CERTAIN KINEMATIC CHARACTERISTICS OF THE BOUNDARY LAYER AT A STREAMLINED ELASTIC PLATE

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Results of measurements are presented pertaining to the coefficients of lateral, in space, correlations and the spectral density of longitudinal velocity fluctuations at a rigid plate and at an elastic plate.

Many theoretical and experimental studies have to this time been made concerning the interaction of a stream and elastic surfaces [1]. Most of those studies were integral in scope and did not yield sufficient data on the stream structure, not making it possible to explain the physical pattern and to construct a reliable theory of interaction between a stream and elastic plates. Some of the results are favorable and indicate a decrease of either the aerodynamic drag or the magnitude of fluctuation velocities within the boundary layer at elastic plates [2-5].

Other unfavorable results were obtained mainly because of incorrect measurement techniques and inappropriate choices of elastic plates in terms of their design and mechanical characteristics. In one study [6] measurements at the plate were made at low velocities. For making it possible to read small values of the measured quantities, this plate had been suspended on highly sensitive elements responding simultaneously to minimal variations of static pressure and stream velocity. Moreover, the inappropriate mounting of the elastic plate and large clearances between this plate and the active tube segment caused the readings to spread widely. Interaction of a stream and membrane surfaces [1] was found to generate surface waves of large amplitudes destabilizing the boundary layer and, owing to the arbitrary selection of the plate material, the elastic plates hardly ever had mechanical properties approaching the optimum ones relative to the stream velocity [4,7]. All this points to the necessity of carefully preparing and performing such experiments with elastic plates, also of studying more attentively the flow pattern in the boundary layer.

Studies were already made earlier [7] to determine the physical laws of fluid flow in a laminar boundary layer at various kinds of elastic surfaces. These studies have revealed that certain kinematic characteristics in this case differ from the analogous ones in the case of a rigid surface.

In this study an attempt was made to explain the physical flow pattern in a turbulent boundary layer at an elastic plate. The experimental results were compared with characteristics of a boundary layer at a rigid reference plate made of acrylic glass as well as with experimental data obtained by other authors [1,4,6,8-11]. Measurements were made at the bottom of the active segment of the hydrodynamic test stand [7], where at a distance of 2 m from the entrance and flush with it, a 0.5 m long strain gauge had been inserted, either the reference plate or the elastic plate was mounted to it. The latter was a 10-mm-thick strip of grade 20 pores per cm (ppc) polyurethane foam with a 0.01-mm-thick varnish coat on the outside. This varnish coat was bonded on with grade BF-88 glue, not water resistant and softening somewhat in the course of the experiment so that the elastoplastic plate became more compliant. The velocity of the mainstream was 0.5-0.6 m/sec and a turbulent boundary layer was observed within the region where the strain gauge had been inserted.

The kinematic characteristics were measured at various locations across the thickness of the boundary layer, with DISA thermoanemometric instruments used for this purpose. Two probes were simultaneously placed at a distance of 0.4 m from the front edge of the plate, one remaining stationary and one movable by tabs with a 0.1 mm precision relative to the

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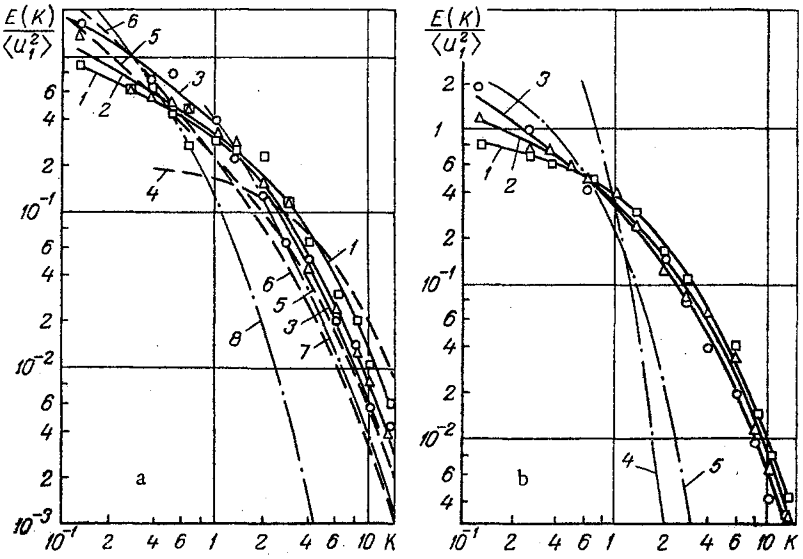

Fig. 1. Spectra of $\langle u_1^2\rangle$ in the boundary layer at (a) the rigid plate and (b) the elastic plate: (a) measurements by these authors at $x_2/\delta = 0.0135$ (1), 0.135 (2), 0.27 (3); by Klebanov [11] at $x_2/\delta = 0.0011$ (4), 0.05 (5), 0.2 (6); and by Kawamata et al. at U = 5.9 cm/sec (7), 53 cm/sec (8); (b) measurements by these authors at $x_2/\delta = 0.0135$ (1), 0.135 (2), 0.257 (3), and by Kawamata et al. at U = 9.6 cm/sec (4), 63.6 cm/sec; $E(K)/\langle u_1^2\rangle$ (cm), K (cm^{-1}).

former in a plane normal to the direction of the oncoming stream. Fluctuations of velocity u_i and its correlation coefficients were measured relative to the coordinate axes.

The results of measurements pertaining to the fluctuation characteristics of the boundary layer at the elastic plate were recorded on magnetic tape and then processed with a model S4-29 spectrum analyzer. The velocity of the quiescent stream was checked and the thermoanemometer probes were calibrated with a Pitot tube including an inclined differential manometer as well as with a Kherkherulidze microvane including readout on the frequency meter and on a loop oscillograph. The temperature of the stream was checked with a thermometer graduated into 0.1°C divisions.

The energy spectrum of the fluctuation velocity u_1 at various points x_2/δ is shown in Fig. 1a for the streamlined rigid plate. The results obtained for this plate agree closely with those obtained by Klebanov [11] and indicate that farther away from the wall the low-frequency range of the spectrum predominates, evidence of a contribution of large vortices to the turbulence energy. Closer to the wall the contribution of the high-frequency range of the spectrum to this energy increases. There is also a close agreement between the trends of function E(K) at different points x_2/δ.

Curves 7 and 8 refer to $x_2 = 0.7$ mm in the tube [8] and have been calculated from the relation $E(n)/E(0) = f(n)$ according to the expression

$$\frac{E(K)}{\langle u_1^2\rangle} = \frac{E(n)}{E(0)}\,\frac{U}{2\pi}\left[\int\limits_0^\infty \frac{E(n)}{E(0)}\,dn\right]^{-1}.$$

The energy spectrum of a turbulent boundary layer at the elastic plate is shown in Fig. 1b. This spectrum is not substantially different than that for the rigid plate, because the average characteristics of the stream do not change significantly. However, the spectrum curves obtained at the same x_2/δ in each case do differ somewhat. At $x_2^+ \approx 220$ (Fig. 1a, b, curves 3), for instance, the energy density of velocity fluctuations u_1 with wave numbers up to approximately 3 during streamlining is lower at the elastic than at the rigid plate. At $x_2^+ \approx 110$ (Fig. 1a, b, curves 2) $E(K)/\langle u_1^2\rangle$ with wave numbers up to approximately 2 is somewhat higher at the elastic than at the rigid plate. At $x_2^+ \approx 11$ (Fig. 1a, b, curves 1) $E(K)/\langle u_1^2\rangle$ during streamlining is higher from $K \approx 0.2$ to $K \approx 2.2$ and lower from $K \approx 2.2$ up at the elastic than at the rigid plate.

A comparison of curves 3 for the rigid and the elastic plate indicates that in the latter case the power law with exponent −1 holds true over a wide range of small wave numbers. Moreover, the interaction between average flow and turbulent flow within the turbulent core of the boundary layer at the elastic plate ($x_2/\delta = 0.135$–0.26) becomes stronger. A comparison of curves 1 in Fig. 1a, b indicates that within the range of small wave numbers the spectrum of the viscous sublayer, characteristic of the rigid plate (Fig. 1a, curve 4), is retained near the elastic plate, which is indirect evidence of a thicker viscous sublayer at the streamlined elastic plate.

These data also indicate a lower energy of low-frequency vortices within the turbulent core and a lower energy of high-frequency dissipative vortices, due to more intensive absorption, within the transition zone as well as the outer region of the viscous sublayer (at $x_2/\delta = 0.0135$) of the boundary layer at the elastic plate. This results in a higher energy of large vortices near the elastic plate and, as a consequence, in a redistribution of the energy balance across the boundary layer.

The spectra of $\langle u_1^2 \rangle$ for the elastic plate could be compared not only with data pertaining to the rigid reference plate but also with some data pertaining to other forms of an elastic plate. Thus, the energy spectra of velocity fluctuations u_1 at $x_2/\delta = 0.0033$ have been compared [4] which characterize streamlining of the rigid plate and an elastic plate made of grade 16-ppc polyurethane foam with an outside 0.064-mm-thick film of polyvinyl chloride. These experiments have been performed in an aerodynamic tube at the Reynolds number $N_{Re} = 4.2 \cdot 10^6$. It has been stated that at various x_2/δ points an elastic plate decreases the energy of high-frequency fluctuations (by up to 35% at $x_2/\delta = 0.0033$) and decreases the energy of low-frequency fluctuations (by up to 10%). These data and those obtained at $x_2/\delta = 0.0135$ are in close agreement.

In another study [8] the energy spectra of velocity u_1 at $x_2 = 0.7$ mm for the case of water streamlining a plate of Neoprene rubber with a layer of olive oil underneath were obtained. Here, the elastic plate was found to decrease the energy of high-frequency fluctuations of the longitudinal velocity at various values of the Reynolds number.

The results of experimental studies are explainable by the earlier-proposed theory [12] including, specifically, the coefficient of absorption of fluctuation energy by an elastic plate. Theoretical studies have revealed that an elastic surface is capable of more intensively absorbing the high-frequency fluctuations in the boundary layer of a turbulent stream. The high-frequency velocity fluctuations u_1 decrease then and, consequently, the fluctuation energy is transferred at a rate which decreases as the frequency increases from low to higher ones. This is a consequence of the dissipation of turbulence energy in the stream as well as the rate of energy transfer at different frequencies being increasing functions of the intensity of high-frequency fluctuations. Accordingly, above an elastic surface there builds up a turbulent stream with a somewhat different balance of turbulent energy.

The coefficients of lateral correlation between longitudinal components of the velocity fluctuations can be expressed as

$$g_i = \frac{\langle u_1(\xi)\, u_1(\xi + x_i) \rangle}{\sqrt{\langle u_1^2(\xi) \rangle \; \langle u_1^2(\xi + x_i) \rangle}},$$

where i = 2, 3 when the displacement of the movable probe relative to the stationary one has been along the Ox_2 axis or along the Ox_3 axis, respectively.

The results of measurements of the correlation coefficients shown in Fig. 2a refer to streamlining of the rigid plate with the movable probe of the thermoanemometer displaced along the Ox_3 axis at various x_2/δ points. The initial distance between both probes was 1.3 mm. In another study [10] was measured the lateral, in space, correlation for the velocity in a rectangular channel, the results agreeing satisfactorily with our results. Our results agree best with those of study [9].

An examination of these curves from the integral scale standpoint (no conclusions about the microscale can be drawn from this series of experiments, because of the structural characteristics of the probes) would suggest that the integral scale depends strongly on the distance from the plate to the plane of measurement. The curves in Fig. 2b characterize the correlation coefficients for the rigid plate at various distances of the stationary probe from the bottom, at the time of displacement of the other probe along the Ox_2 axis. The initial distance between them was 1 mm. These curves indicate an anisotropy of the turbulent

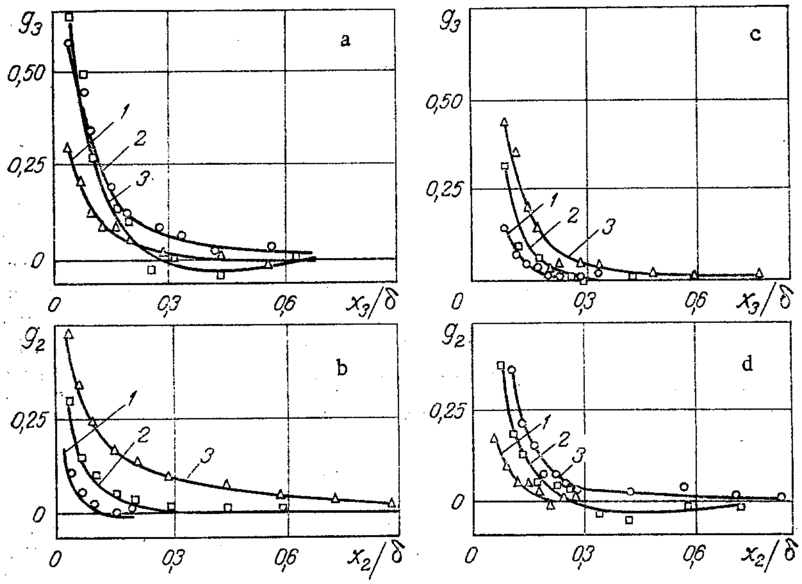

Fig. 2. Coefficients of lateral correlation for the longitudinal fluctuation velocity at (a, b) the rigid plate and (c, d) the elastic plate: (a) $x_2/\delta = 0.0135$ (1), 0.135 (2), 0.27 (3); (b) $x_2/\delta = 0.0405$ (1), 0.122 (2), 0.222 (3); (c) $x_2/\delta = 0.0135$ (1), 0.135 (2), 0.23 (3); (d) $x_2/\delta = 0.0135$ (1), 0.297 (2), 0.297 (sic) (3).

stream near the plate, with the integral scale increasing as the distance from the latter increases.

The correlation coefficients shown in Fig. 2c refer to streamlining of the elastic plate with the second probe displaced relative to the first one along the Ox_3 axis. The initial distance between the probes was 1.4 mm.

The results of measurements made with the movable probe displaced along the Ox_2 axis are depicted by curve 1 in Fig. 2d. The initial distance between the probes was 1 mm. Curve 3 characterizes the same measurements as curve 2, but for an elastic plate with somewhat different mechanical characteristics.

The correlation coefficients are qualitatively analogous for streamlining an elastic and the rigid plate, but there are some quantitative differences. A comparison of the data in Fig. 2a and in Fig. 2c readily reveals that curves 1 and 2 for the elastic plate lie below curves 1 and 2 for the rigid plate, while the relation between curves 3 is reversed. A comparison of the data in Fig. 2b and Fig. 2d reveals that all curves for the elastic plate lie far above the curves for the rigid plate, the difference between values of g_2 as well as between values of g_3 being the largest near the plate. It is interesting to note that the trends of $g_2(x_2/\delta$ and $g_3(x_3/\delta)$ relations differ for the rigid plate but are similar for the elastic plates.

The integral scale

$$\Lambda_i = \int_0^\infty g_i(x_i)\,dx_i$$

will be regarded as the maximum magnitude of a vortex, Λ_3 being its dimension across the stream parallel to the Ox_3 axis and Λ_2 being its dimension across the stream parallel to the Ox_2 axis. The magnitude of Λ_3 is somewhat smaller near the elastic plate than near the rigid plate, but the magnitude of Λ_2 is larger for the elastic than for the rigid plate. This means different vortex patterns at the two streamlined plates: an asymmetric vortex at the rigid plate, more elongated in Ox_3 than in the Ox_2 direction, and a symmetric vortex with an increased Ox_2 dimension at the elastic plate. This increase in the vortex dimension near the elastic plate, with the earlier-mentioned higher intensity of turbulent fluctuations here, indicates lower energy losses in the stream and confirms the earlier conclusion regarding a redistribution of the energy balance across the boundary layer.

These experiments have thus revealed qualitative as well as quantitative differences between the characteristics of turbulent flow at a rigid and an elastic plate, respectively.

NOTATION

$0x_1$, $0x_2$, $0x_3$, longitudinal, vertical, and transverse axes of coordinates, respectively; $i = 1, 2\ 3$, directions along, respectively, the longitudinal, vertical, and transverse axes of coordinates; δ, thickness of the boundary layer; x_2, vertical coordinate of the probe location; $x_2^+ = x_2 u_*/\nu$, dimensionless vertical dynamic coordinate; $u_* = \sqrt{\tau_\omega/\rho}$, dynamic velocity; τ_ω, shearing stress at the plate surface; ν, kinematic viscosity; ρ, density of the liquid; U, longitudinal velocity; u_1, longitudinal fluctuation velocity; $\langle u_1^2 \rangle$, mean-square value of the longitudinal fluctuation velocity; K, wave number; E(K), spectral density function of the longitudinal fluctuation velocity; n, frequency (Hz); gi, coefficients of lateral correlation; ξ, an arbitrary point in the stream; Λ, an integral turbulence scale; and ppc, number of pores per centimeter.

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