INVESTIGATION OF TURBULENCE BY OPTICAL METHODS

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Optical methods of measuring the characteristics of turbulence have excited much interest for investigating the flow of liquids, gases, or plasma. The fact that there is no disturbance of the medium being investigated, and the possibility of making measurements in heated and rapidly moving gas flows, favors optical instruments for investigating turbulence rather than probe instruments such as thermoanemometers , electrical discharge and induction anemometers, Pitot tubes, etc. At the same time, compared with other probeless methods based, for example, on the use of ultrasonic or microwave oscillations, radioactive isotopes, etc., optical methods have the considerable advantage of possessing high spatial resolution.

Optical methods are useful to the same extent for investigating turbulence both in liquids and in gases, flames, or plasma. Although some of them have been known for a long time (for example, the diffusion method), the majority of the optical methods have only come into use recently.

The optical methods which are used at the present time to investigate turbulence can be divided into three main groups: diffusion, densitometry, and anemometry methods.

1. Diffusion Methods. This group of methods depends on using the dependence of the diffusion of heat, micro-, or macro-particles in the medium on the turbulence characteristics.

The first diffusion method of observing turbulence was used by Osborne Reynolds. To do this he used the diffusion of a dye in water; the diffusion increases sharply when the flow changes from laminar to turbulent.

To investigate gas flow, local heating of the medium by an electrical discharge [1], by a filament [2], or by a laser spark [3] is used.

The diffusion of a heated cloud of gas is recorded by means of a suitable optical system (interferometric, shadow, or Schlieren). Instead of heating the gas, Schlieren can be obtained by introducing a foreign gas with a different refractive index [4] from that of the medium under investigation. Smoke is the material most widely used as a diffusion "probe" in gas flow due to the ease of obtaining and recording it. To investigate diffusion in heated gas flows it is possible to use materials which give a characteristic glow, for example, sodium, etc. (See A. G. Prudnikov, "Measurements of the turbulence of air flow and flames by an optical-diffusion method," Dissertation, Moscow Physico-Technical Institute, 1956.)

Recently an interesting method [5] has been described for investigating the turbulence of liquid flows. A dilute solution of 2(2, 4-dinitrobenzene)-pyridine in ethyl alcohol is illuminated by a fine pulsed beam of light perpendicular to the flow. The light gives the solution a blue color which lasts for some time. The diffusion of the colored region enables the degree of turbulence of the medium to be judged.

To investigate turbulence in water, dyes [6], fluorescein compounds [7], or solutions of salts [8] are widely used.

In measuring turbulence by the diffusion method two cases occur: when the diffusing substance is introduced or produced in the flow continuously (Fig. 1), and when the formation and recording of the diffusing substance has a discrete character (Fig. 2).

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 9, No. 4, pp. 105-116, July-August, 1968. Original article submitted February 8, 1968.

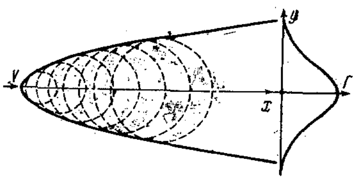

Fig. 1

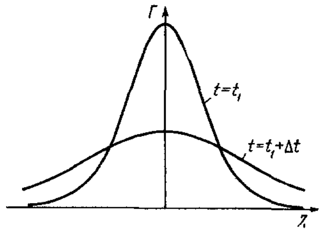

Fig. 2

In the latter case the diffusion is measured either by means of stroboscopic photography or by means of photoelectric scanning.

The analysis of the results of measurements is usually based on relations first obtained by Kampé de Feriet [9] for uniform turbulent flow:

$$\langle y_2^2(t)\rangle = 2v_2'^2 \int_0^t (t-\tau) R_L(\tau)\, d\tau \tag{1.1}$$

where $y_2(t)$ is the Lagrangian coordinate of the marked particle in a Cartesian system, v_2^1 is the Lagrangian turbulent pulsation of the velocity, and $R_L(\tau)$ is the Lagrangian correlation.

For small values of the time t $R_L(\tau) \approx 1$, or

$$< y^2_2(t) > \approx v_2'^2 t^2 \tag{1.2}$$

i.e., for small values of t the standard deviation $< \nu_2'^2 >^{1/2}$ can be obtained from the slope of the $< y_2^2(t) >^{1/2}$ curve.

For values of the time $t \gg t^*$, for which $R_L(t^*) \approx 0$, we have

$$\langle y_2^2(t)\rangle \approx 2v_2'^2 t \int_0^{t^*} R_L(\tau)\, d\tau \tag{1.3}$$

or

$$\langle y_2^2(t)\rangle \approx 2v_2'^2\, t\, T_L \tag{1.4}$$

where T_L is the Lagrangian integral time scale.

It follows from (1.1) that the correlation curve can be obtained by double differentiation of the $< y_2^2(t) >$ curve, if $< \nu_2'^2 >$ is obtained from (1.2).

It follows from (1.4) that the Langrangian scale of the turbulence can be obtained from the slope of the $< y_2^2(t) >$ curve for large values of t.

From the diffusion of the impurities along the flow the coefficient of turbulent diffusion B can also be obtained.

Since the distribution of the substance Γ in the plane perpendicular to the direction of the flow velocity v at a distance x_1 from the source in the case of uniform isotropic turbulence is described by a Gaussian error curve [10], we have the relation

$$B = \langle v\rangle\ (x_2)^2{}_{0.5}/4\, x_1 \ln 2 \tag{1.5}$$

Here $(x_2)_{0.5}$ denotes the coordinate for which $< \Gamma > = 0.5\ \Gamma_{max}$. The advantages of the diffusion methods of measuring turbulence are the comparative simplicity of the equipment required and the clarity and variety of the characteristic obtained.

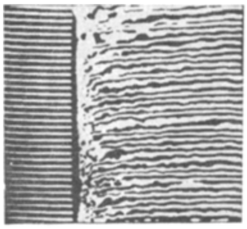

Fig. 3

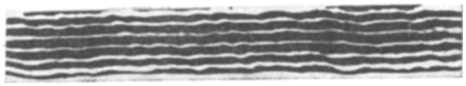

Fig. 4

The drawbacks of these methods are the considerable difficulty involved in processing the measurement results mathematically, the small spatial resolution and the low accuracy due to the disturbing effect of the probe introduced into the diffusing substance, the finite dimensions of the source, etc.

2. Densitometer Methods. This group of methods is based on the observation of turbulent fluctuations of the density and of the associated refractive index of the medium, the gradient or second derivative of the density, and also the impurity concentration.

One of the characteristic features of this group of methods is the fact that the observed optical effects may depend simultaneously on several parameters of the medium, so that it is not always possible to give an unambiguous interpretation of the results obtained. For example, the fraction of the transmitted light beam scattered by an elementary volume of the medium depends simultaneously on the value of the gradient of the refractive index, the concentration and composition of the medium, the concentration and size of the sol, etc.

It is convenient to divide the methods in this group into two subgroups, although there is no sharp boundary between them. These are a) methods which use transmitted light, and b) methods based on recording the scattered or characteristic radiation. The first subgroup enables one to obtain values which are integral along the line of observation, and the second subgroup gives the local values.

2a. Transmitted Light. This group includes interferometric, Schlieren, shadow, and absorption methods, and also the statistical beam deviation method.

Interferometric methods enable the integral density fluctuations along the line of observation z to be measured. The shift in an interference fringe S is equal to the change in the optical path length measured in wavelengths of the light λ:

$$S = \frac{1}{\lambda} \int_z [n(x, y, z) - n_0]\, dz \tag{2.1}$$

Here $n(x, y, z)$ and n_0 are the refractive indices in the turbulent and original medium respectively.

The gas density ρ is related to the refractive index by the Gladstone-Dale equation,

$$n - 1 = (n_0 - 1)\rho / \rho_0 \tag{2.2}$$

Hence

$$S = \frac{n_0 - 1}{\lambda \rho_0} \int_z [\rho(x, y, z) - \rho_0]\, dz \tag{2.3}$$

As a result of averaging along the beam the pulsation spectrum recorded by the interferometer is narrowed compared with the actual spectrum, as in the case of measurements made with a thermoanemometer with a long filament.

Both photographic [11-13] and photoelectric [14] recording are used to record the turbulent fringe shift.

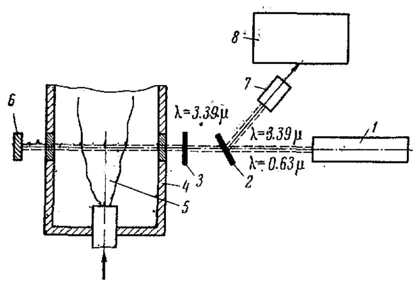

Fig. 5

Figure 3 shows an interferogram of a detonation wave in a mixture of $2H_2 + O_2 + 2CO$ in a shock tube [11], which illustrates the turbulence of the gas behind the wave. Photographic recording on a moving film enables one to obtain a time scan of the pulsations (Fig. 4) [12]. However, it is more convenient to obtain time spectra by using photoelectric recording.

As an example of such devices Fig. 5 shows a laser interferometer used to measure the spectral density power in a jet issuing from a sonic nozzle [14]. The interferometer used a helium-neon laser 1, operating in the two-frequency mode ($\lambda = 3.39\ \mu m$ and $\lambda = 0.63\ \mu m$). The laser radiation passing through the semitransparent mirror 2 and the infrared filter 3 is incident on the chamber 4 containing the jet under investigation 5. The part of the radiation which is reflected from the mirror 6 is returned to the resonator. The intensity of the laser radiation depends strictly on the phase of the reflected light, i.e., on the optical path length of the beam.

Therefore, the presence of turbulent pulsations in the gas density produces pulsations in the intensity of the infrared radiation and, consequently, in the visible radiation of the laser also. The system is adjusted so that the intensity of the visible radiation depends approximately sinusoidally on the phase of the reflected light. The visible radiation reflected from the semitransparent mirror 2 is recorded by the photomultiplier 7 and is analyzed by the audio analyzer 8.

The advantages of interferometric methods is the linear dependence of the response on the density of the medium, and also its high sensitivity. For example, by using a Fabry-Perot interferometer together with a laser a change in refractive index of the order of $\Delta n = 10^{-7}$-10^{-8} can be detected [15].

However, when investigating turbulence it often turns out to be more convenient to use shadow or Schlieren methods [16], which record the second or first derivative of the refractive index respectively, in a direction perpendicular to the direction of the beam. This is due to the fact that turbulent pulsations in density are usually small but the dimensions of the nonuniformities are also small, so that the gradient and higher derivatives are large.

When using these methods it is also possible to use photographic and photoelectric recording. Schlieren photography of turbulent flow gives a characteristic porous structure, corresponding to the structure of the turbulent vortices. An example of such a photograph is shown in Fig. 6 (a plasmotron jet). Correlation processing of shadow or Schlieren photographs enables the scale of the turbulence to be obtained.

If the density pulsation field is isotropic it can be represented by a single function, namely, by the three-dimensional spectrum of the density field, which characterizes the portion of the density spectrum per average density pulsation for a wavelength $\lambda = 2\pi/k$.

The correlation of the light intensity pulsations along the flow is related to the three-dimensional spectrum of the isotropic density field E(k) by the following relationship [12]:

$$k^4 E(k) = \text{const} \int_0^\infty \xi R(\xi) I_0(k\xi)\, d\xi \qquad (2.4)$$

Here $I_0(k\xi)$ is the Bessel function of zero order, $R(\xi) = \langle h(x, y) h(x+\xi, y) \rangle$ is the correlation of the shadow pattern, and $h(x, y)$ is the intensity of the shadow pattern pulsations.

Instantaneous shadow and Schlieren photography has become widely used in studying turbulence when carrying out aerodynamic and plasma investigations [17-20] in view of the clarity of the results and the possibility of presenting the flow as a whole. The use of holography [21] opens up interesting possibilities in this direction.

Shadow patterns can be processed using comparatively simple optical autocorrelators [21, 22], which do not require much effort.

Fig. 6

It is also possible to find the scale of the turbulence by using photoelectric recording. A simple model can be used to interpret the results, according to which the nonuniformities in the refractive index can be considered as random converging or diverging lenses [23]. When a uniform plane wave of intensity I_0 falls on such a "lens" with focal length f, the intensity of the light I behind it at a distance $L \ll f$ from it is

$$I \approx I_0(1 \pm 2L / f) \quad (2.5)$$

where the plus and minus signs correspond to the converging and diverging "lenses" respectively.

Consequently, the relative changes in the intensity for such a "lens" is of the order of

$$\left|\frac{I - I_0}{I_0}\right| \approx \frac{2L}{f} \quad (2.6)$$

Using the fact that for air $n_0 \approx 1$ and $[n - n_0] \ll 1$ and, in addition, assuming that the "lenses" have a spherical shape (i.e., $\left|\frac{1}{r_1}\right| \approx \left|\frac{1}{r_2}\right| \approx \left|\frac{1}{r}\right|$, where r is the characteristic dimension of the lens), we obtain

$$\langle I - I_0\rangle \;/\; I_0^2 \sim C_n^2 l_0^{-7/3} L^2 L_1 \quad (2.7)$$

where l_0 is the internal scale, C_n is the structural constant for the refractive index, and L_1 is the thickness of the layer. Relation (2.7) is sufficiently accurate provided $L \gg L_1$. If this condition is not satisfied, for an accurate calculation of the intensity fluctuations in the approximation of geometrical optics it is necessary to know the three-dimensional spatial spectrum $\Phi_n(\varkappa)$ of the refractive index fluctuations in the range of wave numbers $\varkappa \approx 1/l_0$.

One of the advantages of Töpler systems is the possibility of obtaining a small image depth of field, for example, of the order of 2-3 mm [24].

This enables one to obtain local and not integral values along the beam, which is particularly important when investigating turbulence. Such Töpler systems with sharp focusing can be regarded as the limiting case of forward scattering.

The characteristics of the amplitude and phase fluctuations of the transmitted waves are related to the form of the spectral density of the fluctuations in refractive index n [25, 26] as follows:

$$F_I(\varkappa_2, \varkappa_3) = \pi k^2 L\left[1 - \frac{k}{\varkappa^2 L}\sin\frac{\varkappa^2 L}{k}\right]\Phi_n(0, \varkappa_2, \varkappa_3) \quad (2.8)$$

$$F_\varphi(\varkappa_2, \varkappa_3) = \pi k^2 L\left[1 + \frac{k}{\varkappa^2 L}\sin\frac{\varkappa^2 L}{k}\right]\Phi_n(0, \varkappa_2, \varkappa_3) \quad (2.9)$$

Here $F_\Phi(\varkappa_2, \varkappa_3)$ and $F_I(\varkappa_2, \varkappa_3)$ are respectively the two-dimensional spectra of the density of the fluctuations in the phase and the logarithm of the amplitude, which are the Fourier expansion of the two-dimensional correlation functions in the plane z=const, perpendicular to the direction of wave propagation.

However, it is extremely difficult to obtain $\Phi_n(\varkappa)$ from these formulas. To solve this problem $\Phi_n(\varkappa)$ is usually approximated by a power function (which holds if $\sqrt{\lambda L} \gg l_0$ and $\sqrt{\lambda L} \ll L_0$), which contains free parameters. This enables the experimental data to be approximated by a suitable choice of parameters.

Using this function, after integrating (2.8) and (2.9), an equation is obtained from which the index of the power function is first obtained and then the second characteristic of the turbulence, namely, the value of the structural coefficient of the refractive index.

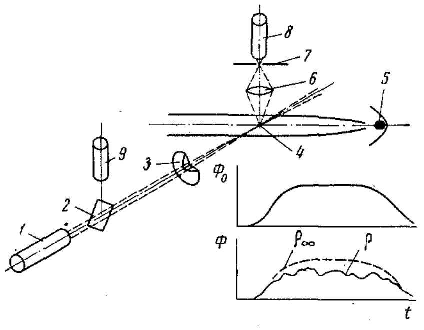

Fig. 7

It was shown in [27] that for an atmosphere under inversion conditions the root mean square deviation of the logarithm of the amplitude is proportional to the vertical temperature gradient. Consequently, the intensity of the twinkling of the light can serve as a characteristic of the mixing conditions in the atmosphere. The method, which uses the characteristics of the amplitude and phase of the transmitted waves, has been used to investigate both the atmosphere [26, 27] and plasma [28, 29].

If the medium through which the beam of monochromatic light is passing absorbs the radiation the fluctuations in its intensity when it emerges from the medium will contain information on the concentration of the absorbing substance. In the majority of cases we can use Beer's absorption law:

$$\Phi = \Phi_0 e^{-\alpha C x} \tag{2.10}$$

Here Φ and Φ_0 are respectively the final and initial values of the intensity, C is the concentration of absorbing material, x is the length of the light path, and α is the absorption factor.

Using the appropriate resonance radiation [30-32], one can obtain the fluctuations in the concentration of the separate components of the medium. Colored impurities can be used when investigating liquid flow [33].

In the case when the correlation scale is small compared with the dimensions of the flow, local fluctuations can be obtained from the correlations of two intersecting beams of light in the absorbing medium [34].

2b. Scattered and Characteristic Radiation. Scattered waves which are formed when electromagnetic waves pass through a turbulent medium can also be used to investigate turbulence. As shown in [25], the effective scattering cross section $d\sigma_0$ is determined by the spectral density of the refractive index $\Phi_n(\varkappa)$, taken for the point $\varkappa = \mathbf{k}_0 - \mathbf{k}_s$:

$$d\sigma_0 = 2nk^4 \sin^2\chi \, \Phi_n(\mathbf{k}_0 - \mathbf{k}_s) d\Omega \quad (\mathbf{k} - 2\pi / \lambda) \tag{2.11}$$

Here $\mathbf{k}_0$ and $\mathbf{k}_s$ are the wave vectors of the incident and scattered waves respectively, and χ is the angle between the electric vector of the incident wave and **k**.

Therefore, by investigating the scattering of electromagnetic waves for different values and directions of the scattering vectors $k = k_0 - k_s$ we can obtain directly the values of the turbulence spectral density $\Phi_n(\varkappa)$ for various $\varkappa$ (by investigating the scattering indicatrix). It is easy to interpret the data if the refractive index fluctuations and the wave amplitudes are much less than unity and if the equations of geometrical optics are used. These conditions are equivalent to the requirement that the wavelength should be small compared with the dimensions of the nonuniformities and that the uniformities should be small compared with the radius of the first Fresnel zone $\sqrt{\lambda L}$ (where λ is the wavelength and L is the distance from the source to the receiver).

The scattering indicatrix of the light for turbulent fluctuations of refractive index is strongly extended forward, so that, for example, in pure air, turbulent scattering backwards is much less than molecular scattering [35]. However, despite this, the use of backward scattered laser radiation for observing turbulence in aviation is attracting much attention [36].

Interesting results on the turbulent scattering of light in water have been obtained in [37], where it is found that the nature of the scattering depends very much on the state of the liquid flow. The viscosity obviously plays a great part in the scattering of light by the liquid [38].

In the laminar flow of a liquid the optical characteristics of the flow are continuous functions of the hydrodynamic parameters. Loss of stability leads to the appearance of discontinuities on the experimental curves.

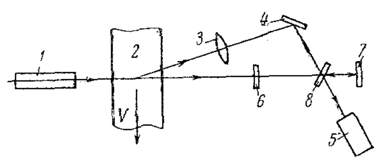

Fig. 8

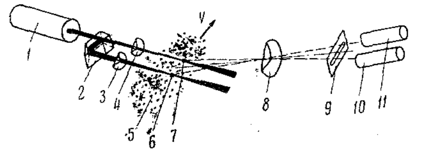

Fig. 9

The frequency spectrum of the pulsations of the scattered light obviously corresponds to the frequency spectrum of the turbulent pulsations of the refractive index of the medium.

As an example of the devices used to investigate turbulence by means of scattered radiation, Fig. 7 shows an arrangement used to investigate turbulence in the track behind spheres flying freely with speeds corresponding to M=2.5-9 [39].

In this arrangement the radiation of a ruby laser 1 is focused through a semitransparent mirror 2 and a lens 3 onto a point 4, which is in the track of the freely flying spheres 5. The light flux Φ scattered by the gas in the track is focused by the lens 6 onto the stop 7 and is recorded by a photomultiplier 8. The intensity of the initial radiation Φ_0 is recorded by the photomultiplier 9. The ratio of the scattered to the incident light flux enables the gas density at the given point of the track to be obtained as a function of time. Both light fluxes are recorded by a two-beam oscilloscope. The form of the oscillograms obtained is shown in Fig. 7. The comparative simplicity and also the high spatial and time resolution given by the scattering method should be noted. However, the interpretation of the results obtained by this method depends very much on the conditions in the medium being investigated. In a pure gas scattering by coupled electrons (Rayleigh scattering) will predominate. At high temperatures scattering by free electrons (Thomson scattering) will predominate. If there are suspended particles in the medium Mie-law scattering will be important. To compare these forms of scattering we give the values of the scattering cross sections [40].

$\sigma=1.8\times10^{-27}\text{cm}^2$ for Rayleigh scattering in air under normal conditions,
$\sigma=6.8\times10^{-25}\text{cm}^2$ for Thomson scattering,
$\sigma=4.2\times10^{-17}\text{cm}^2$ for Mie scattering ($\alpha=0.1$),
$\sigma=3.6\times10^{-11}\text{cm}^2$ for Mie scattering ($\alpha=1$),
$\sigma=3.4\times10^{-8}\text{ cm}^2$ for Mie scattering ($\alpha=5$).

Here $\alpha=2\pi r/\lambda$, r is the particle radius, and λ is the wavelength of the light. The refractive index is assumed to be 1.33.

When investigating turbulence in a plasma or in flames one can use the characteristic radiation of the medium, visible [41] or infrared [42]. By suitable frequency and correlation analysis of the recorded signals one can obtain the frequency spectrum and the scale of correlation. By analyzing the infrared radiation of the pulsations its intensity can be related to the temperature pulsations. When analyzing the visible radiation the problem is complicated by the effect of spatial fluctuations on the concentration of the radiating impurities. This occurs particularly in arc plasmas and flames. The spatial resolution when using characteristic radiation is lower than in the case of scattered light. It is determined by the depth of field of the optical system.

The use of fluorescein excited by a beam of fast electrons [43, 44] has interesting possibilities in investigating turbulence in gases at low pressures. The experimental arrangement is similar to that used for scattered light. Both of these methods complement one another, one being used in the case of large density of the medium and the other being used in the case of low density. One of the advantages of the fluorescein method is the possibility of simultaneous recording of the concentration of several components of the gas (from the intensity of the corresponding characteristic radiation).

3. Anemometry Methods. Anemometry methods of measuring turbulence are based on measuring the fluctuations in the velocity of the medium. Unlike the previous groups the quantity recorded by the device when using these methods depends only on one parameter of the medium, namely, the velocity. This is a considerable advantage in view of the possibility of unambiguous interpretation of the results.

Anemometry methods can be divided into two subgroups: spectral and kinematic.

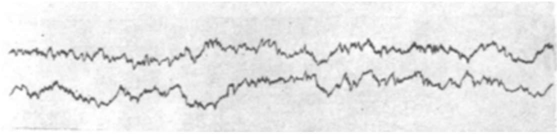

Fig. 10

3a. Spectral methods. Spectral methods are based on the use of the Doppler and Fizeau effects:

$$\nu = \nu_0 \left(1 - \frac{v^2}{c^2}\right)^{1/2} \Big/ \left(1 - \frac{v}{c}\right) n \cos \varphi \quad \text{or} \quad \frac{\Delta\nu}{\nu} \approx \left(\frac{v}{c}\right) n \cos \varphi \tag{3.1}$$

$$\frac{\Delta\nu}{\nu} = \frac{v}{c}\left(1 - \frac{1}{n^2}\right) \tag{3.2}$$

Here ν_0 is the frequency emitted by the source, ν is the observed frequency, v is the velocity of motion of the radiating body, c is the velocity of light, n is the refractive index of the medium, and φ is the angle between the velocity of the radiating body and the line of observation.

To measure the velocity of flow and its variations with time both the characteristic and transmitted and scattered radiation are used.

According to the method of recording the frequency shift we can divide the methods into the spectroscopic method and the optical heterodyne method. In the first case we imply the presence of a spectral device, the dispersing element of which converts the frequency shift of the radiation into a spatial shift of the spectral line. A recording photoelectric system with a beam-dividing wedge [45], two gray wedges [46], or a servodrive [47] converts this shift into an electrical signal. The minimum absolute error when measuring a frequency shift by the spectroscopic method is 10-15 m/sec, so that the method can be used to investigate high-speed gas and plasma flows.

The optical heterodyne method is based on recording the beat frequency of two beams of coherent light, one of which is the reference beam and the other either travels a certain distance in the moving medium being investigated or is scattered by it. The Fizeau effect enables the integral values of the velocity pulsations along the line of observation to be obtained [48, 49] by a method similar to that described in section 2a. Local values can be obtained by using scattered light.

Figure 8 shows an arrangement for measuring local velocities in liquid or gas flows, using heterodyning of the scattered light [50]. The laser 1 radiates light perpendicular to the flow 2. The scattered light is focused by means of the objective 3 through the mirror 4 onto a photodetector 5. The reference beam, reduced in intensity by a neutral filter 6, is reflected from the mirror 7 and the transparent plate 8 and falls on the same point of the detector. The mirror 7 is controlled in such a way that the optical path lengths of both beams are equal; this is necessary for satisfactory heterodyning. The beat frequency is recorded by a spectrum analyzer.

To increase the intensity of the scattered light in the medium sols are introduced, for example, polystyrene globules in water [51], smoke in a gas [52], etc. If a strong light source is available this enables one to achieve heterodyning of the light scattered directly by the turbulent density fluctuations [53].

The heterodyning method enables one to obtain a frequency resolution unobtainable with the spectroscopic method and enables one to measure speeds of the order of millimeters per second. However, this is as regards the measurement of average velocity. The possibility of measuring pulsations in velocity is limited by the bandwidth of the laser radiation itself. Thus in [50] the half-width of the recorded spectrum was of the order of 3 Mc, which corresponds to a velocity of 2 m/sec. Therefore, although the frequency corresponding to the spectral maximum is determined extremely accurately it is quite a difficult problem to detect a broadening of the spectrum due to small turbulent pulsations of velocity.

The method of optical heterodyning using radiation scattered by the medium is, in view of the high spatial and frequency resolution, one of the most promising methods of measuring turbulence in liquids and in gases and plasma. The design of suitable devices is at present held up by the lack of suitable high-power lasers which give sufficiently monochromatic radiation.

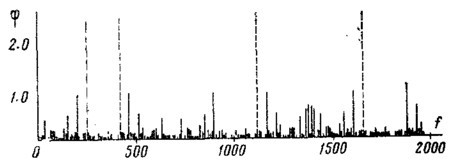

Fig. 11

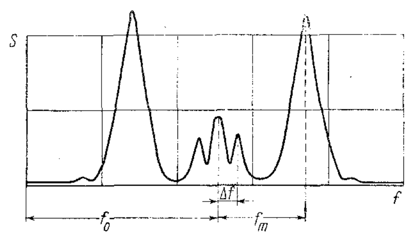

Fig. 12

3b. Kinematic Methods. Kinematic methods of measuring turbulence are based on a time of flight analysis of the motion of optical nonuniformities in the medium concerned. To do this one can use both the natural fluctuations in the refractive index, the density, the luminosity, etc. and suspended particles in the medium. Two types of measurement can be distinguished, namely, when the recorded nonuniformities are discrete and when they are continuous.

The velocities of motion of suspended particles can be measured visually (the so-called ultramicroscope method) [54] or by means of a cine-camera [55]. Subsequent statistical analysis of the results of the measurements enable the degree of turbulence to be obtained [56]. However, this method is extremely laborious and gives a low accuracy due to insufficient statistics.

A method of measuring turbulence is described in [57], based on a statistical time analysis of the photoelectric signals from two closely spaced points in the medium containing discrete optical nonuniformities. These points (small regions) are displaced relative to one another by a certain known distance along the flow so that some of the particles passing through the first point (region) then pass through the second point also. The arrangement for using this method is shown in Fig. 9. Here the radiation of a laser 1, after passing through the splitter 2 and the lenses 3, 4 is incident on the medium in question 5. The light scattered from the regions 6 and 7, when traveling through the suspended particles, is focused by an objective onto the stop 9 which limits the dimensions of the separable regions 6-7. The light then falls on photomultipliers 10 and 11, the signals from which are analyzed.

If some particle after passing through the first region then passes through the second, there will be a time shift between the pulses due to it in both channels of the photomultipliers, determined by the average speed of the particles along the path between these regions (the measurement base). Hence, the method enables fluctuations in the average velocity along the measurement base to be measured. The minimum base for measurements by this method can have a value of the order of 0.5-1 mm.

To obtain the spectrum of the time of flight one can use a delayed coincidence circuit [58], an oscilloscope [59, 60], or a suitable multichannel time analyzer. When investigating high-temperature flows the characteristic luminescence of the particles can also be used [58, 59]. This method enables one to obtain the mathematical expectation and dispersion of the average velocity of the flow along the measurement base, and in the case when the position of the second region is scanned, the same characteristics for the velocity vector. The method can be used to investigate liquid and gas flows and the flows of low-temperature plasma and flames. The upper limit of the possible temperatures of the medium are governed by the thermal stability of the tracing particles and is 3,500-4,000°K.

In investigating liquid media both the lower and the upper limits of the velocity of flow are practically unlimited. For gases the lower limit of velocity is determined by the sedimentation velocity of the sol (1-10 cm/sec), and the upper limit is determined by the response of the recording system. The values of the permissible accelerations of the medium in question in the case of different particle and medium specific gravities are governed by the required visualization accuracy [61].

If the medium does not contain discrete inhomogeneities, to measure the turbulence one can also use continuous fluctuations of the refractive index, brightness, density, impurity concentration, etc. at two neighboring points, displaced in the direction of the flow, which can be observed by suitable optical instruments. For example, the arrangement shown in Fig. 9 records fluctuations of the scattered light in the same way as the arrangement shown in Fig. 7, but for two points. The form of the recorded signals is similar to that shown in Fig. 10.

In [62] an optical method of measuring velocity pulsations in plasma jets is described which uses correlation analysis of the signals from two points of the flow (luminosity pulsations are recorded).

If these points are situated at a certain distance along the flow the pulsations of luminosity which pass through the first point arrive at the second point with a certain delay determined by the velocity of their motion. The shift in the maximum of the cross-correlation function for these two points with reference to the axis is the average delay time, i.e., the average speed of flow. Information concerning the pulsations of velocity can be obtained from the spectrum of the cross-correlation function.

If there are certain harmonic pulsations of luminosity in the flow of the form $\theta = \cos \omega_0 t$, then for a velocity of motion $\nu(t) = \langle \nu \rangle + \Delta\nu G(t)$, where G(t) is any time function, at the first point we can write the oscillation in the form

$$S_1(t) = \cos \frac{2\pi}{\lambda} \int_0^t [\langle v \rangle + \Delta v G(t)]\, dt$$

Since at the second point the velocity variation law is the same as at the first point but differs in phase, we can write for the second point

$$S_2(t) = \cos \frac{2\pi}{\lambda} \int_0^t [\langle v \rangle + \Delta v G(t + \varphi)]\, dt$$

i.e., we will record frequency-modulated oscillations on the oscillograms, where the velocity-time variation law is the modulating function.

The cross-correlation function, by suppressing noise, reproduces the signal which is the result of frequency modulation of the initial signal, due to the fact that its linear velocity along the section L in question is not constant. Therefore, by obtaining the carrier frequency ω_0 and the deviation $\Delta\omega$ from the spectrum of the cross-correlation function and knowing the average flow velocity $\langle v \rangle$, we can obtain the velocity pulsations

$$\Delta v = \Delta\omega \langle v \rangle / \omega_0 \qquad (3.3)$$

If there are a few such carrier frequencies the deviation of each of these will determine the relative velocity of propagation of the separate waves (for example, acoustic disturbances, if they are sufficiently intense to be recorded). A typical example of spectra obtained in this way is shown in Fig. 11.

A similar method can also be used to investigate the intensity of the frequency spectrum of the longitudinal components of the turbulence in gas flow [63].

Unlike [62], in this case the cross-correlation function at two points separates the signal which is the result of frequency modulation of a single random process $\varepsilon(t)$ (fluctuations of color, refractive index, brightness of characteristic luminosity, amount of scattered light, etc.) by the other random process, namely, the velocity pulsations u(t). In this case the spectrum has a continuous form as, for example, in Fig. 12. Here the carrier frequency corresponds to the most probable frequency of the optical fluctuations while the effective modulation frequency f_m is determined by the most probable frequency of the velocity pulsations.

The value of the root mean square velocity pulsations $\sqrt{\langle u'^2 \rangle}$ is proportional to the effective deviation Δ_f:

$$\langle u'^2 \rangle^{1/2} / \langle u \rangle = \Delta f / f_0, \qquad \Delta f = f_0 \langle u'^2 \rangle^{1/2} / \langle u \rangle \qquad (3.4)$$

where $\langle u'^2 \rangle^{1/2}$ is the root mean square velocity pulsation and $\langle u \rangle$ is the average velocity of flow.

The deviation Δf can be calculated from the formula

$$\Delta f = \left[\int_{-\infty}^{\infty} (f - f_0)^2 S(f)\, df \right] \left[\int_{-\infty}^{\infty} S(f)\, df \right]^{-1} \qquad (3.5)$$

if it is assumed that the spectral density function S(f) duplicates the frequency distribution of the probability density.

Hence, the energy spectrum carries information both regarding the amplitudes of the turbulent velocity pulsations and about their frequencies. At the same time we can also obtain a representation of the spectrum of the original process ε(t), which characterizes the nonuniformity of the color along a current line, i.e., the microstructure of the turbulent nonuniformities.

The advantages of this method are high accuracy, simplicity of interpretation of the results, and also the variety of the characteristics obtained. It can be used both in gases and in liquids.

The interpretation is simplest of all in flows with a small relative intensity of the turbulence, i.e., in which the following inequality is satisfied:

$$\langle u'^2\rangle^{1/2} / \langle u\rangle < 1 \tag{3.6}$$

This requirement does not impose any restrictions on the value of the average flow velocity.

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