SPECTRAL MEASUREMENTS IN A TURBULENT BOUNDARY LAYER AT A PERMEABLE PLATE WITH INJECTION

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UDC 532.526.4

The intensity spectra of longitudinal, transverse, and lateral velocity fluctuations were measured with a thermoanemometer in the boundary layer at a permeable plate, at various injection levels V_W/U_∞ from 0 to 0.0243.

In the development of effective thermal protection measures there arise problems concerning the turbulence structure in the boundary layer during injection. By examining the flow at permeable walls, one can follow the trend of turbulent processes through all successive changes in the average-velocity profile of the boundary layer. A study of large-scale eddy structures associated with an average-velocity field, as well as a study of small-scale eddy structures which disrupt those large formations and dissipate the turbulent energy, may provide the key to an understanding of the mechanism by which an average-flow mode within the boundary layer develops and may reveal the complete pattern of energy transfer within this region.

The authors have made thorough thermoanemometric measurements of average-flow and fluctuation characteristics in the boundary layer at a flat model plate 2.5 m long and 400 mm wide, with the principal stream flowing at a velocity of 10 m/sec. The model consisted of a preliminary stage 1 m long, a permeable stage 1030 mm long, and a wake stage 0.5 m long. The measurements were made in an A-10 aerodynamic tunnel in the Institute of Mechanics Laboratory at the Moscow State University, with a DISA constant-temperature thermoanemometer and a Bruel–Kjer spectrum analyzer. The result of these measurements had been partially published already [1-3], together with a description of the test apparatus and the procedure for measuring both longitudinal and transverse velocity fluctuation during injection. The test data on the intensity distribution of longitudinal, transverse, and lateral velocity fluctuations during injection, as well as the measurements of turbulent tangential stresses, indicate a significant distortion of the eddy pattern within the boundary layer, but the energy aspects of turbulence have remained unexplored.

The spectral measurements made by the authors here should have confirmed the universality of a small-scale eddy structure in a distorted average-velocity field. The spectral measurements were undertaken for the basic purpose of verifying the universality of the small-scale eddy structure independently of the distribution mode of the average velocity during injection, also for the purpose of establishing the range of wave numbers within which changes due to injection should be most pronounced. The instrumentation for these measurements yielded the spectra of longitudinal and transverse fluctuations and, after rotation of the cruciform probe through 90° about its axis, also the spectrum of lateral fluctuations. In Fig. 1a are shown spectra of longitudinal fluctuations at various injection levels, recorded at a section 700 mm from the front edge of the permeable plate at points within the boundary layer where the velocity was equal to approximately two-thirds of the oncoming stream velocity. These spectra have been normalized to

$$\int_\infty^0 F_{u^2}(k)\,dk = 1.$$

N. E. Bauman College of Engineering, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 24, No. 6, pp. 1109-1113, June, 1973. Original article submitted October 25, 1972.

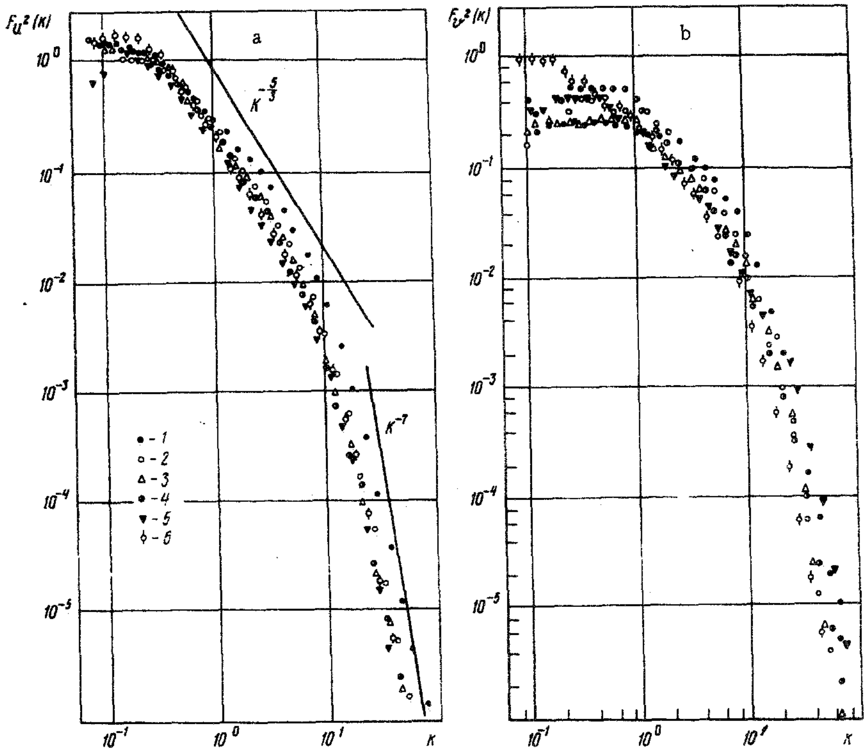

Fig. 1. Spectra (a) of longitudinal velocity fluctuations (at $x_{permeable}$ = 700 mm, U = 2/3) at various injection levels V_W/U_∞: 1) 0; 2) 0.010; 3) 0.0142; 4) 0.018; 5) 0.02125; 6) 0.0243. Spectra (b) of transverse velocity fluctuations at an injection level V_W/U_∞: 1) 0 at y/δ = 0.0417; 2) 0.010 at y/δ = 0.453; 3) 0.0142 at y/δ = 0.379; 4) 0.018 at y/δ = 0.465; 5) 0.0212 at y/δ = 0.530; 6) 0.0243 at y/δ = 0.790.

The data obtained with injection deviate from the spectra for an impermeable plate, but they are consistent and in the range of lowest wave numbers such deviations become regular. For comparison, we also show here straight lines with slopes representing the "minus five-thirds power" and the "minus seventh power" law, respectively, derived analytically for the viscous–inertial spectrum band and for the range of large wave numbers, respectively, the latter characterizing small-scale dissipative eddies ([4], p. 43). The test data concur with those laws, especially during injection. The overall effect of injection is such that the range of locally isotropic turbulent fluctuations expands to include lower wave numbers. Most of the changeover from one to another spectral function occurs at rather low injection levels (up to V_W/U_∞ = 0.01). The small-scale eddies are in equilibrium at high wave numbers, regardless of the extent to which the average-flow field has been distorted. Analogous conclusions can be drawn concerning the spectra of transverse and lateral velocity fluctuations recorded at the same section, as shown in Figs. 1b and 2. The inertial range of these spectra, characterized by a slope of −5/3, is much narrower and the normalized values are not as consistent as before: they differ more at low wave numbers and follow more closely the "minus one power" law, thus indicating a strong interaction between the average flow and the fluctuations. Noteworthy are the differences between the different velocity components in terms of the manner in which their spectral functions change during injection and thus indicate a change in the large-scale eddy structure. It could be that large and very elongated eddies, characteristically appearing when the gradient of the longitudinal velocity component is large, become more isotropic within the boundary layer at an impermeable plate when the longitudinal gradient of the average velocity is much smaller during injection. It is also to be noted that the attenuation characteristics of all spectra here are approximately the same. This means that the energy contents of all components of the fluctuation velocity equalize at higher wave numbers.

The degree of anisotropy of turbulent fluctuations was checked indirectly by converting the spectrum of longitudinal fluctuations into a spectrum of transverse fluctuations according to the formula ([4], p. 45)

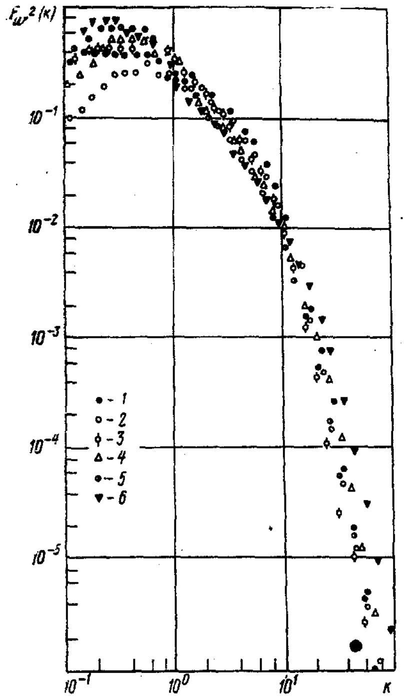

Fig. 2

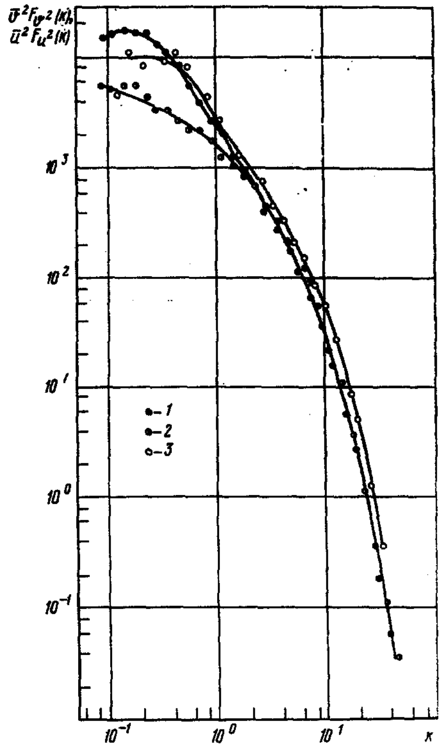

Fig. 3

Fig. 2. Spectra of lateral velocity fluctuations ($x_{permeable} = 700$, U = 2/3) at various injection levels V_w/U_∞: 1) 0 at $y/\delta = 0.0416$; 2) 0.005 at $y/\delta = 0.216$; 3) 0.01 at $y/\delta = 0.267$; 4) 0.0142 at $y/\delta = 0.530$; 5) 0.018 at $y/\delta = 0.458$, 6) 0.0212 at $y/\delta = 0.528$.

Fig. 3. Comparison between the measured and the calculated spectra at an injection level $V_w/U_\infty = 0.0242$: 1) $u^2F_{u^2}(k)$ at $y/\delta = 0.790$; 2) $\bar{v}^2F_{v^2}(k)$ at $y/\delta = 0.790$; 3) $\bar{v}^2F_{v^2}(k)$ calculated according to the formula in ([4], p. 45).

$$\bar{v}^2 F_{v^2}(k) = \frac{\bar{u}^2}{2}\left[F_{\bar{u}^2}(k) - k\frac{d}{dk}F_{\bar{u}^2}(k)\right].$$

The results of such a recalculation are shown in Fig. 3. The differences between the spectra are especially pronounced in the range of low wave numbers, which confirms the anisotropy of fluctuation components in the low-frequency range. In the range of high wave numbers, on the other hand, the measured and the calculated values are close, which indicates a local isotropy. Simultaneous strong injection does not produce significant changes in the trend of the spectra, whether measured or calculated, and this confirms that the structure of dissipative turbulence remains independent of the average-velocity profile of the boundary layer.

NOTATION

x	is the longitudinal coordinate;
y	is the transverse coordinate;
U	is the longitudinal average velocity;
V	is the transverse average velocity;
u	is the longitudinal component of the instantaneous velocity;
v	is the transverse component of the instantaneous velocity;
w	is the lateral component of the instantaneous velocity;
f	is the frequency;
$k = 2\pi f/U$	is the wave number;
F (k)	is the normalized spectral function;
δ	is the thickness of the boundary layer.

Subscripts

w denotes the wall;

∞ denotes the stream.

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