INVESTIGATION OF THE TURBULENCE OF A LIQUID USING A DIFFERENTIAL TYPE DOPPLER OPTICAL VELOCITY METER

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The article discusses the reasons for the instrumental broadening of the Doppler signal in a differential type Doppler optical velocity meter. It is shown that this broadening can amount to no more than 0.1%. The degree of turbulence in the flow of a liquid in a vortical chamber is measured.

Doppler optical velocity meters have recently been used to investigate flows of liquids and gases [1]. If the photo-heterodyne method is used to isolate the Doppler shift of the frequency in a Doppler optical velocity meter, there is obtained, at the output of the photoreceiver, an electrical signal whose instantaneous frequency corresponds to the instantaneous value of the velocity of the flow at the point in space under investigation. Therefore, the Doppler signal contains complete information on the statistical characteristics of the local velocity of a turbulent medium.

The present article discusses a spectral method for the analysis of an electrical signal with a Doppler frequency. In this case, the degree of turbulence is measured using the relationship

$$\sqrt{\langle u'^2 \rangle} / \langle u \rangle = k_1 \Delta f / \langle f_D \rangle \tag{1}$$

where $\langle u \rangle$ is the mean velocity of the flow; u' is the pulsation flow velocity; $\langle f_D \rangle$ is the mean Doppler frequency; Δf is the breadth of the spectrum of the Doppler signal; k_1 is a proportionality symbol, depending on the character of the velocity distribution and on the level with respect to which the breadth of the spectrum is measured.

Formula (1) is valid if the ratio of the mean-square value of the variance of the frequency of the Doppler signal to the highest frequency of the velocity pulsations is great.

It is of interest to analyze the lower limit in measurement of the degree of turbulence, and to elucidate the reasons for its limitation.

Since a Doppler optical velocity meter measures the rate of motion of optical nonhomogeneities, it is first necessary to consider the question as to how accurately the velocity of the nonhomogeneities corresponds to the velocity of the surrounding medium.

In an investigation of liquid flows, the optical nonhomogeneities are usually set up artificially, i.e., by introducing into the flow small particles with a refractive index different from the refractive index of the liquid.

Thus, for example, in the investigation of flows of water, monodisperse particles of polystyrene with a size of $\sim 0.5\ \mu$ are added. The characteristic frequency, determining the frequency of the particles in the stream, and the reciprocal of the time required to bring the particle around which the flow is taking place out of its state of rest, is 10^6 Hz [2]. This frequency is considerably greater than the frequencies of the turbulent pulsations of the liquid. Therefore, the mean-square velocity of the relative motion of such particles is always much less than the mean-square velocity of the liquid.

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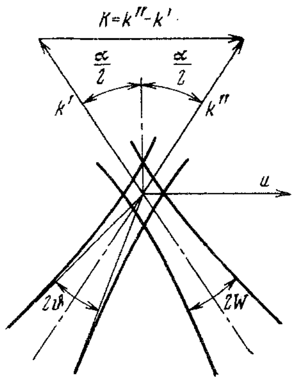

Fig. 1

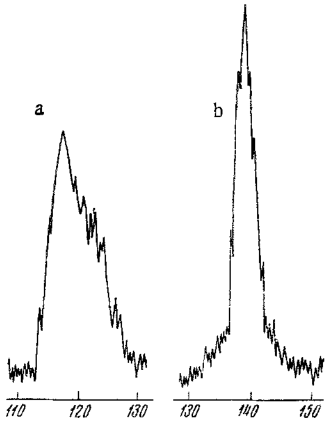

Fig. 2

The selection of particles with a still smaller size is not advisable, since in this case they will be subject to intense Brownian movement, which leads to an additional broadening of the spectrum. Thus, based on the theory of the scattering of coherent light on small particles [3], it can be shown that for particles of polystyrene with a size of 0.1 μ the breadth of the spectrum of the signal due to Brownian movement is ~ 0.5 kHz, which is considerable in the investigation of slow flows, for example, with natural convection.

The lower limit of measurement of the degree of turbulence is determined by the instrumental broadening of the Doppler signal, which depends on the optical and radiometric parts of the scheme of a Doppler optical velocity meter.

Modern spectral analyzers, used in velocity meters, have a Q of 10^3-10^4, i.e., their relative instrumental broadening is 0.1-0.01%.

Let us make a more detailed analysis of the broadening due to the optical part of the scheme. Let us consider the differential scheme of a Doppler optical velocity meter [4], in which two coherent beams from a single laser generator are focused, using lenses, at the point of the flow under investigation, and the observation is made in scattered light from both beams. In this case, information on the velocity is obtained only from the region of the intersection of the beams (Fig. 1), and the difference in the Doppler frequencies is determined by the scalar product of the vector **K** and the vector of the flow velocity **u**

$$f_D = \frac{1}{2\pi}\mathbf{K}\mathbf{u} \tag{2}$$

where $\mathbf{K} = \mathbf{k}'' - \mathbf{k}'$, $|\mathbf{k}'| = |\mathbf{k}''| = 2\pi/\lambda$; $\mathbf{k}'$, $\mathbf{k}''$ are the wave vectors of the incident beams; λ is the wavelength of the laser radiation.

If we consider the case when the velocity vector **u** is directed with respect to **k**, the relative broadening due to the finite divergence of the incident beams will be

$$\delta f_D / f_D = \sqrt{2}\vartheta \operatorname{ctg} \alpha / 2 \tag{3}$$

where ϑ is the angle of convergence of a beam; α is the angle between the incident beams.

In [5], with an analysis of the reasons for the broadening of the spectrum, the beam of light from the laser generator was assumed to be homocentric. In this case, the divergence of a beam is connected with the focusing action of the lens and, for both schemes of a Doppler optical velocity meter, $\vartheta = 0.1$-$1°$, which gives a broadening of 0.5-5%.

We shall show that, using the special characteristics of laser beams, and by focusing them accurately, this broadening for the differential scheme of a Doppler optical velocity meter can be considerably decreased. A beam of coherent light from a laser generator, operating in a basic mode, is Gaussian, and its caustic surface has a hyperbolic form. The radius of a Gaussian beam, w, at a distance z from the constriction (the minimal transverse cross section), evaluated from the drop in the amplitude of the field by e times in comparison with the amplitude of the field at the axis of the beam, is determined by the expression [6]

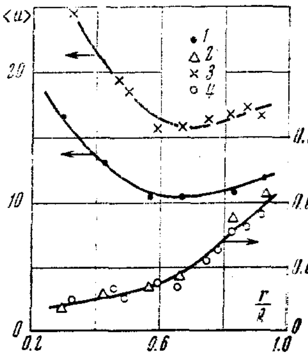

Fig. 3

$$w = w_0 \sqrt{1 + 4z^2 R_0^{-2}} \tag{4}$$

where $w_0 = (R_0/k)^{1/2}$ is the radius of the constriction, R_0 is the confocal parameter of the beam, depending on the parameters of the laser generator and the geometry of the experiment.

The radius of curvature of the wave front of a Gaussian beam, R, is equal to infinity at the constriction and varies with distance in accordance with the formula

$$R = z + R_0^2/4z \tag{5}$$

If the axes of the beams intersect in the region of the constriction, the relative broadening of the spectrum has the form

$$\frac{\delta f_D}{f_D} = \frac{4\sqrt{2}\,\mathrm{ctg}^2\,\alpha/2}{kR_0} \tag{6}$$

Expression (6) holds with an accuracy up to a coefficient on the order of unity, connected with the level at which the effective scattering volume is determined, and with the condition that the region of the intersection amounts to several radii of the beam; this, as a rule, is satisfied in all cases which are important in practice. The confocal parameter R_0 can be made as large as desired by varying the optical strength of the lens which focuses the beam at the point of the flow under investigation, and the distance from this point to the constriction of the starting beam. This permits obtaining an expansion not greater than 0.1%. The broadening connected with the finite time of passage of a particle through the scattering volume was estimated in [7]. We note that, to obtain a small amount of broadening, only the linear dimension of the scattering volume in the direction of the velocity of the flow is important. The greater this dimension, the less the broadening. However, a large dimension will lead to averaging of the small-scale pulsations.

A special characteristic of the differential scheme of a Doppler optical velocity meter is the fact that the difference in the Doppler frequencies does not depend on the direction of the observation [4]. This permits collecting light over a large solid angle without bringing about additional broadening. Thus, a Doppler optical velocity meter, using a differential scheme, may have an instrumental broadening of ~0.1%. Consequently, the lower limit in measurement of the degree of turbulence is a value on this same order of magnitude.

The above analysis of the broadenings of the spectrum of the Doppler signal relates to flows in which there is no velocity gradient. In the latter case, there arises an additional broadening, connected with a change in the mean velocity at the limits of the effective volume, which may considerably exceed the above limit in measurement of the degree of turbulence.

An experimental study was made of the degree of turbulence, in a vortical chamber with tangential feed of the liquid, in which a previous study had been made of the distribution of the tangential velocities. The optical part of the experimental Doppler optical velocity meter unit was the same as in determination of the averaged velocities [8]. Only the radiometric part of the unit was different. The signal arriving from a photomultiplier was amplified and fed to the input of a spectroanalyzer with a transmission band of 200 Hz, at the output of which a voltage is developed which is proportional to the spectral density of the signal at the tuning frequency. This voltage, through a congruent cascade, entered the measurement input of an automatic-recording automatic potentiometer. The axis of the frequency scale of the spectroanalyzer was connected mechanically through a reducer with the axis of the drum of the automatic recorder, which moved the band. Thus, with operation of the automatic recorder, there was scanning of the spectroanalyzer at the tuning frequency, and the spectrum of the signal under investigation was traced on the band. The analysis time was 5 min.

As study was made of a vortical flat chamber, analogous to [8]; its thickness was 10 mm, and its diameter 60 mm. The working liquid was distilled water, to which were added particles of polystyrene with a diameter of ~0.5 μ. Measurements were made of the pulsational tangential velocities as a function of the instantaneous radius r of the twisted flow.

Figure 2a and b shows typical spectra of a signal, obtained on the band of the automatic recorder at two points of the chamber; along the axes the values of the frequency are expressed in kHz. Figure 3 shows the dependence of the degree of turbulence of the flow on the instantaneous radius and the value of the tangential velocity of the flow. Curves 1 and 2 show, respectively, the distribution of the tangential velocity, in cm/sec, and the degree of turbulence in the vortical chamber, with a mass flow rate of 10 cm^3/sec. Curves 3 and 4 give values of the same quantities at a mass flow rate of 15 cm^3/sec. There is a considerable lowering of the turbulence with motion of the liquid toward the center, from 0.08 to 0.02. The total instrumental broadening in the unit used was 0.5%. The absolute value of the degree of turbulence was calculated under the assumption of a Gaussian distribution of the velocity distribution function.

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