic turbulence. Batchelor devotes the last section of his monograph to a discussion of 'the small-scale properties of the motion'. His remarks concerning the small-scale motion will be utilized in discussing the results presented herein.

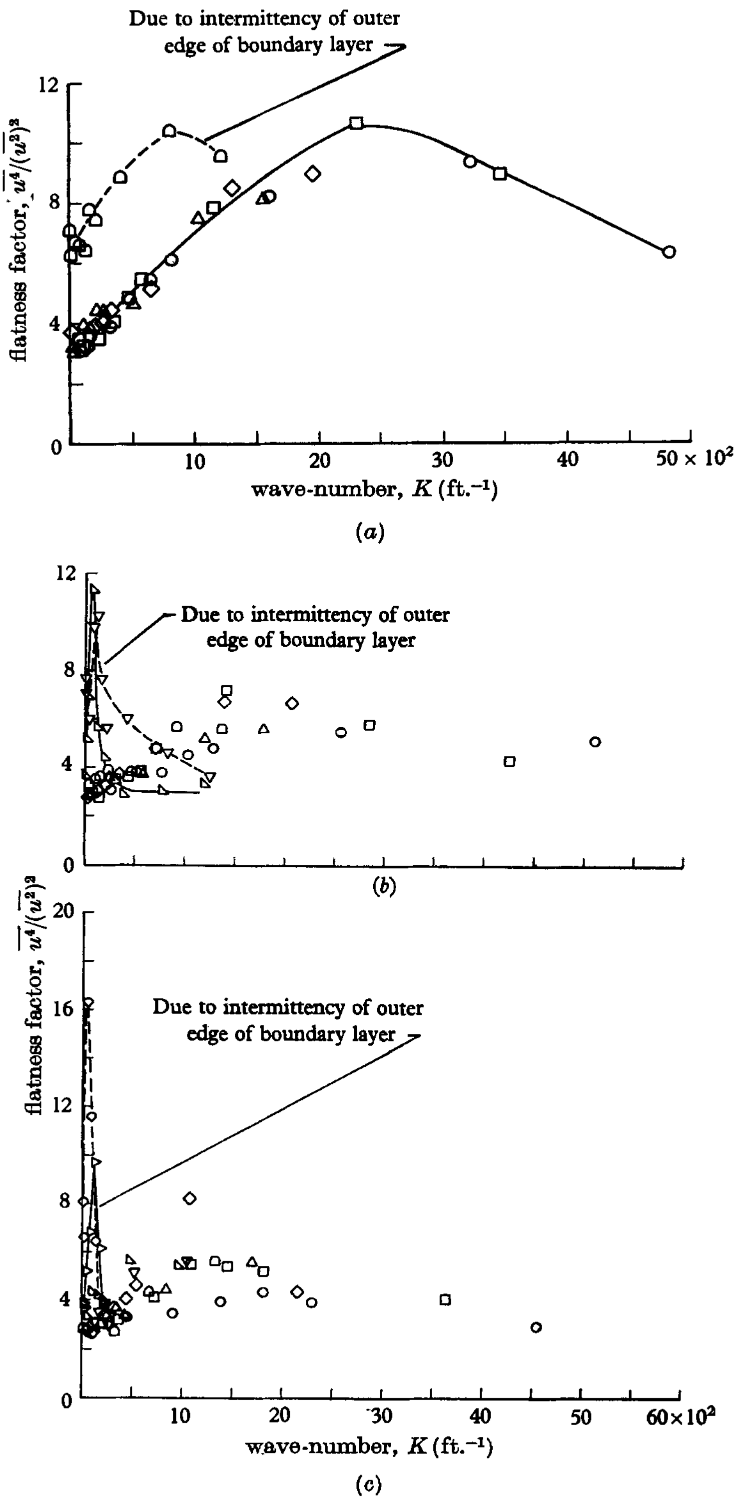


FIGURE 11. For legend see p. 236.

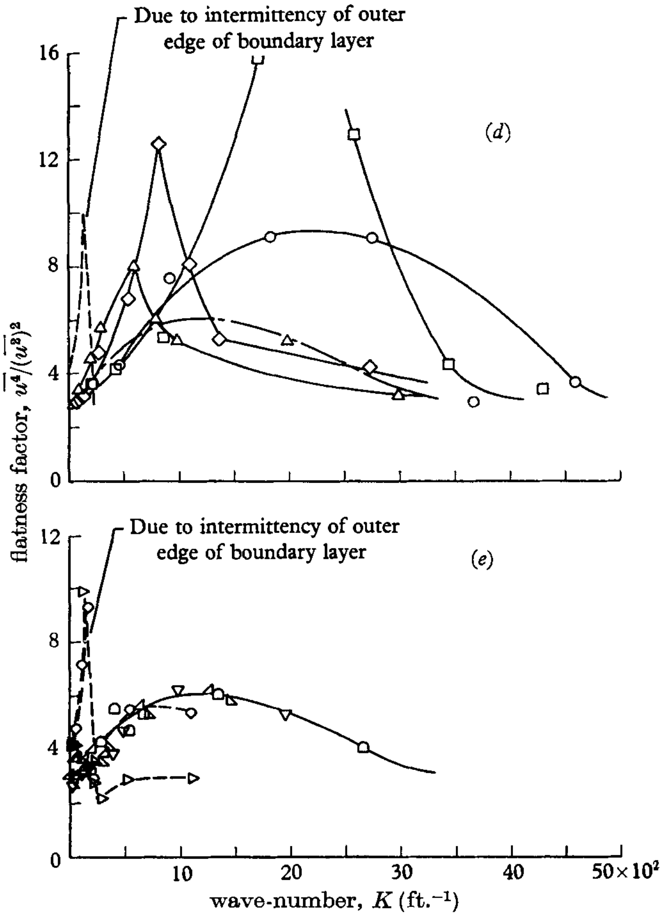


FIGURE 11. Flatness factor at various wave-numbers. (*a*) Station 1. y-distance (in.): ○, 0·005; □, 0·010; ◇, 0·040; △, 0·100; ▢, 0·400. (*b*) Station 2. (*c*) Station 3. y-distance (in.): ○, 0·005; □, 0·010; ◇, 0·040; △, 0·100; ▢, 0·400; ▽, 1·00; ⊾, 1·40; ▷, 2·00; ▽, 4.00. (*d*) Station 4, very near wall. (*e*) Station 4, outer region of layer. y-distance (in.): ○, 0·005; □, 0·010; ◇, 0·40; △, 0·100; ▢, 0·400; ▽, 1·00; ⊾, 1·50; ◺, 2·00; ▽, 3·00; ▷, 4·00.

It appears logical to assume that the present observations are directly related to the increase in flatness factor with successively higher velocity derivatives reported by Batchelor & Townsend (1949). However, since Batchelor & Townsend employed successively higher velocity derivatives to indicate the character of the turbulence at high frequencies, while the present measurements employ frequency bands, it is impractical to make a direct comparison of measurements. The orders of magnitude of the flatness factors reported by Batchelor and Townsend are the same as found for stations 2, 3, and the outer region of station 4 (figures 11*b*, *c* and *e*).

The uniformity of the intermittency with distance from the wall, observed at station 1 (figures 7 and 11*a*), appears to require that the intermittency has developed at some distance upstream. The high values of flatness factor observed at station 1, as compared with the values at stations 2 and 3, also indicate that the intermittency may have started upstream of station 1 and is decreasing somewhat with flow distance. Since station 1 is only slightly downstream of the region of transition from laminar to turbulent flow, it is to be expected that this intermittency must originate within the transition region; but the mechanism is not understood. Bursts or intermittency in the over-all hot-wire signals have been observed in the transition region by Schubauer & Klebanoff (1956), but no information is available on the intermittency at high frequencies in this region. Since it is still not clear what causes the transition bursts to appear in the laminar flow, there is no clear picture of the chain of events that will lead to the observed intermittency at high frequency.

There is limited evidence, both theoretically and experimentally, to suggest how intermittency may arise. The general ideas of the effects of inertia forces would seem to suggest that intermittency is possible. Batchelor (1953, p. 186) cites several examples to show that the non-linear inertia forces give rise to regions of strong isolated vortices; and, since it is also known that turbulent energy is transported from one part of wave-number space to another by inertia forces (Batchelor, 1953, p. 84), it is not hard to see that regions of intermittency might exist. Further measurements must be made in the transition region before it is possible to trace the exact development of the intermittency.

Stations 2 and 3, as well as the outer region of station 4 (figures 11*b*, *c* and *e*), suggest a somewhat constant value of flatness factor with wave-number. The decrease in magnitude of the flatness factors over that of station 1 indicates a trend toward homogeneity. It has been suggested that the tendency to homogeneity with motion downstream is due partly to the shearing action in the boundary layer drawing out turbulent spots. Since the magnitudes of flatness factor are similar to those reported by Batchelor & Townsend (1949) one may suggest that the turbulence for stations 2, 3 and outer 4 is quite similar to the free turbulence flow. There is, of course, the possibility that the scale size of the turbulence is decreasing; thus, the finite wire length would make it appear that the flatness factor has decreased at these stations. While the increase in flatness factor at low wave-numbers is similar for all stations, the peaks in the curves appear to be reached at a lower wave-number the farther downstream the station is located. There is always a question in regard to what the peak and downward slope in these curves of flatness factor mean. It is possible that the electronic noise of the instrument, which will have a flatness factor near 3, may actually be causing the decrease. Again, how accurately the instruments can be read when the signal becomes very intermittent may also influence the measured values of intermittency.

Near the wall at station 4 a completely different type of intermittency is apparently encountered (figure 11*d*). While there is some question as to the accuracy of determining the mean velocity near the wall, it does not appear that the wave-numbers could ever be corrected in a consistent way to give one curve. These distributions suggest a production of intermittency is in progress. This flow at station 4 is near separation; however, there is reason to believe that the profile is not in the separation region as yet ($\delta^*/\theta < 2$). Visual observations of oscillograph traces downstream of station 4 in the separation region suggest very much the same patterns as seen at station 4, except that the frequencies are lower and the over-all signal has an intermittency also.

Several observations from the present set of data can be qualitatively related to flow observations made in a water table by Kline (1957). Water-table observations, explored with dyes, show that the turbulent boundary layer separates first in a highly irregular, intermittent manner. The outbreak of bursts such as shown in figure 11 (*d*) is certainly suggestive of an approach to an intermittent separation. Injection of smoke into the present boundary layer near separation also suggests that an intermittent separation is occurring downstream of station 4.

In a very recent water-channel study, Kline & Runstadler (1958) were able to observe the flow visually in the region of the boundary layer very near the wall. By injecting dye into the layer very near the wall, they observed 'islands of hesitation' very near the wall at all locations in the boundary layer from transition to separation. The islands appear as stretched filaments of dye in the direction of flow, which move downstream slower than the surrounding fluid. With each island a longitudinal vortex appears to be generated. (There is a striking similarity between the observations in the water channel and the rather idealized model of an unstable viscous sublayer proposed sometime ago by Einstein & Li (1955). This instability near the wall is of interest here in that it suggests a possible source of the high-frequency intermittency.) The present data have been examined for evidence of such islands. However, Kline has pointed out that the islands are very small and may be obscured by the hot-wire length.

If these islands exist near the wall it was thought that their presence might be indicated by bursts in the over-all (all frequencies) hot-wire signal. However, only at station 4 was there evidence of a rise in the value of flatness factor (of the over-all signal measured from the magnetic tape) in the region where the islands might be expected. The over-all flatness factor for station 4 is shown in figure 12. The points at the outer intermittent edge of the layer are not faired in, since the data are too meagre to define the curve. (The higher values of flatness factor appearing in the over-all signal at $y = 0{\cdot}005$ and $0{\cdot}010$ in. on figure 12 correspond to the y values of the circles and squares on figure 11 (*d*).) For the other stations (1, 2 and 3), although not shown, the measurements suggest, if anything, a trend toward a periodic signal, since the flatness factors are less than 3 (for a sine wave $\overline{u^4}/(\overline{u^2})^2 = 1{\cdot}5$, for a triangular wave $\overline{u^4}/(\overline{u^2})^2 = 1{\cdot}8$). Thus, from the intermittency measurements, any indication of islands near the wall is limited to the region approaching separation.

A second observation appears to have some connexion with the concept of islands of hesitation. The over-all signals being monitored on an oscillograph indicated a rather pronounced trend toward skewness at the wall as the flow continued toward separation. A rough idea of this skewness can be obtained by considering the pen recorder traces for $y = 0{\cdot}005$ at station 4 shown in figure 13, where the skewness is associated with the large-amplitude sharp peaks in one direction on the trace and the low-amplitude broad peaks in the other direction. (Unfortunately, the loss of low-frequency response for the tape recorder depresses the skewness, so the pen recorder gives a somewhat more graphic picture in this case.) The suggestion of a predominant direction for the fluctuation would be compatible with the idea of islands of hesitation. It will, of course, be of value to pursue the study of this skewness further.

While the observations made in a water table may suggest possible ways in which the high frequencies become intermittent, it is evident that a direct chain of events is yet to be defined. There is a suggestion from the data that the intermittency phenomenon is associated with transition and separation rather than

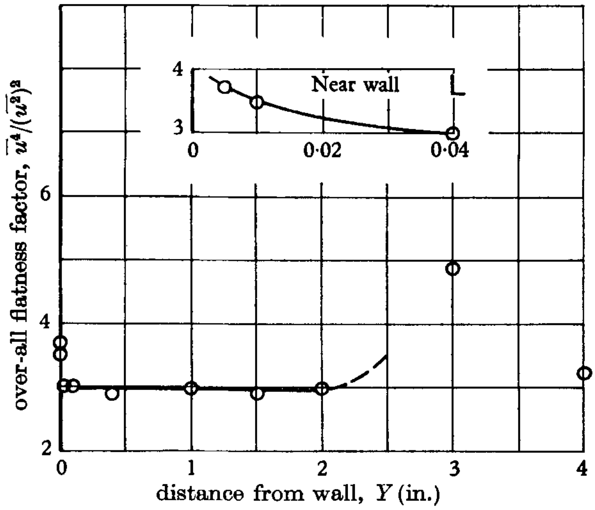


FIGURE 12. Flatness factor distribution for over-all signal at station 4.

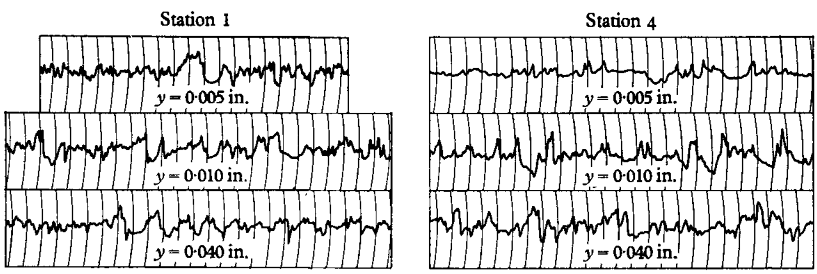


FIGURE 13. Low-frequency part of over-all turbulent fluctuations.

with the turbulent layer far from either region. The intermittency at stations 2 and 3 appears to be more a consequence of something that has happened upstream rather than something developing at the particular point of measurement. Thus, one may conclude that if islands exist at stations 2 and 3 they are too small to affect the observations.

The present measurements are still somewhat crude, partly because of a lack of appreciation of the mechanism causing the intermittency. The data would appear in fact to add another complication, that of spatial inhomogeneity, to an already too complex problem. There are, however, some rather encouraging results to be found in the data. In particular, the existence of a fairly uniform flatness factor with wave-number independent of distance from the wall indicates the extent to which the turbulence is mixed throughout the boundary layer. This assumes that the bursts are generated locally and not at all y-distances in the boundary layer. The uniformity further suggests that the effects of the inertia terms, which will vary in the boundary layer, on the bursts are not pronounced.

It was first suspected that intermittent separation could be traced directly to the intermittency observed after transition; however, the measurements at station 4 suggest that a second mechanism enters as separation is approached. The second mechanism could well be the islands of hesitation suggested from Kline's observations.

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