LASER DOPPLER VELOCIMETER WITH ELECTRO-OPTIC MODULATOR FOR INVESTIGATING SLOW VARIABLE-SIGN FLOWS WITH CONTINUOUS VELOCITY SPECTRA

A. V. Priezzhev, A. G. Tikhomirov, and V. A. Yakovlev

Vestnik Moskovskogo Universiteta. Fizika,
Vol. 34, No. 6, pp. 93-96, 1979

UDC (535.241.13:537.228):621.373.826

We discuss the problem of employing an electro-optical shift of the frequency of laser radiation in laser Doppler velocimetry. We examine a differential laser Doppler velocimeter that was designed for studying slow variable-sign flows. We present the results of measurements of the flow of cytoplasm in living cells.

The field of application of laser Doppler velocimeters (LDV's) is constantly broadening [1]. They have recently been applied in biophysical research; in particular, for measuring the parameters of the motion of the cytoplasm in living micro-organisms [2,3]. In a number of cases this motion is complex, imposing certain restrictions on the LDV optical circuit and on the system for processing the Doppler signal. In particular, it is necessary to eliminate the low-frequency component of the Doppler signal (which impedes accurate recording of the velocity spectrum of the object under study), to shift the signal component into a suitable frequency range (for example, for recording on magnetic tape and subsequent digital processing), to make provisions for measuring the sign of the velocity, and to decrease the volume from which information is extracted.

In order to solve these problems, we built an LDV on a differential scheme [1] with a frequency shift in one of the beams (see Fig. 1). Linearly polarized He-Ne laser radiation (1) is separated according to amplitude by mirrors (2) into two parallel coherent beams. One of the beams passes through an electro-optical modulator (3), resulting in a frequency shift by the modulation frequency f_m. Further on, both beams pass through filters (9) and are focused and converged by an optical system (4) on some region of the flow under study. The radiation scattered by moving optical inhomogeneties (5) is collected by optical system (6) and falls on a quadratic photodetector (7). The beat frequency set up in the photodetection of the scattered radiation is shifted by f_m. Thus the optical signal of the photodetector corresponding to zero velocity has frequency f_m, and signals corresponding to positive or negative velocities have frequencies that are shifted by the Doppler shift f_d, which is directly proportional to the velocity. This enables one to determine the direction of the velocity from the direction of the shift in the signal component. The low-frequency component of the Doppler signal is not shifted. One can thus consider the

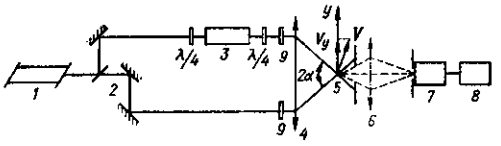

Fig. 1

Doppler spectrum obtained at the output of the signal-processing system (8) to be close to the velocity spectrum in the flow. Total fidelity of the spectrum is, of course, unattainable since the instrumental and gradient broadening of the Doppler spectrum cannot in principle be eliminated.

For shifting the frequency of the radiation we used the double transverse Pockels effect in an optically nonlinear crystal. It was implied in Ref. [4] that it is theoretically possible to have total conversion of the energy of a beam entering the crystal at frequency f into an output beam whose frequency is shifted by an amount f_m. The conditions for ideal conversion are that the light wave entering the crystal be circularly polarized, that the wave in the crystal propagate along its optic axis, and that the modulating electric field applied to the crystal at frequency f_m be circularly polarized and strictly transverse. Under these conditions the light field at the output of the crystal is of the form

$$E(z) = E_0 \begin{pmatrix} 1 \\ \pm i \end{pmatrix} e^{i2\pi ft} \cos Bz \pm iE_0 \begin{pmatrix} 1 \\ \pm i \end{pmatrix} e^{i2\pi(f \pm f_m)t} \sin Bz,$$

where E_0 is the amplitude of the input wave $B = \pi \frac{n^3 r_{22} E_m}{\lambda}$, $E_m = U_m/d$, U_m is the amplitude of the modulating field, r_{22} is a component of the electro-optical effect tensor, and d is the thickness of the crystal. It is seen that total conversion is realized under the condition $Bz = \pi/2$.

In our apparatus we used a $LiNbO_3$ crystal with dimensions $30 \times 1.5 \times 1.5$ mm^3 with silvered electrodes applied to its lateral faces for shifting the frequency. Sinusoidal voltages of amplitude U_m = 250 V, phase shifted by $\pi/2$, were applied to the mutually perpendicular electrodes. The conversion of the linearly polarized radiation to circularly polarized radiation and vice versa was accomplished by a quarter-wave plate.

In the actual experiment we could not achieve total conversion for a number of reasons: Because of the nonuniformity of the modulating field and the nonconstancy of the properties of the crystal boundaries, acoustic waves are excited in the crystal, causing energy losses from the light field [5]; because of the hard-to-eliminate residual linear polarization of the wave entering the crystal, there is amplitude modulation of the output wave at frequency f_m; and a slight ellipticity of the modulating field causes two-band conversion to waves with frequencies $f - f_m$ and $f + f_m$. Along with this, harmonics of the modulating frequency appear. The harmonics of the modulating frequency also appear in the output radiation if the electrodes to which the modulating voltage is applied are not parallel.

However, these factors can be made rather small in the experiment. A certain loss of energy in filtering out the parasitic components and the subsequent leveling of the intensities in the probing beams (filters 9, Fig. 1) is completely acceptable, since for investigating living micro-organisms the overall intensity should be rather small.

The shift of the signal component of the Doppler spectrum obtained from a laminar flow with globules of polysterol is shown in Fig. 2. Here f_m = 3 kHz and f_d = 1 kHz, corresponding to a projection of the flow in the y direction of $V_y = \frac{f_d \lambda}{2 \sin \alpha/2}$ = 1.68 mm/sec. The spectrum was recorded by an N-328 recording potentiometer with an S4-12 spectral analyzer.

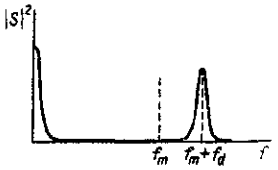

Fig. 2

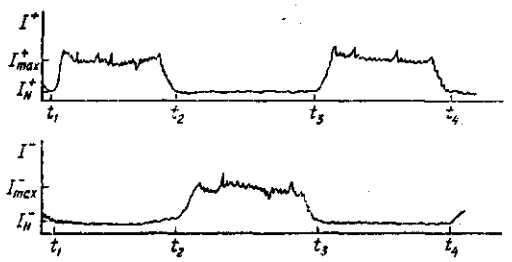

Fig. 3

Using this apparatus, we investigated the variable-sign flow of the cytoplasm in strands of plasmodium of the myxomycete Physarum. This flow is distinguished by a continuous spectrum of velocities - at the instants of most intense flow the various cytoplasmatic inclusions move along the strand at velocities from 0 to 3 mm/sec. In addition, the presence of comparatively large transverse velocity components has been detected [2,3]. However, the nature of this motion was not investigated, since the LDV schemes that were used were insensitive to the sign of the velocity. Our problem was to compare the motion in the longitudinal and transverse directions. To do this we used parallel recording of the Dopller signals at frequencies $f_m + f_d$ and $f_m - f_d$ by means of two S4-12 spectral analyzers. The frequency f_d varied from 0 to 2.5 kHz.

Figure 3 shows the parallel-recorded time dependence of the intensities I^+ and I^- of the Doppler signals at frequencies of $f^+ = f_m + f_d = 4$ kHz and $f^- = f_m - f_d = 2$ kHz, respectively. Here the sensitivity vector of the LDV was directed along the strand. The instantaneous value of the intensity I' at a fixed frequency f' is proportional to the number of particles moving at velocity $V = \frac{f_d\lambda}{2\sin\alpha/2}$ (up to a quantity I_N which characterizes the noise level). Similar behavior was found at various frequencies all the way up to a value $f_{d.max} = 2.5$ kHz, at which the signal decreased to the level I_N. The exact value of $f_{d.max}$ was different for each strand of plasmodium.

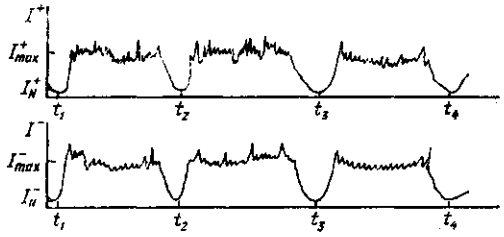

Fig. 4

Figure 4 shows analogous functions taken at the same frequencies but with the sensitivity vector oriented transverse to the strand. It is seen that at any instant of time there are particles moving in opposite directions, their average number being the same. Instants t_1, t_2, t_3, and t_4 correspond to moments of cessation of the flow of the cytoplasm. As the frequency f_d increases the maximum intensity I_{max} of the signal falls off monotonically, and only at $f_d \approx 2$ kHz does it decrease to the noise level; the duration of the pauses near the moments of cessation increases with increasing f_d.

The observed difference of the Doppler signals in Fig. 3 and Fig. 4 can evidently be explained by the fact that the motion of the light-scattering cytoplasmatic inclusions is not rectilinear. Colliding with one another, the granules deviate from rectilinear motion along the strand, and their velocity vectors

acquire a transverse component, which is detected by the apparatus. One can't see the motion transverse to the strand in an optical microscope, apparently because of the small free path of the particles.

The information obtained is important for constructing a correct model of the cytoplasmatic motion, but additional research is necessary to answer the question of whether the granules of different sizes have different speeds and trajectories and to elucidate the role of the collisions of particles in the motion of the flow.

The authors wish to thank Yu. M. Romanovskii and B. N. Ydin for their constant interest and help in this work.

REFERENCES

1. B. S. Rinkevichus, Laser Anemometry [in Russian], Moscow, 1978.
2. R. V. Mistacich and B. R. Ware, Protoplasma, vol. 91, no. 4, p. 351, 1977.
3. A. V. Priezzhev et al., Biofizika, vol. 23, no. 3, p. 541, 1978.
4. C. Buhrer et al., Appl. Phys. Lett., vol. 1, no. 2, p. 46, 1962.
5. F. P. Campell and W. H. Steier, IEEE J. Quant. Electron., vol. QE-7, p. 450, 1971.

4 September 1978

Department of General Physics
and Wave Processes