METHOD OF EXPERIMENTAL INVESTIGATION OF A SYSTEM OF LONGITUDINAL VORTICES IN THE BOUNDARY LAYER

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A method and results of an experimental investigation of the transition boundary layer are presented for the formation and development of a system of oppositely rotating longitudinal vortices.

The practical interest in the flow mode in whose boundary layer systems of longitudinal vortices are observed is due both to the necessity to take such a structure into account in the flow around real bodies [1, 2], and to solve problems associated with singularities in heat and mass transfer [3, 4] and turbulence.

The results of experiments [5-12] permit a qualitative picture to be given for the development of a vortex system and certain parameters, and dependences to be determined. However, the resolution of individual contradictions associated with different viewpoints on the sequence of the structural states of the boundary layer during the natural transition [5, 13], on the possibility of utilizing measurement technique and a different interpretation of the results [8, 9, 12], and also the obtaining of more detailed information about the nonlinear behavior of vortices require the formulation of carefully planned experiments.

The investigations were performed on a low turbulence test stand ($\varepsilon \leq 0.05\%$) with a drop bottom of the working section which can be both planar and concave with the curvature $1/R = 1$, 0.25, 0.08 1/m in the 0.05-0.5 m/sec velocity range [14]. The measurements were executed by a tellurium method [12, 15] and a laser anemometer [16]. A diagram of the working apparatus and the mutual arrangement of the adapters permitting the velocity profiles U(y) and U(z) to be obtained in any planes are shown in Fig. 1. To observe the flow field in the plane xz, a tellurium wire cathode is soldered to the ends of the streamlined holder 3 fastened in the support 4, which by being on a mobile wagon 8 can be displaced along the working section 1 along the guide 9, and across the boundary layer by using the micrometer screw 5. The anode 10 in the form of two streamlined plates is fastened to the moving wagon near the side walls of the working section at a fixed distance from the cathode. Tellurium jets (streamline visualization) and profiles U(y) are obtained by replacing the holder 3 by another in which the tellurium wire is located along x or y and is displaced along z by using a dial gauge.

The velocity field is recorded by two LOMO-135 BC photographic apparatus in the xy and xz planes. The spring-catch of the camera shutter assures a 8-10 frame scan without subfactory. This affords the possibility of triggering the shutter of the photographic apparatus 6 by using electromagnetic relays 7 which are supplied from an electronic module with regulatable frequency and duration of the pulses. The voltage from this same module is delivered to the tellurium wire: (100-600) V in the pulse mode to obtain velocity profiles and (20-60) V in the continuous mode for streamline visualization.

The holder 2 with vortex generators for the artificial formation of a system of longitudinal vortices is set at a regulatable distance from the holder 3, i.e., the experiment is controlled [17]. Such an approach affords a possibility of varying the vortex scale and to select conforming measurement points. The distribution of disturbances along z in a natural transition or in experiments with a vibrating ribbon [5, 6, 9] is random and irregular in nature, which makes difficult, and in certain cases impossible, the study of vortex system behavior.

Two methods are known for the formation of three-dimensional disturbances: mechanical [9, 10, 18], and thermal [7] based on the action of convective currents due to the heating of a number of wires embedded in the surface. Application of this latter requires great

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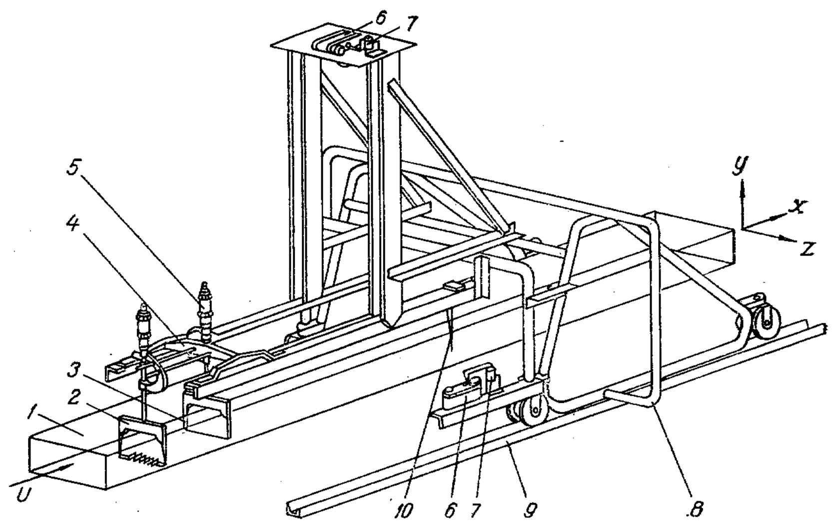

Fig. 1. Diagram of the working part of the apparatus and location of the adapters in a flow investigation by the tellurium method: 1) working section of the hydrodynamic test stand; 2, 3) holders of the vortex generators and tellurium wire; 4) support; 5) micrometer screw; 6) photographic apparatus; 7) relay; 8) moving wagon; 9) guide; 10) anode.

care because of the possibility of the appearance of a temperature boundary layer and the necessity to consider the total effect of the influence of curvature and thermal stratification. In this connection, three sizes of vortex generators mounted at the necessary spacings between each other (a spacing of $2 \cdot 10^{-3}$ m) were constructed and fabricated. In contrast to the cellophane strips glued to the bottom which were used in [9], the system developed produces not only a regular change in the local Reynolds number along z, that governs the rate of growth and deformation of the plane disturbances, but also the periodic sign-varying fluctuation in the transverse velocity component. Moreover, the vortex generators can be placed at any height, i.e., the intensity of the induced disturbances can be changed. Compared to [11, 18] where the effect of collapse of tip vortices from foil strips located outside the boundary layer is used, a finer, clearer, and more easily controllable mechanism for the generation of a vortex system with a large wavelength λ range is realized in this case.

Figure 2a, b gives graphic prints of photographs of the flow field visualized in the xz plane behind a number of vortex generators mounted on a flat bottom. For all the parameters, except λ ($\lambda_a < \lambda_b$), equal, the shape of the tellurium lines indicates the different structure of the boundary layer in these two cases. If a strictly periodic "regular" distribution of the mean velocity U along z is obtained in the first (a) with "peaks" behind the vortex

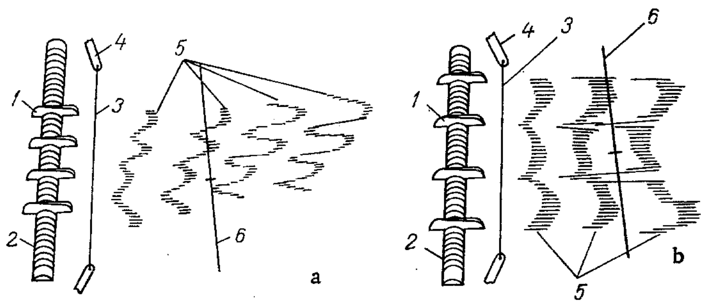

Fig. 2. Graphic prints of photographs of boundary-layer visualization in the xz plane: 1) vortex generator; 2) holder with grooves; 3) tellurium wire; 4) tellurium-wire holder; 5) tellurium cloud; 6) marks on the bottom of the working section.

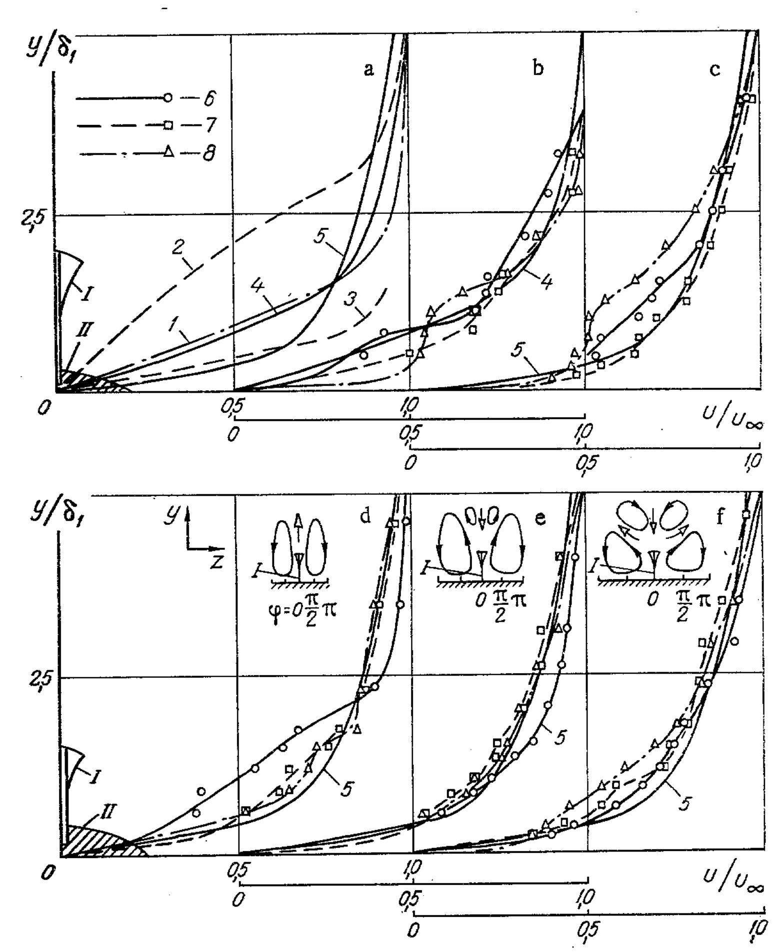

Fig. 3. Average velocity profiles for different flow modes and their corresponding boundary layer structure diagrams: 1) Blasius profile; 2, 3) profiles at the "peak" and in the "valley" from measurements in [11]; author's measurements: 4, 5) without inducing disturbances for $Re = 2.2 \cdot 10^5$ and $Re = 4.4 \cdot 10^5$; b, c) with vortex generators for $y_0 = 7.6 \cdot 10^{-3}$ m and $\lambda = 12 \cdot 10^{-3}$ m and $Re = 2.2 \cdot 10^5$ and $Re = 4.4 \cdot 10^5$, respectively; d, e, f) with vortex generators for $y_0 = 5.6 \cdot 10^{-3}$ m, $Re = 4.4 \cdot 10^5$, and respectively $\lambda = 8 \cdot 10^{-3}$; $12 \cdot 10^{-3}$; $16 \cdot 10^{-3}$ m; 6, 7, 8) values of the velocity at the peaks ($\varphi = 0$), in the valleys ($\varphi = \pi$), and in the intervals between ($\varphi = \pi/2$).

generators (streamlines directed upward, value of U minimal), and "valleys" between them (streamlines directed downward, U maximal), then flattening and even concavity of the profiles is observed in the valleys in the second (b), i.e., the velocity there attains the value characteristic for case *a*, which can be explained by the occurrence of ascending streams bringing the retarded fluid particles into the upper layer.

The results of measuring the profiles U(y), performed on a flat horizontal surface by using a laser Doppler velocimeter for three values of z and different values of Re and λ, can be interpreted analogously. Such families of profiles are represented in Fig. 3. Because of the nonlinearity of the measurable characteristics and their great uncertainty in the region of small values of y, the intervals between the points are here also selected smaller so that the curves constructed over the whole extent would have identical accuracy [17]. Velocity profiles that occur in the absence of vortex generators for $U_\infty = 0.1$ m/sec (curve 4) and $U_\infty = 0.2$ m/sec (curve 5) are presented in Fig. 3a. They differ from the Blasius profile (curve 1) but do not disclose any tendencies toward the inflections characteristic for the presence of three-dimensional disturbances. Here velocity profiles at the peak (curve 2) and the valley (3) obtained in [11] for a vortex system close to rupture, when the difference between the magnitudes of the mean velocity at the peak and in the valley is $U_{-} \approx 0.7U_{\infty}$, are constructed here. The vortex systems in the present experiment are weaker and the maximal value is $U_{-} \approx 0.23U_{\infty}$.

The numbers I and II denote the vortex generator and the section of the lower part of the holder in the scale y/δ_1, respectively (δ_1 is the mean displacement thickness with respect to z).

The results represented in Figs. 3b, c, and d, e, f are obtained by using two size vortex generators so that their effective height over the bottom of the working section was $y_0 = 2\,\delta_1$ in the first case, and $y_0 = (1.4\text{-}1.6)\delta_1$ in the second. The wavelength of the disturbance along z was $\lambda = 3.3\,\delta_1$ in the case of Fig. 3b, $\lambda \approx 3.1\,\delta_1$ for c, $\lambda \approx 2\,\delta_1$ for d; $\lambda \approx 3.1\,\delta_1$ for e, and $\lambda \approx 4.6\,\delta_1$ for f. It turns out that the best conditions for exciting a system of longitudinal vortices are produced for $\lambda/y_0 \approx 1.3\text{-}1.6$. The velocity profiles obtained here (Figs. 3b, c, d) are characteristic for the development of vortex systems [12] with wavelength given by the spacing between the vortex generators: the profiles have an inflection at the peaks, and are filled in strongly in the valleys as compared to the Blasius profile, where the fullness increases as Re grows. Visualization of the flow field in the xz plane yields a strongly periodic, almost sinusoidal line along z, analogous to that shown in Fig. 2a. A schematic diagram of the vortex system described in the yz plane is shown in the upper part of Fig. 3d.

Growth of the ratio λ/y_0 causes a change in the shape of the longitudinal vortices, and additional vortex pairs start to be developed near the peak for $\lambda/y_0 > 2$. This is illustrated in Figs. 3d, e, and f, where the wavelength for $y_0 = \text{const}$ is $8 \cdot 10^{-3}$, $12 \cdot 10^{-3}$, and $16 \cdot 10^{-3}$ m, respectively, and $\lambda/y_0 \approx 1.3$; 2; 3. The appearance of fullness of the profiles U(y) at the peaks due to fluid motion to the wall carrying accelerated particles to the lower layers indicates structure modifications. Moreover, as λ increases the profiles for $\varphi = \pi/2$ become less and less full, which denotes the formation of ascending streams here, as is shown in the diagrams. Furthermore, the retarded fluid particles move to the domain $\varphi = \pi$ and for the case of Fig. 3f this results in troughs at the sites of the highest values of the velocity in the U(z) profiles, for which the flow visualization in the xz plane yields a graphic representation (Fig. 2b).

Therefore, obtaining a "regular" vortex system should be performed with the wavelength of the disturbance produced taken into account.

On the other hand, a study of the conditions for the appearance of the additional vortex pair is an independent problem since it characterizes the further nonlinear development of the vortex system [7, 12]. In the case considered such conditions could be considered to be the diminution of the derivatives of the boundary layer parameters with respect to z, i.e., $\partial U/\partial z$, $\partial \delta/\partial z$, etc. In fact, if these vortex generators produce a definite amplitude of the change in parameters with respect to z, then the increase in the distance between them results in a diminution in its derivative.

The appearance of additional vortex pairs noted by Klebanoff et al. [9] was observed, in contrast to the present paper, near the valley for large values of $\partial U/\partial z$, $\partial W/\partial z$, etc.

The above permits making the deduction that a successful investigation of the fine structure of the transition boundary layer during nonlinear development is only possible upon executing a controlled experiment and using complementary measurement methods such as the undisturbing laser Doppler and spatial visualization by tellurium methods. The production of regular three-dimensionality of the boundary layer is most expediently done here by using a system of mechanical vortex generators which can be shifted relative to all three coordinates in the stream. The profiles U(y) and U(z) obtained for different disturbing motion conditions and parameters afford the possibility of assessing the boundary layer structure and its modifications. The broad range of variation of λ is of great value since it was obtained from preliminary computations based on a theoretical diagram for the surface curvature values used and $U_{\infty} = 0.01$, 0.02 m/sec that the wavelength of the neutral disturbances should vary from $5 \cdot 10^{-3}\text{-}5 \cdot 10^{-2}$ m along the working section, i.e., the apparatus described and the method proposed permit a complete study of the system of longitudinal vortices in the boundary layer.

NOTATION

x, y, z, coordinate axes; y_0, effective height of the vortex generator above the bottom of the working section; U_∞, incoming stream velocity; U, W, longitudinal and transverse average local velocity components; R, surface radius of curvature; Re, Reynolds number along the length; δ, boundary layer thickness; δ_1, mean displacement thickness relative to z; λ, wavelength of the three-dimensional disturbance along z; φ, phase of the three-dimensional disturbance (the location of the measurement plane in z relative to the disturbance wave).

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