A FREQUENCY METHOD FOR MEASURING FLUID FLOW VELOCITY

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A time-of-flight method is usually employed for measuring local flow velocity in streams containing optical irregularities. It is based on recording signals caused by the passage of the irregularities through two given points [1, 2].

In what follows it is shown that if we replace the correlation analysis of two signals by the frequency analysis of signals from several points we can simplify considerably the problem of finding the mean flow velocity in a given region of the stream. This method is used to measure the flow velocity of water in a rectangular channel, and some results are given.

Let the field of optical irregularities, which is a random function of the coordinates, be attached to the particles of the stream, and let its translational velocity be equal to the fluid flow rate.

When the optical fluctuation field N(x, y, z, t) is observed through an optical system with a transmission coefficient k(x, y, z) (a modulator), we have the transformation

$$Q(x, y, z, t) = k(x, y, z)\, N(x, y, z, t). \qquad (1)$$

We isolate from the stream a series of cubic volumes with linear dimension b, situated a constant distance Λ apart (the modulator wavelength) along the x-direction. The transmission coefficient k(x, y, z) will then be a periodic function of the x-coordinate and can be represented in the form of a series,

$$k(x, y, z) = a_0 + \sum_{n=-K}^{K} a_n e^{in\varkappa x} \qquad (0 < y = z < b),$$

$$k(x, y, z) = 0 \qquad (y = z > b,\ y = z < 0).$$

Here $\varkappa$ is the wave number, determined by the modulator wavelength: a_0 is the mean value of the transmission coefficient in the x-direction; a_n is the amplitude of the n-th harmonic. Transformation (1) then acquires the form

$$Q(x, y, z, t) = a_0 N(x, y, z, t) + \sum_{n=-K}^{K} a_n N(x, y, z, t)\, e^{in\varkappa x},$$

$$(0 < y = z < b) \qquad Q(x, y, z, t) = 0\ (y = z > b,\ y = z < 0). \qquad (3)$$

Assuming that the field N(x, y, z, t) corresponds to isentropic conditions, we obtain the following expression for the three-dimensional spectral density of transformation (3):

$$\Phi_Q(\nu) = a_0 \Phi_N(\nu) + \sum_{n=-K}^{K} a_n \Phi(\nu + n\varkappa), \qquad (4)$$

where ν is the wave number determined by the scale of optical irregularities in the stream (corresponding to the wavelength λ). For a "frozen" field, carried with constant velocity, the spatial spectrum is associated with the time spectrum by the relationship [3]

$$\Phi_Q(\nu) = -\frac{v^2}{2\pi\nu} W'(v\nu).$$

Substituting this expression into (4) we obtain

$$W_Q(\nu v) = a_0 W(\nu v) + \sum_{n=-K}^{K} a_n W(\nu v + n v\varkappa). \qquad (5)$$

Thus the time spectrum of transformation (3) is the sum total of spectra $W_N(\nu v)$ for the scale size a_n with their frequencies shifted by $nv\varkappa$. The signal arriving at the analyzer is the sum of the m signals isolated by the optical system of volumes.

Thus the spectrum of the resulting signal will be equal to the sum of the spectra of signals delayed relative to each other by the time $t_3 = x/v$. Introducing the delay into (5) and carrying out the summation we obtain

$$W(\nu v) = \int_0^{m\Lambda} \Big\{ a_0 W_N(\nu v) + \sum_{n=0}^{K} a_n W(\nu v + n v\varkappa)\, e^{-i\varkappa x} + \sum_{n=0}^{K}{}' a_n W(\nu v - n v\varkappa)\, e^{i\varkappa x} \Big\} e^{-i\nu x}\, dx =$$

$$= a_0 W_N(\nu v) \left[-\frac{1}{i\nu} e^{-i\nu m\Lambda} + \frac{1}{i\nu} \right] + \sum_{n=0}^{K} a_n W(\nu v + n v\varkappa) \times \left[-\frac{1}{i(\nu+\varkappa)} e^{-i(\nu+\varkappa)m\Lambda} + \frac{1}{i(\nu+\varkappa)} \right] + \sum_{n=1}^{K} a_n W(\nu v - n v\varkappa) \times \left[-\frac{1}{i(\nu-\varkappa)} e^{-i(\nu-\varkappa)m\Lambda} + \frac{1}{i(\nu-\varkappa)} \right]. \qquad (6)$$

It follows from (6) that as $m \to \infty$, the spectrum received at the analyzer tends to the time spectrum (5) of transformation (3). The smaller the value of m the larger the effect of the phase shifts, and the larger the ratio of the modulated wavelength to the irregularity scale size (Λ/λ), the smaller the distortion of the spectral components for a given m. As the number of apertures is decreased the amplitude not only decreases but the spectrum also broadens because of the increase in the number of harmonics in expansion (2).

If the transmission coefficient of the modulator is a harmonic function this enables the broadening of spectral components to be reduced to a minimum. In this case the spectrum of optical irregularities in the stream is transmitted without distortion.

The flow velocity may be found from the following relationship independently of the form of the modulating function:

$$v = \Lambda \Delta f, \qquad \Delta f = \frac{\Delta\omega}{2\pi}. \qquad (7)$$

Here Δf is the difference in cycles per second between the maximum of the spectral side band and the carrier frequency.

The optical irregularities used for determining the flow velocity can have the most varied character. They may be discrete large-sized particles, suspended in the stream, local anomalies in the refraction coefficient, or of the concentration of light absorbing mixtures, fluc-

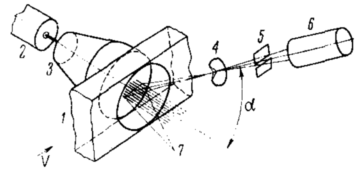

Fig. 1

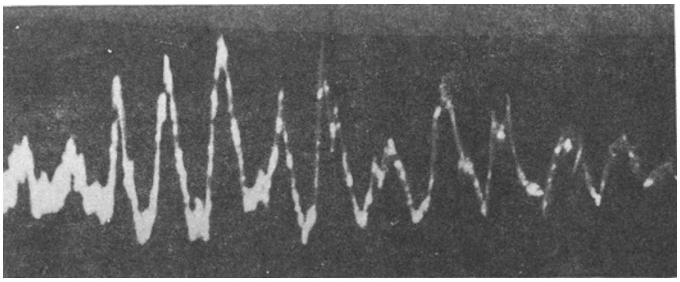

Fig. 2

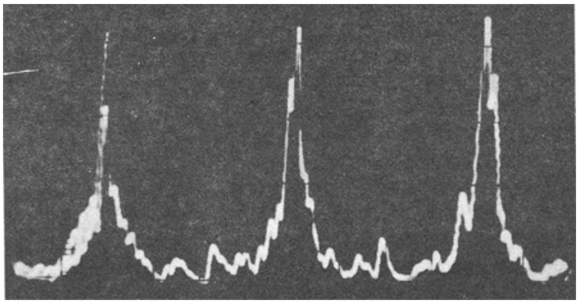

Fig. 3

tuations in the brightness of self-luminescence, etc. When using self-luminescence or refractive-index fluctuation a spatial resolution along the line of sight of the order of 2–3 mm [4] can be obtained by applying high resolution optics or a schlieren system with a small depth of resolution.

When the radiation scattered from optical irregularities is used as the signal a considerably greater resolution can be obtained.

The light scattered from natural macroparticles contained in tap water was used in our experiments. A diagram of the apparatus is given in Fig. 1. The water flows through a calibrated rectangular channel 1 of cross section 12.5 × 28.6 mm. The beam of light from a He-Ne laser 2 is separated into a series of parallel rays with the help of collimator 3 (from 2 to 20) of diameter 0.4 mm and with a distance of 0.8 ± 0.01 mm between the axes of the rays. The best arrangement turns out to be 8–10 rays. In this case a fairly small width of spectral side bands is obtained for a small spatial averaging. Lens 4 is used to project the image of rays which are distinctly visible in water on diaphragm 5, behind which the FEU-11 photomultiplier 6 is situated. The diaphragm segregates a series of regions 7 from the image of the rays, and these are situated along the direction of flow.

The modulating field may also be transformed by means of a diaphragm with a variable transmission coefficient, situated in the image plane of the scattered light in front of the photomultiplier. The angle α between the direction of the rays and the axis of the recording system is chosen to be within the limits 10–90°.

Increase of angle α leads to a decrease in the scattered light falling on the cathode of the photomultiplier, but even for $\alpha = 90°$ an acceptable signal/noise ratio was obtained (not less than 5/1). A typical oscillogram for signals from the photomultiplier is given in Fig. 2, and Fig. 3 gives their typical spectrogram. The center of the mean peak corresponds to the zeroth frequency, and the centers of the side peaks correspond to the modulation frequency. The frequency determined in our measurements corresponds to the maximum of the side peaks. The magnitude of the flow velocity was found from this frequency. Simultaneously the mean flow frequency was measured from the flow rate of the water.

Grids causing turbulence were introduced into the stream by means of a moveable diaphragm situated 50 mm upstream from the windows. Grid 1 contains eighteen orifices of cross-sectional diameter 3.5 mm while grid 2 contains 30 orifices of cross-sectional diameter 1.75 mm.

The average cross-sectional velocity V (cm/sec) of the stream determined from the flow rate of the water and the velocity v (cm/sec) at the center of the channel as found from an analysis of the spectrograms are compared in Fig. 4. Curve 1 corresponds to a stream in a channel without the turbulence grids, curve 2 corresponds to flow with grid 1 and curve 3 to flow with grid 2.

It can be seen from the curves that the velocity measured at the center of the channel is higher than the mean velocity over the cross section in the case in which the turbulence grid is absent, and when the turbulence grid has large scale openings. For the turbulence grid with fine openings the velocity is close to the mean velocity over the whole range of measurements. A bend is visible in curve 1 for a mean velocity of 8–9 cm/sec, and this corresponds to the transition from lamina to turbulent flow.

Velocity field measurements along a straight line parallel to the shorter side of the rectangular channel and passing through the center of the transverse channel cross section are given in Fig. 5 for two average flow velocities 8 and 15 cm/sec. The ratio of the velocity v measured at the given point of the cross section to the mean velocity of the flow V is given on the abscissa, while the ordinate gives the distance in mm along the cross section from its center. Curve 1 corresponds to laminar flow, and curve 2 corresponds to turbulent flow.

The same coordinates are used in Fig. 6 which gives the measured velocity fields for turbulence without a turbulence grid for a mean flow velocity V of 4.3 cm sec (curve 1) and with the turbulence grid 1 for a mean velocity of 5 cm/sec (curve 2).

These experiments show that the frequency analysis of the optical signals from a series of points in a stream enables us to find the aver-

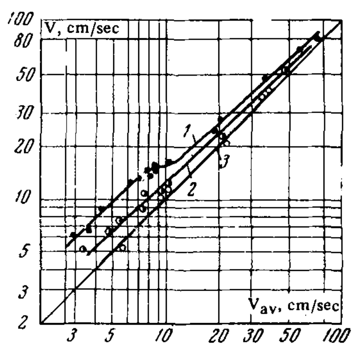

Fig. 4

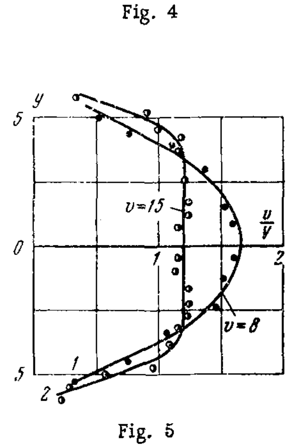

Fig. 5

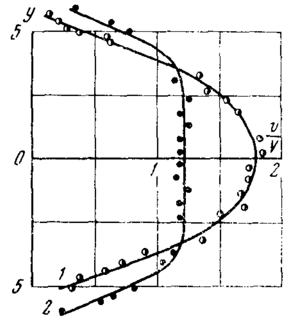

Fig. 6

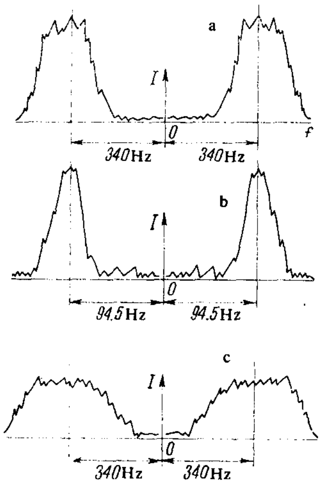

Fig. 7

age flow velocity of the fluid in a given region with a spatial averaging on the order of several millimeters in the direction of flow and on the order of one millimeter in the other two directions. The resolution was determined by the choice of modulator geometry only and could be considerably better. The scatter of values obtained was about 2–3% for flow velocity measurements within the limits 0.01–1 m/sec and was chiefly determined by the limited analysis time for the spectrum. The necessary analysis time is less for higher flow velocities. The upper limit of the range of velocities measured was determined by the maximum velocity obtainable in the apparatus, and the lower limit by the resolution of the recording device. In the case in which the optical fluctuation field moves with a velocity which varies in time, the spectrum is broadened, and this may be used for measuring the turbulence.

By way of illustration Fig. 7 gives the spectra of signals for turbulent a and laminar b flows, as well as for turbulent flow with a mean velocity which is the same as in case a but with the introduction of the turbulence grid 1. The mean flow velocities for the spectra a and b are equal to 27.2 cm/sec, while for spectrum c its value was 7.56 cm//sec.

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