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Experimental investigation of the origin of residual disturbances in turbulent MHD flows after laminarization

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The problem of the strong velocity disturbances remaining after the laminarization of an electroconductive fluid flow in a transverse magnetic field was investigated experimentally. The turbulence intensities, two-point correlations, and energy spectra of the velocity pulsations were measured using two-electrode probes and hot-film sensors. The two hypotheses with regard to a physical explanation of the persistence of the disturbances were examined, and it was concluded that these disturbances are generated mainly at the entry of the flow into the magnetic-field region. An almost undisturbed laminarized flow was obtained by eliminating the entry effects.

1. Introduction

The problem of residual disturbances is one of the most paradoxical problems of fluid mechanics. Various hypotheses have been suggested to explain this phenomenon, which appeared in a number of experimental investigations.

Briefly, the essence of the phenomenon is as follows: friction measurements and a comparison of these with laminar-flow theory established that for every channel of a particular geometry placed in a transverse magnetic field there is some critical ratio of Hartmann number to Reynolds number at which the friction begins to correspond to laminar flow: $(Ha/Re)_{\text{cr}} = [215-85 \exp(-0{\cdot}35\beta)]^{-1}$. Here $\beta = b/a$, where b is the half-width of the cross-section in the direction perpendicular to the magnetic field, and a is the half-width parallel to the field. It was naturally assumed that this critical ratio also corresponds to a complete disappearance of flow disturbances in an initially turbulent flow. However, the very first direct measurements of velocity pulsations already revealed that in fact about a third of the initial turbulence remains (Branover, Slyusarev & Shcherbinin 1965). Further studies performed with the aid of two-electrode probes, dynamic sensors, and hot-wire and hot-film techniques confirmed the existence of residual disturbances ranging from 12 % to 50 % of the initial turbulence level (Branover, Gel'fgat, Kit & Tsinober 1970; Slyusarev 1971; Gardner & Lykoudis 1971; Branover & Platnieks 1971; Hua & Lykoudis 1974). These studies showed the phenomenon to be even more sophisticated, there being cases where the turbulence intensity even increases after the flow becomes 'laminar' according to the friction values. Measurements of disturbance-intensity profiles over the cross-section of the channel showed that, when the magnetic field increases, the intensity gradients change from negative (i.e. a disturbance intensity higher near the wall and lower on the flow axis) to positive. This seemed to indicate that a strong magnetic field causes a new type of flow, which is laminar but which carries very strong, very slowly decaying, disturbances. Such a laminar flow could be expected to have unusually marked heat-transfer and mass-transfer properties.

Two main hypotheses were proposed to explain the origin of the residual disturbances. The first suggests that the three-dimensional disturbances carried by turbulent flow entering the transverse magnetic field are converted into two-dimensional disturbances in the plane perpendicular to the magnetic field, making further interaction with the field impossible (Branover, Gel'fgat, Kit & Platnieks 1970; Kit & Tsinober 1971). This was based on theoretical predictions of the development of strong anisotropy in turbulence brought by the flow into a magnetic field (Moffatt 1967). It should be noted that theoretical studies have shown that turbulence tends to become two-dimensional only in the sense that variation in the direction of the magnetic field becomes negligible, while velocity fluctuations in the field directions do not vanish. However, it could be supposed that in a duct flow, because of the presence of walls perpendicular to the magnetic field, turbulence tends to become two-dimensional in a stronger sense, i.e. with only two velocity components in the plane perpendicular to the magnetic field and negligible variation in field direction.

The second hypothesis stresses the role of M-shaped mean-velocity profiles which are created in the magnetic field (Slyusarev 1971). The M-shaped mean-velocity flow profiles are assumed to be unstable to the growth of large two-dimensional disturbances with their axes parallel to the magnetic field.

The present paper presents the results of further experiments undertaken in an attempt to explain the origin of the residual velocity disturbances in laminarized MHD flows in ducts.

The solution of the problem described above is important for understanding MHD flows and for designing MHD machines, while in addition it is correlated to the basic problems of turbulence in general. Indeed, the question of whether an actual transition from laminar to turbulent flow is essentially three-dimensional or not is one of the very general questions of fluid mechanics. Furthermore, since two-dimensional flow disturbances are characteristic of flows in the atmosphere, it follows that if the turbulence in a flow of an electro-conductive fluid really becomes two-dimensional this would provide a rare opportunity for the experimental study of some peculiar properties of atmospheric turbulence.

2. Residual velocity disturbances in laminarized MHD flows and the problem of their origin

While examining the experimental results, we will single out two extreme cases.

(1) The 'Hartmann case', when the geometrical parameter of the rectangular channel cross-section $\beta \to \infty$ and the field interacts strongly with the average flow;

(2) the 'azimuthal-field case', when $\beta \to 0$ and the field does not interact with the average flow.

It should also be mentioned here that, except when indicated otherwise, all the dimensionless parameters used below (Reynolds number, Hartmann number, etc.) are based on the 'hydraulic radius' (cross-sectional area divided by the perimeter), corresponding in a high-aspect-ratio rectangular duct to the smaller half-width of the cross-section.

There is some experimental evidence that the structure of the residual velocity disturbances is close to two-dimensional, at least in the limited sense that variation in the magnetic field direction is negligible. In particular, in the already mentioned work by Branover & Platnieks (1971) two-point cross-correlations of the longitudinal velocity pulsations were measured and a drastic increase in correlation at two points on a line parallel to the magnetic field was established. A similar conclusion was arrived at by studying the effect of the magnetic field on mass transfer (Kolesnikov & Tsinober 1974). Finally, some assumptions were made on the basis of spectral measurements (Kolesnikov 1972). In these measurements a trend toward a k^{-3} spectrum instead of the usual $k^{-\frac{5}{3}}$ was established, which could well be an indication of the existence of two-dimensional turbulence in the strong meaning (Kraichnan 1967, 1971; Batchelor 1969). It should be mentioned, however, that the analysis of angular transfer of turbulent energy in the presence of magnetic field (Moreau 1968; Moreau & Almany 1976) and especially the most recent experimental and theoretical results of Moreau & Alemany (1977) show that, in the presence of a magnetic field, conformity to the k^{-3} law does not necessarily imply that the turbulence is two-dimensional (with zero component in the field direction). The interaction between the Joule dissipation and energy transport over the angular spectrum may be responsible for the conformance of the k^{-3} law. Nevertheless, it seems to be possible to conclude that, at least in duct flows in transverse magnetic fields, residual disturbances are indeed close to two-dimensional.†

There is also some evidence that the disturbances are of low frequency. The two above-mentioned properties – two-dimensional nature and low frequency – also explain satisfactorily the slow decay of the residual velocity disturbances and their persistence over very long sections of ducts in the presence of transverse magnetic fields.

Indeed, a flow which is two-dimensional in a plane perpendicular to the magnetic field does not interact with the latter. On the other hand, if the disturbed motion is a low-frequency (large-scale) motion, then viscosity influences it very little. Thus, in the disturbed motion which we now conceive of, there is almost no energy dissipation.

All the foregoing, however, still leaves the question of the origin of the residual disturbances unanswered. To answer this question, some very specially designed experiments have to be carried out. The single experiment in which an undisturbed laminarized flow was observed (Gel'fgat, Kit & Tsinober 1971) does not allow us to draw any conclusions with regard to the aforementioned question, since this experiment was performed under very special conditions (electrically driven flow with no pressure gradient in an annular duct) and since in this experiment neither upstream turbulence nor entrance effects existed.

† However, in none of the works on duct flows cited above was the velocity component in the magnetic-field direction measured. Thus the conclusion about a two-dimensional nature of the residual disturbances is still only an indirect consequence of the experimental results.

As mentioned above, according to one point of view, the residual turbulence observed in the experiments is the result of the decay of turbulence transported by the flow into the region affected by the magnetic field from upstream parts of the flow which lie outside the field. According to another viewpoint, the fluctuations recorded in an MHD channel flow at supercritical values of Ha/Re are generated at the entry of the flow into the magnetic field, as a result of the instability of the M-shaped structure of the mean-velocity distribution, while the turbulence carried by the flow from upstream regions ahead of the magnetic field is more or less completely damped out.

The difference between these two explanations is a fundamental one. In fact, if the almost two-dimensional turbulence persisting after laminarization owes its origin to a decay of the initially three-dimensional turbulence transported by the flow from upstream into the part of the channel to which the magnetic field is applied, then this means that the application of a magnetic field to the decaying isotropic turbulence is capable of transforming it into a two-dimensional turbulence; this is then followed by a kind of turbulence 'preservation', since the mechanism of Joule and viscous dissipations become highly attenuated.

If, however, the turbulence persisting after laminarization of the flow in the channel is due to new fluctuations arising when the flow enters the magnetic field, then it obviously cannot be postulated that the turbulence 'adjusts itself' to the magnetic field. The conclusion that must be drawn in this case is that the disturbances are close to two-dimensional and have a high correlation in the direction of the magnetic lines of force from their very inception.

If this conclusion is correct, then the residual two-dimensional turbulence has nothing in common with the turbulence transported by the flow into the magnetic field, the existence and intensity of the residual turbulence being a result solely of conditions (geometric in part) in the flow entry region.

To arrive at a decisive experiment, it is necessary to separate the two possible phenomena: 'tuning' of the entering turbulence and generation of disturbances due to instability of the M-shaped mean-velocity profiles. In other words, the experimental facility has to make possible a study of the following flow cases.

(1) The flow entering the magnetic-field region is still laminar, and transition occurs (if it occurs) in the field region. Since under these circumstances a sufficiently strong magnetic field would prevent transition, and since there is no turbulence upstream, the existence of any remaining disturbances would prove the validity of the hypothesis connecting the residual disturbances with the M-shaped mean-velocity profiles appearing at the entry of the flow into the magnetic field.

(2) Fully developed turbulent flow enters the magnetic field region, but the formation of M-shaped velocity profiles is prevented (or at least greatly attenuated). The persistence of disturbances after laminarization in this case would obviously prove the hypothesis of 'convected and tuned' turbulence.

Performing such a study presents a serious challenge to the experimenter. Obviously, in the first case the magnetic-field region has to begin at a point upstream from the laminar-to-turbulent transition region. An additional requirement is that no external disturbances can enter the test channel. This can be achieved by damping effectively the disturbances in the upper tank and by providing the test channel with a strongly converging smooth inlet.

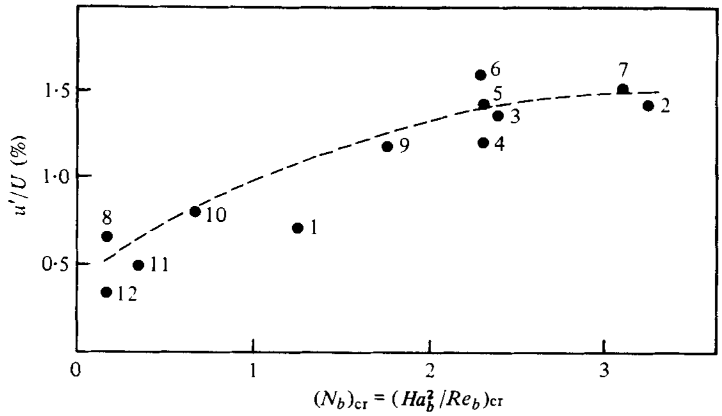

FIGURE 1. Relation between level of residual disturbances and critical interaction parameter $(N_b)_{cr}$. The numbers refer to the conditions indicated in table 1.

To realize the second flow case, i.e. to eliminate the creation of M-shaped velocity profiles, probably only a single possibility exists: flow in an 'azimuthal' magnetic field ($\beta \ll 1$) at relatively low Reynolds numbers. Let us analyse this situation in a little more detail. In any MHD duct with arbitrary $0 < \beta < \infty$, the critical ratio of Hartmann number to Reynolds number changes within a narrow range: $7{\cdot}4 \times 10^{-3} > (Ha/Re)_{cr} > 4{\cdot}6 \times 10^{-3}$. At the same time, the sharpness of the M-profile is proportional to the interaction parameter (Stuart number) $N_b = (Ha^2/Re)_b$, where b is the half-width of the channel in the directions transverse to the magnetic field (see Shercliff, 1965). In the case being considered, this number can be expressed as $(Ha/Re)_{cr}.Ha.b/a = (4{\cdot}6 \text{ to } 7{\cdot}4) \times 10^{-3} Ha.\beta$. Furthermore, for laminarization $Ha = (4{\cdot}6 \text{ to } 7{\cdot}4) \times 10^{-3} Re$. Hence the critical Stuart number corresponding to laminarization will be $(N_b)_{cr} = (4{\cdot}6 \text{ to } 7{\cdot}4)^2 \times 10^{-6} Re.\beta$, the lower coefficient corresponding to $\beta \gg 1$ and the higher one to $\beta \ll 1$. This proves the assumption made before, namely that the conditions at which the M-profiles are least developed at $Ha/Re = (Ha/Re)_{cr}$ are met by the flow in an azimuthal field ($\beta \ll 1$) for small Reynolds numbers.

Table 1 presents most of the available data on residual disturbances in laminarized flows, with varying $(N_b)_{cr}$. The measured intensity of the remaining disturbances is definitely lower for lower values of $(N_b)_{cr}$. Surprisingly enough, however, no note seems to have been taken of this obvious fact. Figure 1 presents graphically the relationship between the level of the remaining disturbances and the critical interaction parameter $(N_b)_{cr}$ (see also table 1).

Finally, it should also be mentioned that the flow in an azimuthal field provides conditions which are extremely suitable for the possible development of two-dimensional turbulence, since the channel cross-section is aligned relative to the magnetic-field lines.

3. Apparatus and measurement techniques

3.1. *The experimental facility*

The goals outlined in the previous section led us to design a channel allowing a flow in an 'azimuthal' field. The channel was made of Perspex, with a rectangular cross-section $2b \times 2a = 0{\cdot}63 \times 3{\cdot}0$ cm^2 and a 69 cm ($L = 230b$) test length. The selection

Shape of cross-section	Aspect ratio $\beta = b/a$	Place of measurement (distance from flow entry into magnetic field) L	Method†	Re	Interaction parameter under critical conditions $(N_b)_{cr}$	Disturbance level under critical conditions $(u'/U)_{cr}$ (%)	Authors	
	7·5:1	112a	t.e.	9×10^3	1·33	0·7	Slyusarev 1971	(1)
	6:1	73a	h.f.	$2{\cdot}55 \times 10^4$	3·3	1·3	Hua & Lykoudis 1974	(2)
	3:1	70a	t.e.	$2{\cdot}76 \times 10^4$	2·42	1·3	Branover, Gel'fgat, Kit & Platnieks 1970	(3)
	3:1	40a	h.w.	$2{\cdot}6 \times 10^4$	2·31	1·2	Platnieks 1971	(4)
	3:1	55a	t.e.	$2{\cdot}6 \times 10^4$	2·31	1·4	Kit & Platnieks 1971	(5)
	3:1	70a	t.e.	$2{\cdot}54 \times 10^4$	2·26	1·6	Branover, Gel'fgat, Kit & Tsinober 1970	(6)
	1·2:1	16a	h.w.	$2{\cdot}17 \times 10^4$	3·2	1·5	Branover & Platnieks 1971	(7)
Circular	1:1	75R_0	h.f.	4×10^3	0·18	0·66	Gardner & Lykoudis 1971	(8)
				$3{\cdot}9 \times 10^4$	1·71	1·2	Gardner & Lykoudis 1971	(9)
	1:3	70b	t.e.	$1{\cdot}4 \times 10^4$	0·67	0·8	Branover, Gel'fgat, Kit & Tsinober 1970	(10)
	1·7:5	110b	t.e.	$6{\cdot}6 \times 10^3$	0·35	0·5	Branover, Slyusarev & Scherbinin 1970	(11)
	1:5	90b	h.f.	$3{\cdot}54 \times 10^3$	0·19	0·3	Branover, Gershon Yakhot 1977	(12)

† t.e., two-electrode method; h.w., hot-wire method; h.f., hot-film method.

TABLE 1

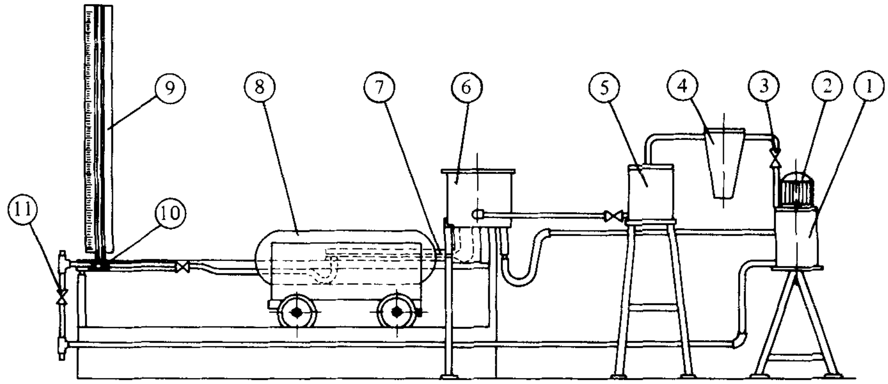

FIGURE 2. Sketch of experimental apparatus: 1, lower tank; 2, centrifugal pump; 3, control valve; 4, filter; 5, buffer tank; 6, upper tank; 7, test channel; 8, electromagnet; 9, manometric system; 10, Venturi flowmeter; 11, control valve.

of the shape and size of the channel cross-section took into account the following requirements.

(1) Small parameter β ($\beta = \frac{1}{5}$);

(2) The possibility of obtaining a flow with a low Reynolds number at a relatively high velocity, for which both the velocity and its fluctuations could still be reliably measured.

The entry section, adjacent to the prismatic test section, was designed as a very smoothly convergent nozzle. This feature makes the test conditions similar to those in the classic Reynolds experiment, the only difference being that in our case the cross-section of the duct was not circular but rectangular, with a high aspect ratio.

The test channel was placed in the gap of an electromagnet, in such a way that the magnetic field was transverse to the axis of the channel and parallel to the larger side of the cross-section. The upstream edge of the magnetic poles could be set anywhere between the entry and the point at a distance $L = 133b$ from the entry, so that various positions between the flow and the magnetic field might be achieved. Experiments could also be run with the whole entry section, including the convergent nozzle, within the uniform magnetic field (note that the nozzle was convergent only in the plane perpendicular to the magnetic-field direction, the width of the nozzle in the direction of the field being constant).

A schematic drawing of the experimental apparatus is shown in figure 2. Mercury was pumped by a centrifugal pump through a filter into a buffer tank. There was no mechanical link between the pump and the buffer tank, the mercury being poured into the latter through a pipe ending a few centimetres above the bottom of the tank. From the buffer tank, the mercury flowed freely into the upper tank, through an elastic pipe. The inherent waves produced by the fall of mercury into the buffer tank were partially damped in this pipe, being further damped out by two successive meshes in the upper tank. Transmission of vibrations from the pump to the floor was prevented by means of rubber shock absorbers.

For Reynolds numbers lower than 3500, tests were run for short periods of time without operation of the pump, using the mercury accumulated in the buffer tank. The turbulence intensities measured in such tests did not differ from those in tests

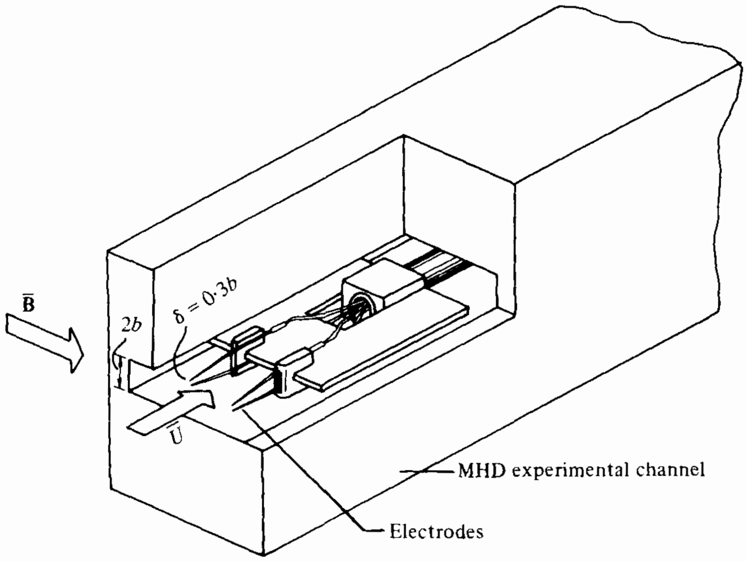

FIGURE 3. Sketch of two-electrode sensors.

run at the same Reynolds number values, but with the pump operating. This verified that pump operation had no effect on the turbulence measurements.

The flow rate in the test channel was measured by a Venturi flowmeter situated downstream. The accuracy of the manometric system was about 1 %. For very low Reynolds numbers, a two-fluid (mercury–water) system made possible an approximately tenfold amplification of the level difference in the manometers.

The tests were run with flow velocities up to about 30 cm s^{-1} (Re = 7800).

The electromagnet, with its rectangular 10×80 cm^2 poles, was mounted on a carriage and could be moved along the test channel. The external width of the experimental channel, determining the air gap of the electromagnet, was 4·2 cm. The maximum field in that gap was 0·71 T (for long runs) with a non-uniformity of the field of less than 1 %.

The water-cooled coils were energized by a battery of lead–acid cells, in order to obtain a ripple-free current, an important feature when working with anemometers of the two-electrode type.

Hartmann numbers up to about 55 could be reached in the described test channel.

3.2. *Turbulence-measurement techniques*

The flow diagnosis in this study was based on measurements of the turbulence intensities, spatial cross-correlations, and frequency spectra of the fluctuating longitudinal component of the velocity.

The turbulence-intensity measurements were performed using two different methods, one with 'two-electrode' potential probes and the other with hot-film quartz-insulated probes. The latter method allowed us to check the results obtained using the former (less common) 'two-electrode' technique. However, since the accent in this paper is not on the measurement method, but rather on the conclusions about the flow pattern, we chose to report here mainly the results obtained using the hot-film method, while presenting only typical results obtained under the same conditions using the 'two-electrode' probes.

The potential probe is shown in figure 3. The prong-shaped copper electrodes were insulated with bakelite lacquer, with the exception of the tips, which were polished until a contact surface of about 0·1 mm^2 was obtained. The distance between the tips was adjusted to $0{\cdot}1 \pm 0{\cdot}005$ cm, i.e. 0·3 of the half width of the channel.

Since the conclusions in this paper are based mainly on hot-film measurements, we will not discuss here either the signal-processing instrumentation for the 'two-electrode' technique or errors caused by neglecting the ohmic potential losses between the electrodes (Kit *et al.* 1970).

For the hot-film measurements we used the cylindrical quartz-coated probes which seem to be favoured by most experimenters (Hill 1968; Hoff 1969; Malcolm 1969, 1970).

The upper frequency limit for a hot-film probe is of the order of some tens of kHz, depending on the Péclet-number values in the experiment. In mercury, for Péclet numbers up to 1·0, the amplitude of fluctuation of the Nusselt number due to the velocity fluctuation is attenuated by 10% at a frequency roughly given by $f = 0{\cdot}0197U^2/\alpha$, and by 90% at a frequency $f = 2{\cdot}70U^2/\alpha$, where U and α are, respectively, the mean free-stream velocity and the thermal diffusivity of the fluid (Malcolm & Verma 1977). For mercury at 26 °C, the value of α is 0·44 cm^2 s^{-1}. In our study ($U \simeq 15$ cm s^{-1}) the attenuation should be 10% at about 100 Hz and 90% at about 14 kHz.

The sensor of the 1210-20 Hg type probe (manufactured by Thermo Systems, U.S.A.) consisted of a platinum film deposited onto a quartz rod substrate about 50 μm in diameter and sputtered with a 2·5 μm insulating quartz coating.

The active length of the sensing element was 1 mm. The upper frequency limit for this type of probe, as indicated by the manufacturer, is about 30 kHz. If we consider the width of the test channel $2b$ as the characteristic length, then the characteristic large-scale turbulent frequencies which are to be expected in an experiment for a mean velocity v_0 will obviously be about $f_{\text{ch}} = v_0/2b$. In our case, the orders of magnitude of v_0 and $2b$ were, respectively, 10^{-1} m s^{-1} and 10^{-2} m. Thus $f_{\text{ch}} \simeq 10$ Hz, which is well below the above-mentioned frequency limit. Moreover, because the active length of the sensor was only 1 mm, the probe could effectively measure the large-scale vortices, of the order of $2b = 6$ mm in size, which characterized the turbulence in the experimental channel.

We also used probes of the same type but with a quartz coating about 10 μm thick, which provided a frequency response that was still satisfactory for our investigation but which had a much longer lifetime and a lower sensitivity to impurities.

The errors due to the imperfection of the spatial resolution of the probe, according to estimates made by Comte-Bellot (1976) on the basis of the studies of Uberoi & Kovasznay (1953), are as follows:

(*a*) For the large-scale velocity fluctuations, with a ratio between the characteristic length $L^* \simeq 2b$ and the hot-film sensor length 21 equal to $L^*/21 \gg 1$, ϵ is considered to be negligible.

(*b*) For the internal scale η of turbulence, $\eta/21 \simeq 10^{-1}$ (with η computed from $\eta/L^* = (Re_{L^*})^{-\frac{3}{4}}$), which means that the error ϵ is less than 0·6% for a fluctuation frequency of about 3 Hz and less than 20 % for a frequency of 150 Hz, with an average velocity of about 20 cm s^{-1}.

In addition to the above-mentioned frequency dependence of the fluctuating heat transfer in a turbulent flow, the application of the hot-film method in the case of mercury gives rise to a few specific problems, concerning: (*a*) the unstable thermal contact resistance created by the impurity layer surrounding the sensor during measurement, and also the change of the properties of this layer with each reimmersion of the probe; (*b*) magnetohydrodynamic effects on the heat transfer from the sensor.

Several correction procedures have been proposed in the literature (Sajben 1965; Malcolm 1969; Hill 1968; Hoff 1969), in order to deal with the first aspect. For turbulence-intensity measurements, however, since any change in the sensor sensitivity is reflected to the same extent in both the fluctuating velocity and the average velocity, such corrections are not necessary, provided a linear voltage–velocity dependence is obtained at the output of the anemometric system.

According to Lykoudis & Dunn (1973) for the flow parameters in our investigation (Hartmann number related to the sensor between 0 and 1, Grashof number based on the sensor diameter equal to 0·3 and interaction parameter of the order of 10^{-2}) no magnetic-field influence is to be expected on the heat transfer from the sensor. Except during the cross-correlation measurements, the sensor of the hot-film probe was directed along the magnetic-field lines.

The anemometric probes were used in conjunction with the 55 M Anemometric System produced by DISA Elektronik (Denmark).

In order to obtain reliable anemometric measurements, the mercury was filtered through a 1 μm mesh filter and its temperature was controlled within $\pm$ 0·1 °C. For the temperature correction, an average of the indications of two thermocouples (one at the inlet and one at the outlet) was taken into account.

Periodically the mercury was cleaned by bubbling it in a strong acid solution.

In order to detect any spurious signals related to impurities in the fluid, the output of the anemometric system was continuously monitored with a Tektronix 5103N oscilloscope.

Spatial cross-correlation measurements with hot-film probes were also carried out. For these measurements, two identical hot-film probes of the 1210-20 Hg type were used. The fluctuating signal from the two anemometric bridges were amplified up to a controlled value of 1 V (r.m.s.) by two Signal Normalizer Units (DISA type 52B 05). The two normalized signals were applied to a Turbulence Processor (DISA type 52B 25), which computed their product and integrated it for a chosen period of time, in order to obtain an output signal proportional to the cross-correlation factor.

The temperature-regulation requirements imposed by the hot-film technique are less critical for spatial-correlation measurements. Impurities in the mercury, however, could influence the measurement by decreasing the value of the correlation factor, so that the signal still had to be monitored on the oscilloscope.

For the spectral measurements the linearized output signal of the anemometric system was processed in a 400-line FFT Spectrum Analyzer (Spectral Dynamics Model SD 340). The averaging time of the Spectrum Analyzer was usually set to 120 seconds.

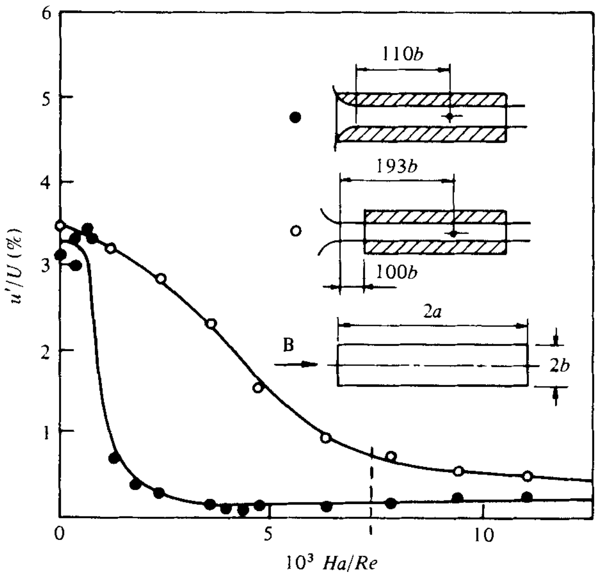

FIGURE 4. Variation of longitudinal velocity fluctuations on axis of duct for different conditions of flow entry into magnetic field (vertical dashed line indicates transition judged according to friction). $Re = 3540$.

4. Experimental results and discussion

4.1. *Intensity of disturbances*

Figure 4 compares the suppression of the intensity of the longitudinal velocity disturbances on the channel axis for the following two positions of the magnet relative to the channel. In the first position the entry to the magnetic poles was far from the inlet to the channel, and the flow entering the magnetic field was developed turbulent flow. The M-shaped velocity distributions were present but not strong at $Ha/Re = (Ha/Re)_{cr}$ (particularly at low Re), since $\beta = \frac{1}{5}$ and the size of the wall perpendicular to the field was small. At the same time, the channel side directed along the field was large, so that conditions were favourable for the creation of a flow which was two-dimensional in planes perpendicular to the field.

In the other extreme position the magnet overlapped the entire channel inlet length, including the convergent inlet region, which (as described above) was constructed in such a manner that the high (by a factor of several tens) contraction of the flow occurred very smoothly, only the dimension perpendicular to the field being reduced, while the cross-sectional dimension along the field remained the same. Here the breakdown of laminar flow occurred (if it occurred) inside the magnetic field. The M-shaped mean-velocity distributions, which may in general form in the fringing-field region, before the flow enters the main magnetic field, were most likely broken up by the very strong flow contraction in the convergent section, so that the flow at the beginning of the prismatic part of the channel was quite uniform.

The probe was so placed along the channel that the distance from the region of transition from laminar to turbulent flow to the sensor, in the case where the magnet was placed at the inlet of the channel, was approximately equal to the distance from

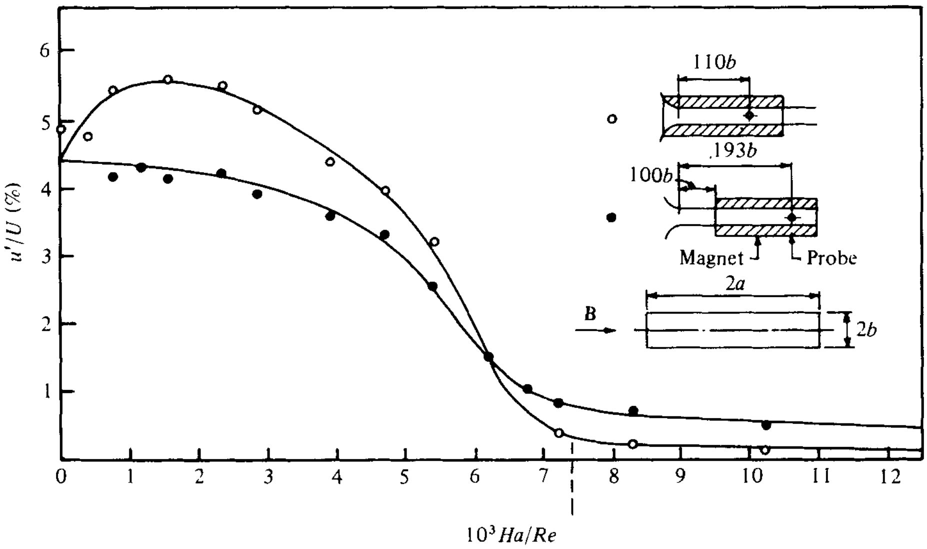

FIGURE 5. Variation of longitudinal velocity fluctuations near wall of duct for different conditions of flow entry into magnetic field (vertical dashed line indicates transition judged according to friction). $Re = 5400$.

the beginning of the magnet poles to the probe, when breakdown of laminar flow occurs before the flow enters the electromagnet gap. This ensures an approximate equality of the distance travelled by the turbulence in the magnetic field in both cases. As seen from the figure, in the case where the magnet covered the inlet to the channel, the suppression of the turbulence intensity was more rapid as well as more complete than in the other case.

In the former case the residual turbulence level amounted to only some fractions of a percent of the mean velocity, that is, it was several times lower than the residual intensity in all the preceding experiments with channels of various types (see table 1). However, in the second case as well, the residual turbulence level amounted to only 0·6 % (at $Ha/Re = (Ha/Re)_{\text{cr}}$), which was still lower than the majority of previous results. This was in complete agreement with the smallness of $(N_b)_{\text{cr}}$ in this case. Since, as noted above, the channel geometry was quite favourable for the preferred 'transformation' of externally supplied three-dimensional turbulence into two-dimensional turbulence, this particularly low value of the residual intensity should be attributed to the low value of $(N_b)_{\text{cr}}$, i.e. to the fact that the M-shaped distribution of the mean velocity at the inlet was not pronounced. Figure 5 is a comparison of the turbulence levels measured near the channel wall (at a distance of $\frac{1}{3}b$ from the wall) for the above two positions of the magnet.

Disturbance-intensity measurements carried out using two-electrode probes yielded similar results. Figures 6 and 7 give the results obtained with the probe located 0·4b from the wall for two relative channel-magnet positions similar to those described above. Fluctuations detected by the potential electrodes behave a little differently from those described above, especially at relatively low Ha/Re values, where a maximum appears on the $u' = f\ (Ha/Re)$ graphs. It is most likely that the

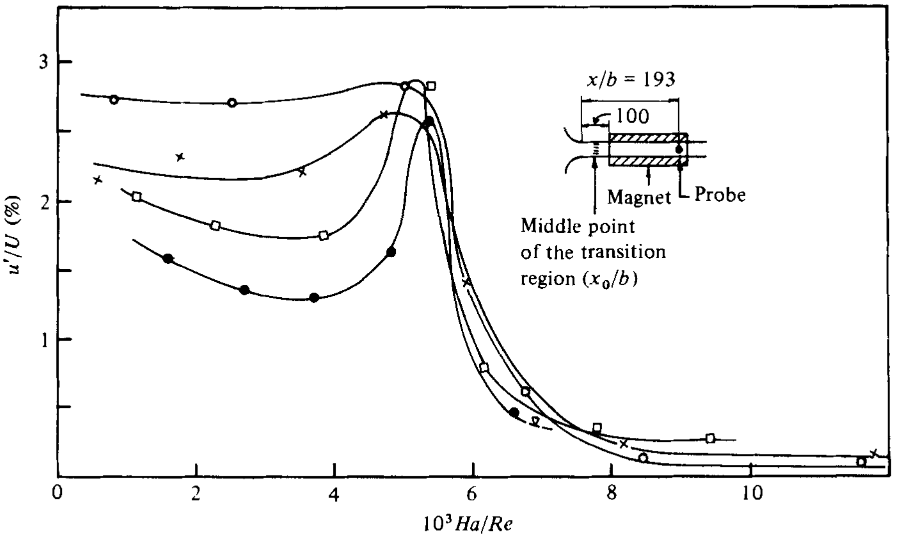

FIGURE 6. Longitudinal velocity fluctuations measured by two-electrode potential probe at distance of 0·4b from wall (turbulent flow enters magnetic field). $Re = 3540$, $x_0/b = 22$; $Re = 5400$, $x_0/b = 41$; $Re = 7750$, $x_0/b = 54$.

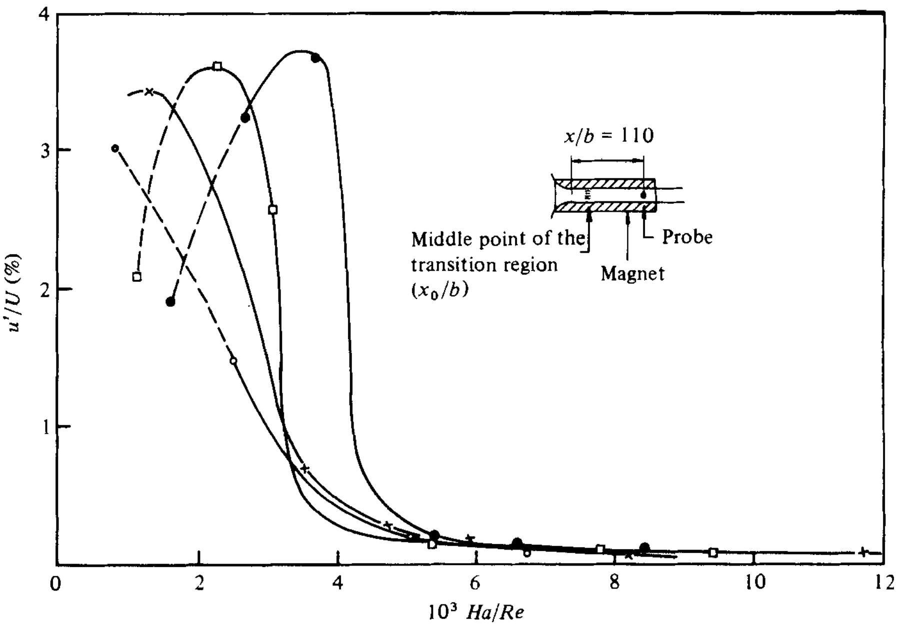

FIGURE 7. Longitudinal velocity fluctuations measured with two-electrode potential probe at distance of 0·4b from wall (magnet placed over inlet convergent length). $Re = 3540$, $x_0/b = 22$: $Re = 5400$, $x_0/b = 41$; $Re = 7750$, $x_0/b = 54$.

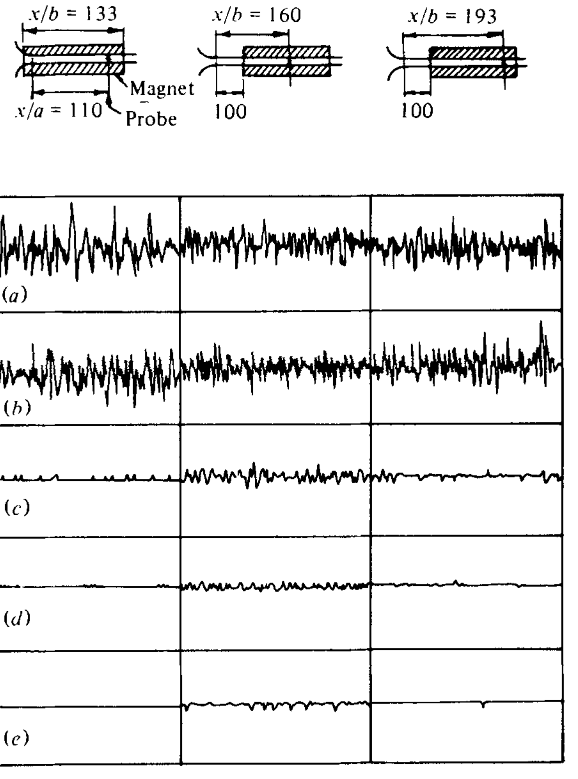

FIGURE 8. Comparative records of longitudinal velocity disturbance suppression for undisturbed flow and disturbed flow entering magnetic field, $Re = 3540$, noise level equivalent to 0·5 %. Above each set of records corresponding relative position of channel and magnet is shown. The values of $10^3 Ha/Re$ are: (a) 0·81; (b) 2·68; (c) 6·8; (d) 8·9; (e) 14·2.

results at small Ha/Re were lower because the ohmic potential losses between the sensing electrodes due to induced electric currents were neglected.

However inaccurate it may be, the two-electrode method has proven to be very convenient for oscillographic measurements, which give a qualitative insight into the flow regime. The instrumentation needed in order to obtain records like those shown in figure 8 comprises only a suitable voltage amplifier and an oscillographic recorder. Intermittency, for instance, has been definitely detected by such measurements, both inside the transition region ($x/b = 10$ to 70) for Ha/Re ratios below the critical value, and in the region where the turbulence should be fully developed at magnetic-field strengths close to the laminarization value.

Figure 9 shows the measured variation in the intensity of fluctuations along the channel for the same two cases: when the magnet covers the inlet convergent part of the channel (a), and when the magnet is shifted downstream below the breakdown of laminar flow (b). It is very remarkable that in the second case (figure 9b) the fluctuation intensity in the region of the fringing field becomes *greater* at certain values of Ha/Re than it was without the field. This phenomenon can apparently be attributed only to a generation of new disturbances in the flow entering the magnetic field due to instability of the M-shaped mean velocity profiles.

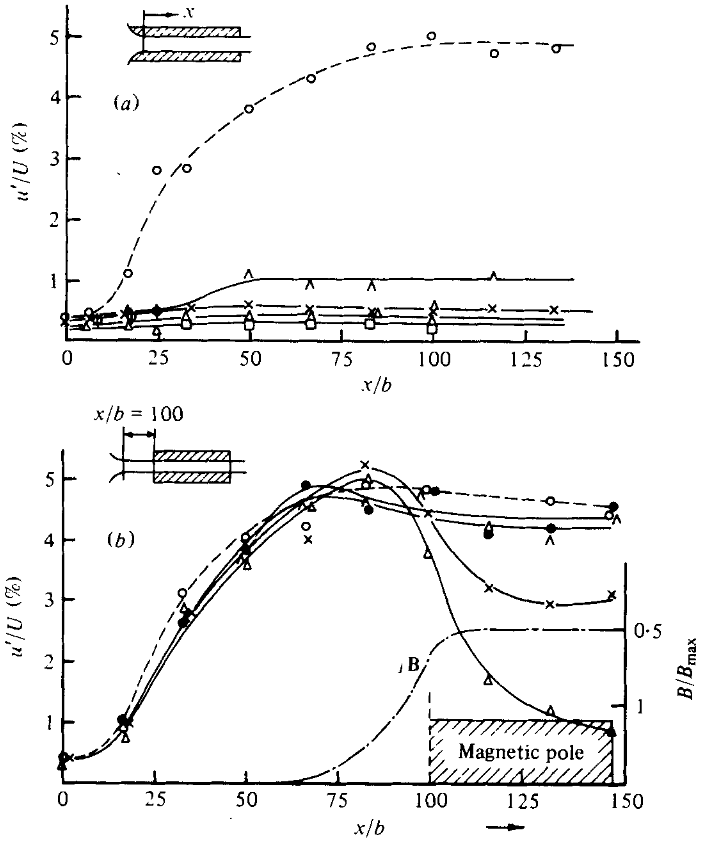

FIGURE 9. Variation of longitudinal velocity fluctuations along duct: (*a*) magnet placed over inlet convergent length; (*b*) developed turbulent flow entering magnetic field. The values of $10^3 Ha/Re$ are: --○--, 0; —●—, 1·58; —∧—, 2·38; —×—, 4·75; —△—, 7·13; —□—, 10·3.

Further results were obtained in the presence of an artificial turbulence-producing grid of irregularly arranged rods (figure 10). As seen from the graph, in the case where the grid was situated outside the field it almost did not change the shape of the $u'/U = f(Ha/Re)$ curve at all, in comparison with the curve in figure 4. Obviously, if the turbulence entering the field had been transformed into residual turbulence, then the presence of the grid ahead of the entry of the flow into the magnetic field would have increased the residual turbulence. However, such an increase was not observed. On the other hand, when the magnetic field was applied to the channel length containing the grid, the residual turbulence increased at supercritical values of Ha/Re, which points to the generation of new disturbances in the presence of the magnetic field. Since the probe was located a relatively large distance from the turbulence-producing grid, it must be concluded that such disturbances are only slightly subject to Joule dissipation, i.e. they are apparently close to two-dimensional in the plane perpendicular to the field.

4.2. *Two-point correlation and spectra*

Important information on the phenomena under study is provided by measurements of two-point correlations of the longitudinal velocity fluctuations. Let us analyse

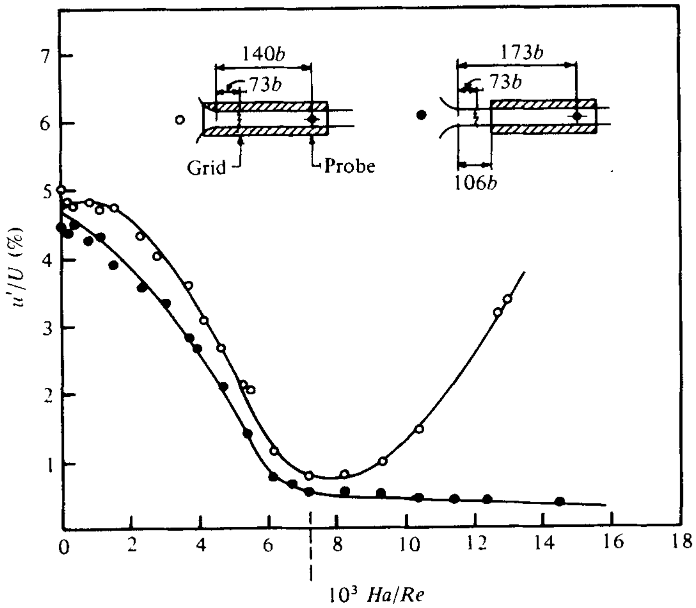

FIGURE 10. Intensity of longitudinal velocity fluctuations in presence of turbulence-producing grid (vertical dashed line indicates transition judged according to friction). $Re = 5400$.

these results on the basis of figure 11(*a*), where they are compared with analogous measurements in a channel with $\beta = 1{\cdot}2$ (Branover & Platnieks 1971). Figure 11(*b*) repeats the corresponding curves of the velocity fluctuations. It can be concluded from the data for the case when breakdown of laminar flow occurs in a magnetic field that, in this case as well, the residual turbulence exhibits an average tendency toward anisotropy. However, attention should be paid to the fact that in the present experiments significant changes in the correlations occur only after the turbulence level becomes so low that it is entirely impossible to use these data with confidence. Conversely, when the magnet is positioned downflow, the anisotropy of the disturbances is more marked, and the correlation decreases rather slowly when *Ha*/*Re* exceeds its critical value. However, the maximum correlation in the direction of the field in our case is much lower than the corresponding correlation of longitudinal fluctuations at two points in a channel with $\beta = 1{\cdot}2$ (the distances between the points were taken to be the same in both cases, when referred to the characteristic cross-sectional dimension). This again suggests that the reason is rooted in the difference between the values of $(N_b)_{cr}$, and consequently in the sharpness of the M-shaped mean-velocity distribution at the entry to the magnetic field.

Finally, we reproduce in figure 12 just a single example of energy spectra of the longitudinal component of the velocity fluctuations (more detailed results of spectral measurements are presented in Branover *et al.* 1978).

The presented spectra correspond to a mean flow velocity $v = 15$ cm s^{-1}, so that for the characteristic size of our channel $b = 0{\cdot}3$ cm the characteristic frequency is higher than 10 per s. Because of the very low Reynolds number, the evaluation of the slope of the spectra under a magnetic field is not relevant, since even without a magnetic field there is no pronounced inertial region with a $-\frac{5}{3}$ slope (the situation is

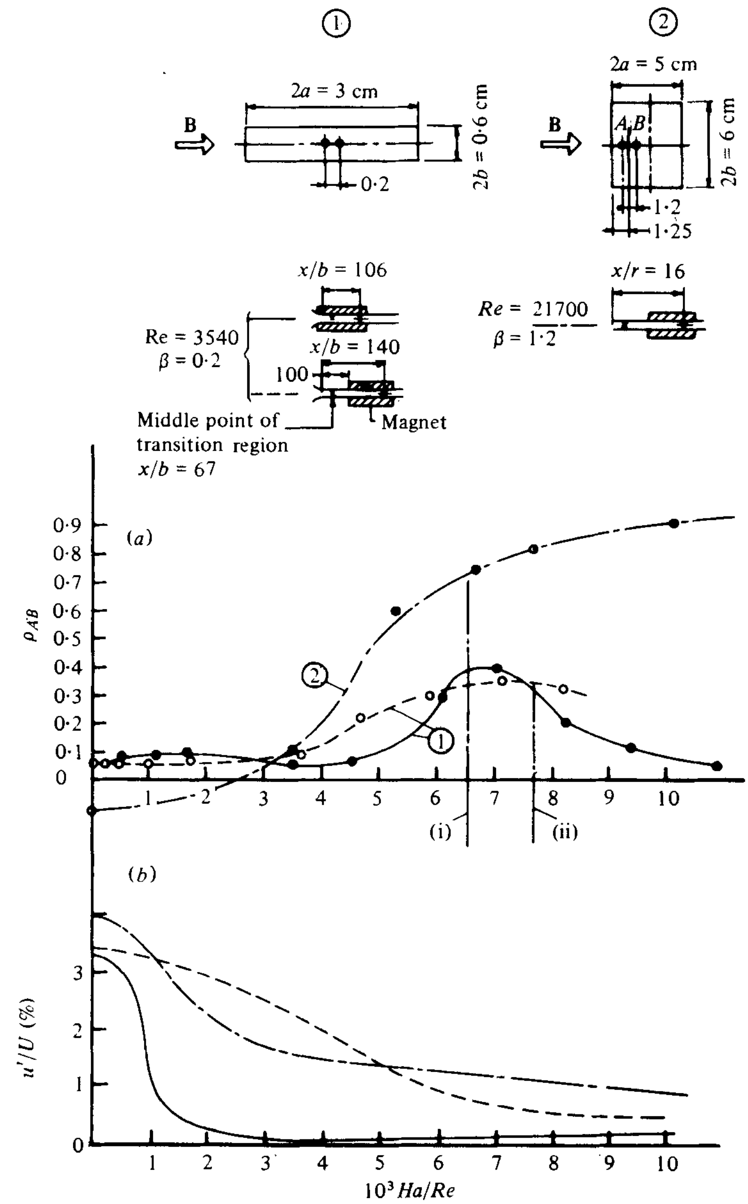

FIGURE 11. (a) Comparison of present two-point correlation measurements with previously measured correlations for β 1·2. (b) Corresponding curves of variation in fluctuation intensity. (i) $(Ha/Re)_{cr}$ for $\beta = 1{\cdot}2$; (ii) $(Ha/Re)_{cr}$ for $\beta = 0{\cdot}2$.

similar to the spectra of Gardner & Lykoudis 1971, which were obtained at low Reynolds numbers). However, our spectra show unequivocally the tendency towards a preservation of low-frequency disturbances at stronger magnetic fields.

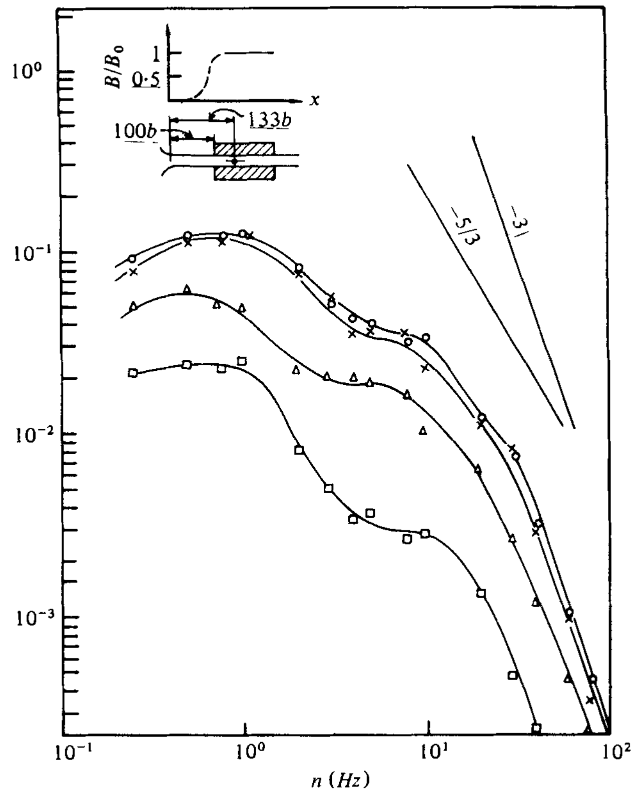

FIGURE 12. Typical energy spectra of longitudinal velocity fluctuations. $Re = 5400$. Values of $10^3 Ha/Re$ are: ○, 0; × = 2·38; △, 4·75; □ = 7·13.

4.3. *Conclusions*

Most of the results shown above indicate quite definitely that the residual disturbances are generated in the field-entry region. They are most probably from their very inception of rather large scale, being strongly stretched along the magnetic field.

In this connexion the measurements of the disturbance-intensity distribution along the channel and the comparison of the flow with and without a grid at two extreme positions of the magnet are most convincing. This conclusion is strengthened, albeit less directly, by the other results discussed above. There is also some indication that the disturbances carried by the flow into the magnetic-field region still have some tendency toward becoming two-dimensional. However, since the process of their 'tuning' to the magnetic field is connected with strong dissipation, they hardly reach the ultimate two-dimensional state before being completely damped out.

Thus we have to conclude that the phenomena at the flow entrance into the magnetic field are the dominating factors responsible for the existence of residual disturbances in a laminarized duct flow.

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