length of the initial section referred to the nozzle radius; d, particle diameter; ρ_1, jet density; ρ, particle density; c_x, particle drag coefficient; v, particle velocity; v_1, axial jet velocity; ν, kinematic coefficient of the flow viscosity; $\bar{x}_0$, dimensionless coordinate referred to the distance L; d_c, cement particle diameter; d_s, sand particle diameter; $\bar{v}_i$, dimensionless velocity of particle insertion into the jet, referred to v_0.

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VELOCITY FIELD IN A LOW-TURBULENCE HYDRODYNAMIC FACILITY, USING A LASER-DOPPLER TECHNIQUE

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This paper describes a laser-Doppler measurement instrument, and also the technique and the results of an investigation of the velocity field obtained with this instrument in the working section of a hydrodynamic facility.

A low-turbulence hydrodynamic facility is designed for the study of physical processes occurring in the boundary layer. In particular, the facility allows one to model various flow regimes, to study the turbulence generation processes, and the physical features in transition of a laminar flow to turbulence, both on rigid surfaces and on elastically damping surfaces [1]. By analyzing available methods for measuring velocity fields in the boundary layer of water flows [2], one can form the following conclusions. The tellurium method is quite simple, economical, and reliable, and also allows one to visualize physical features of the phenomenon studied. It has been used in the low-turbulence hydrodynamic facility to carry out a large number of experiments studying stability of the laminar boundary layer [1]. However, this method has limited capability. For example, for flow velocities greater than 0.2 m/sec it loses information. Although the hydrogen bubble method allows one to enlarge the range of measured velocities, it does not have sufficient accuracy. The track method is extremely laborious. The thermoanemometer has high requirements for purity of the water and temperature stability of the working substance, and in addition, the presence of the sensors in the flow can have an appreciable influence on the results of the investigation, particularly in the study of transition processes. The laser-Doppler velocity meter (LDVM) overcomes a number of these defects, since it is a probeless method, does not require calibration, and is not sensitive to flow temperature fluctuations. The LDVM has high spatial resolution and a linear relation between the flow velocity and the Doppler signal frequency over the entire range of measured velocities.

On the basis of some experience in using the LDVM [3-5], we decided to improve the equipment for processing the Doppler signal. To do this we developed and fabricated an electronic digital analysis system which increases the accuracy of the measurements and yields data on the "instantaneous" velocity.

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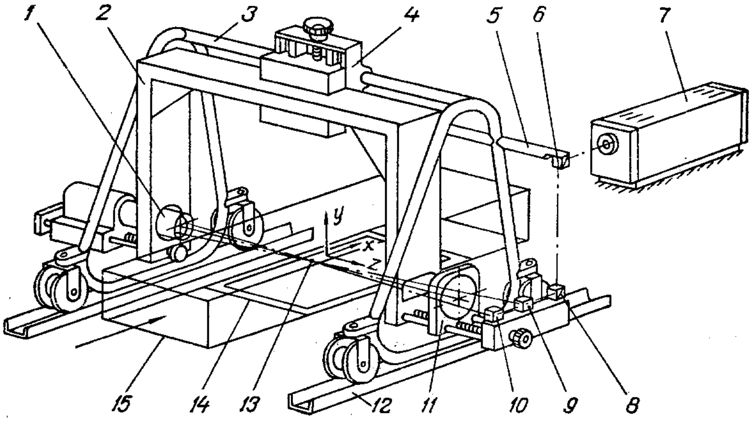

Fig. 1. Layout of elements of the LDVM in the hydrodynamic facility.

The layout and a detailed description of the low-turbulence hydrodynamic facility have been given in [1]. The working substance takes the form of a rectangular channel with a height—width—length ratio of 1:3:33. This ratio can be varied by altering the level to which the working section is filled with liquid. The lower wall of the working section is a movable bottom that is fastened to the floor by several pairs of adjustable bolts, which can be used, first, to level the lower wall, and, secondly, to alter its slope over the range ±3° relative to the horizontal, thus achieving both a zero gradient flow and a flow with a differing longitudinal gradient. In the bottom there is a rectangular window over the entire width of the working section, containing an insert (Fig. 1, 14) flush with the external surface, and mounted on a tension-measurement base. The leading edge of the insert is a distance 2.12 m from the start of the working section, the width of the insert is 0.25 m, and its length is 0.53 m. The gaps between the end surface of the window and the insert are equal: at the leading edge 0.05-0.08 mm, and at the trailing edge 0.1-0.15 mm. The insert takes the form of a composite structure, and its surface can either be rigid, or 75% of the total area can be an experimental type of surface. The side walls of the working section are made of high-quality glass, allowing different optical methods of investigation to be used, in particular, LDVM.

The layout of the basic parts of the LDVM is shown in Fig. 1. A trolley 3 moves along two guides 12 in the facility working section 15. A high-power traverse mechanism 4 is used to attach to the trolley a special truss 2 carrying the photodetector 1 (a type FÉU-79 photomultiplier), the focusing lens 11, the beam splitters 9 and 10, and the rotating prism 8. The prism 6 is fastened to the bracket 5, fixed relative to the trolley. This construction allows the adjustment of the LDVM to be undisturbed during vertical traverse of the entire optical system along the y axis. The trolley has vibration protection for its moving part, allowing it to move smoothly along the working section axis (the x axis). There is provision for locking the position of the trolley with special clamps.

The laser 7 (type LG-38) is mounted on a large vibration-protected base in such a way that its beam is accurately parallel to the trolley traverse direction and is constantly directed to a single point on the prism 6. Because of this measurements may be conducted at any point along the working section without supplementary readjustment of the equipment after each traverse of the trolley along the x axis. The photodetector, the focusing lens, and the beam splitters are mounted, in addition, on individual adjustment devices, not shown in Fig. 1. With these devices the measuring volume 13 (the point of intersection of the focused laser beams) can be moved across the flow, along the z axis. The angle between the focused beams is controlled by the distance between the beam splitter prisms in the range 2 to 11°, and with this one can increase the range of measured velocities by a factor of about 5, and can also control the size of the measured volume.

As a rule, three types of electronic equipment are used to reduce the LVDM signal: spectral-analysis, a digital analysis system, and a frequency-tracking system. The features of each of these are well known [6-8]. In this work we used a two-level digital analysis

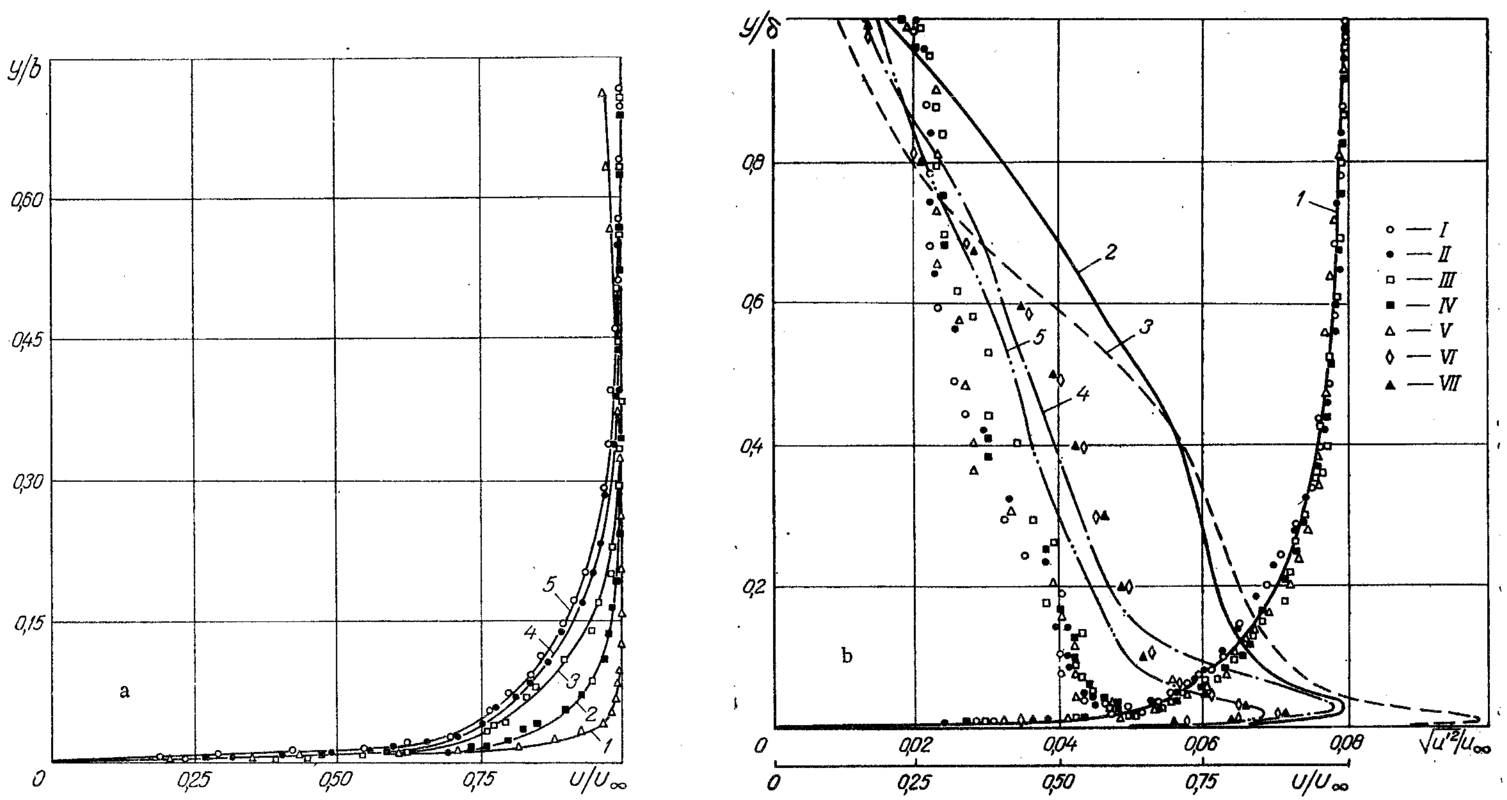

Fig. 2. Profiles of velocity (a, b) and rms values of the fluctuating velocity component (b) along the working section: a) 1-5) number of sections; b) 1) measurements of [10]; 2) of [11]; 3) of [9]; 4, 5) of [12]; I-VII) the present data obtained from the VZ-6 instrument: I) section 6; II) section 7; III) section 8; IV) section 9; V) section 10; from the results of oscillogram reduction: VI) section 9; VII) section 10.

system, analogous in operating principle to that described in [8], but having appreciable differences. Firstly, it uses a single tunable band filter in place of a rack of filters at the input, thus allowing the electronic system to be considerably simplified. Secondly, separation of the analog signal, proportional to the "instantaneous" velocity, is carried out by direct conversion of the output decade counters of a type F 723/2 digital-analog converter. The rate of instantaneous velocity data output was as high as 500 values per second. The entire electronic part system was made up of 22 microsystems of the 155 series, and 25 transistors in the form of a separate unit. In addition to this unit, the signal processing system also used serial devices: an F 571 frequency meter, a type F 5007 programmed reversible counter, a type F 590 digital frequency series generator, and a supply unit. For recording the average velocity data we used a type F 581K digital-printer, and a type N 041U4.2 light-beam oscillograph was used to record the instantaneous velocity analog signal. Control of operation of the entire electronic system was achieved with a type Cl-57 oscillograph and a type C4-25 spectral frequency analyzer. To obtain the rms values of the fluctuating velocity component we used a VZ-6 effective value millivoltmeter, which was connected to the output of the digital-analog converter via an appropriate smoothing filter.

The measurements were conducted as follows. After the LDVM optical system was adjusted, the electronic equipment was warmed up. At the same time, the hydrodynamic facility was brought up to operating conditions. When the equipment was warm a final adjustment was carried out and the flow velocities were monitored. Then the zero of the vertical tranverse was set. To do this the entire optical system was lowered, using the vertical traverse, until the lower wall of the working section touched the point of intersection of the laser beams. The plane of convergence of the laser beams was inclined at a small angle to the detachable bottom, i.e., the xoz plane, to allow measurements to be made as close as possible to the lower wall, and also to determine the time of contact more accurately. The vertical traverse counter was set up by using measuring devices mounted on the traverse. The accuracy of the reading was ±0.01 mm. The steps between the measured points were the same. Near the wall they were 0.2 mm, and then 0.5, 1, 2 mm, and, finally, 4 mm. In all, measurements were taken at 30 points to construct a single profile. Here the velocity value at each point was the average of three readings. Simultaneously, the measurements of the rms fluctuating velocity component were taken, and a monitor record of the readings on the optical oscillograph was made. In transition from one section to another, as was noted above, a special readjustment was not required. The zero of the vertical traverse was set up at each section. The distance between the sections was determined to an accuracy of 0.5 mm from a scale fastened alongside the working section.

In addition to measurements of the velocity profiles at the working section axis ($z = 0$), measurements were also made at $z = 20$ and $z = 45$ mm. In each case the focusing lens was moved along the z axis, which led to displacement of the measuring volume along the same axis and required readjustment of the photodetector. Otherwise, the measurement technique remained unchanged. All the data taken in the work were obtained for $U_\infty = 0.6$ m/sec. The velocity profile was measured at ten different sections of the working section. These sections (1-10) were located at distances 0.15; 0.65; 1.15; 1.65; 1.87; 2.13; 2.28; 2.36; 2.48; 2.60 m from the start of the working section. Sections 6-10 were located within the insert 14. At these sections, in addition to the velocity, its fluctuating component u' was measured. The results are shown in Fig. 2.

Figure 2a shows the velocity profiles at sections 1-5. It can be seen that, as the Re number increases, the boundary-layer thickness increases downstream, and the shape of the profiles varies, as one approaches turbulence. In the span of the working section the boundary layer appears to pass successively through three stages: laminar, transitional, and turbulent. The variation in the profiles is in good agreement with analogous measurements taken using the thermoanemometer [9]. Figure 2b shows the velocity profiles and the rms values of the fluctuating velocity component at sections 6-10. The velocity profiles at these sections are similar in shape, practically coincident, and agree with the results of [10]. The reason is that sections 6-10 are located in the developed turbulent flow region, and the Re number varies only a little from section to section (at section 6 and 10 the Re number is $1.05 \cdot 10^6$ and $1.33 \cdot 10^6$, respectively).

The profiles of rms values of the fluctuating velocity component agree qualitatively very well with the data of [9-12]. The use of the VZ-6 millivoltmeter to measure the rms values leads to underestimated readings, since its operating frequency band is cut off below

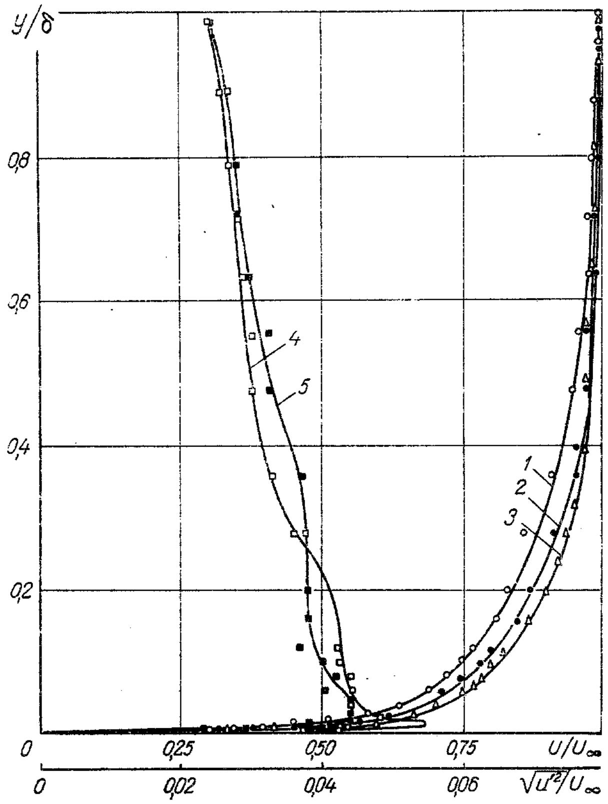

Fig. 3. Profiles of velocity (1, 2, 3) and rms values of the fluctuating velocity component (4, 5) at section 10 for z = 0 (1, 4), 20 mm (2, 5) and 45 mm (3).

at 5 Hz. To estimate the error introduced the fluctuating characteristics at sections 9 and 10 were also obtained from direct reduction of the oscillograms. The results of this reduction agree satisfactorily with the data of Repik and Klebanoff. This confirms our hypothesis regarding the cause of the errors and the need for direct reduction of the oscillogram; e.g., using a computer.

The data of Repik and Klebanoff presented here and the present data were obtained at Re values of the same order. However, for the first case these Re numbers were obtained in an air stream by virtue of a large velocity. In the hydrodynamic facility the velocity of the unperturbed liquid stream is low: $U_\infty \sim 0.6$ m/sec. The large Re values were obtained by virtue of the working section lengths, and therefore the values of the turbulent wall fluctuations differ somewhat from the measured results of Klebanoff and Repik, and better agreement is obtained with the data of [12].

Curve 3 was obtained for $Re = 4 \cdot 10^6$, and curves 4 and 5 for $Re = 0.36 \cdot 10^6$ and $0.74 \cdot 10^6$, respectively. The assumption that the intensity of the longitudinal fluctuating component decreases near the wall with increase of Re [12] is not confirmed in the present investigation, probably because of the small range of change of Re numbers. The intensity of velocity fluctuations in the wall region is possibly determined not only by the Re number, but also by the degree of turbulence of the main flow and the intensity of perturbations in the boundary layer.

Figure 3 shows profiles of velocity and fluctuating velocity component at section 10 for various values of z. It can be seen that as one departs from the working section axis the nature of the flow varies, and the velocity profiles become less full. The variation in shape of the velocity profiles occurs because of the influence of the channel side walls, where the lateral boundary layers are formed. It can be seen that as one gets close to the side walls of the channel, the deformation of the velocity profile increases. This influence also manifests itself in the shape of the fluctuating relations, which lose the form typical of turbulent flow as one withdraws from the channel axis.

The results of the experimental investigation of certain kinematic characteristics of the boundary layer on a rigid lower wall of the working section of the hydrodynamic facility are in good agreement with the data of [9-12]. This confirms the reliability of the technique in carrying out this type of experiment.

NOTATION

x, y, z, coordinate axes; δ, boundary-layer thickness; b, working section height; U, component of the mean velocity along the x axis; u', fluctuating velocity component along the x axis; U_∞, velocity in the oncoming flow.

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