Optica Applicata, Vol. XXII, No. 1, 1992

Measurement of the velocity of a moving body using technique of optical mixing spectroscopy

A. ABDULLAH, A. DROBNIK (SPIE Member), G. OWCZAREK, L. WOLF (SPIE Member)

Institute of Physics, Technical University of Łódź, ul. Wólczańska 219, 93–005 Łódź, Poland.

Laser Doppler Velocimetry (LDV) with an optical-fiber pick up was designed. A single fiber directs the beam to the body and collects the reflected light back to the photodiode. The technique of optical mixing spectroscopy was used for the case of the local beam originating at the exit end of the fiber optics and the light reflected from the moving body. Heterodyning effect was measured with the help of Fast Fourier Transformer (FFT) programme. The velocity of the moving body was measured. Good agreement between the calculated and experimental results was obtained.

1. Introduction

Accurate measurements play an important role in many fields of science, engineering and medicine and very often require reliable instrumentation to yield the demanded information through measurement. Many measurement methods for moving body velocity determination have been reported over the years. The principles of those methods are based on different physical phenomena connected with transmitted or reflected beam. A noninvasive technique, laser Doppler velocimetry which is used to measure the velocity of moving surface, offers a primary advantage, that the surface is not touched or physically contacted, while it is still the source of the scattered light.

The principle of LDV is described in the literature [1]–[4]. The velocity distribution on a moving surface [5], the velocity of particles suspended in water [6] as well as the blood flow velocity [7] were measured using LDV technique. Other cases [2], [3], [8], [9] are based on optical wave heterodyning. The purpose of this paper is to design a velocimeter which is based on the Doppler frequency shift associated with light scattering by moving particles. We have used this technique to measure the velocity of moving bodies for the velocities ranging from 0.4 to 2.5 mm/s. The results were drawn graphically and explained in this paper to show the response of the LDV.

2. Theoretical considerations

Let the wave vector $\boldsymbol{K}_i$ of the incident light make an angle φ_i with the flow velocity $\boldsymbol{V}$, and the wave vector $\boldsymbol{K}_s$ of the scattered light make an angle φ_s with $\boldsymbol{V}$ as shown in

Fig. 1. Then the Doppler frequency shift Δf is given by [1], [10]

$$\Delta f = (\boldsymbol{K}_s - \boldsymbol{K}_i) \cdot V/2\pi \tag{1}$$

or equivalently

$$\Delta f = (\cos\varphi_s - \cos\varphi_i) nV/\lambda \tag{2}$$

since $\boldsymbol{K}_i = \boldsymbol{K}_s = 2\pi n/\lambda$, where n is the refractive index of the flowing medium and λ is the wavelength in the vacuum. Equation (2) is used as a general equation. The magnitude of the frequency shift may be measured by optical heterodyning and the superimposed optical field reaching photodiode surface at the position r and time t is represented as [11]

$$E(r,t) = E_s(r,t) + E_0(r,t) \tag{3}$$

where E_s is the electrical field of the incoming signal, and may be written as

$$E_s = A_s \cos(\omega_s t). \tag{4}$$

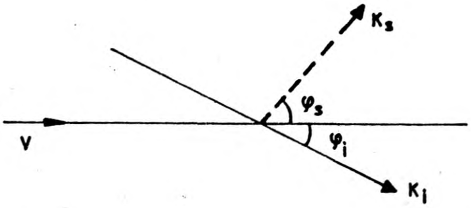

Fig. 1. Schematic diagram of the scattering of laser light by a moving particle

Here A_s, ω_s describe the amplitude and the frequency of the scattered field, respectively. E_0 is the electrical field of the local beam and may be written as

$$E_0 = A_0 \cos(\omega_0 t). \tag{5}$$

Here A_0, ω_0 describe the amplitude and the frequency of a local oscillator, respectively. In this case ω_s is very close to ω_0, and $\Delta\omega/\omega_0$ is equal to 10^{-10} [8], so to detect such a small change in frequency we mix the scattered light of frequency ω_s with local beam of frequency ω_0. The mixing takes place on the surface of the photodiode and gives a fluctuation current output $I(t)$.

In heterodyne detection by a square-law photodiode, the photocurrent of beat frequency is given by

$$I(\mathrm{t}) \sim E^2 = R|E_s + E_0|^2 \tag{6}$$

where R is a constant. If $E_0 \gg E_s$ we may write Eq. (6) as follows:

$$I(\mathrm{t}) = R|E_0^2 + 2E_s E_0|,$$

then

$$I(t) = I_0 + I_h(t) \tag{7}$$

where $I_h(t)$ is the heterodyne beat part of the photocurrent and may be expressed as

$$I_h(t) = 2RE_sE_0. \tag{8}$$

By putting Eqs. (4) and (5) in Eq. (8), we get

$$I_h(t) = RE_0E_s[\cos(\omega_0 - \omega_s)t + \cos(\omega_0 + \omega_s)t].$$

The term $\cos(\omega_0 - \omega_s)t$ oscillates much more slowly than the other one [12], and is of the greatest interest in the output signal, which gives the difference frequency, since all other frequencies are too high to be detected. Thus

$$I(t) = RE_0E_s\cos(2\pi\Delta ft), \tag{9}$$

Δt is a shift frequency, which is given by Eq. (1). It is clear from Eq. (1) that the shift frequency is directly proportional to the velocity of the reflector.

3. Experimental arrangement

The whole system, including the optical system, is shown in Figure 2, which represents a schematic diagram of the experimental setup for the surface velocity measurement. The output beam of 10 mW, $\lambda =$ 632.8 nm of the He-Ne laser (HNA-1881-1), used as a source, falls on a splitter which divides the beam. The first part goes to a nonreflecting plate, while the second part is fed into a silica optic fiber of the step-index type and core diameter 200 μm. The optic fiber is used to transmit the incident beam to the moving surface and receive both the reflected signal from the moving surface and the local beam reflected from the exit end of the optic fiber. These two beams are mixed at the surface of the PIN photodiode (BPYP 44). The output of the photodiode goes to the analyser, which analyses the signal with the help of FFT programme run on the Amstrad PC-1512-CD computer. The spec-

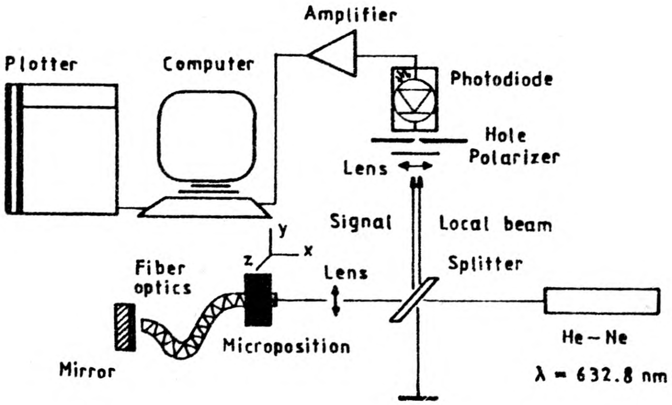

Fig. 2. Schematic diagram of the optical fiber LDV system

trum is drawn by a plotter. A polarizer is applied to reduce the polarization effects of the reflected ray, which generate additional noise. The alignment of the instruments is very important while it is necessary to fix the photodiode and the ends of the fiber optics with the help of suitable micropositioning tools.

4. Experimental results and discussion

The LDV in Figure 2 was constructed to measure the surface speed, however, this construction may be used for measuring velocities of different reflectors. The first experiment was performed to verify the response of the LDV for the cases of moving and nonmoving mirrors, respectively [13], as shown in Fig. 3. The experimental velocities obtained from the known frequencies, using the relation $\Delta f = 2V/\lambda$, were plotted against the linear velocities, which were calculated geometrically as shown in Fig. 4.

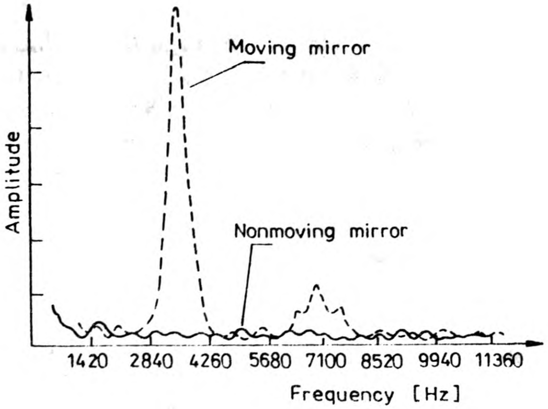

Fig. 3. Response of the LDV for moving and nonmoving mirrors

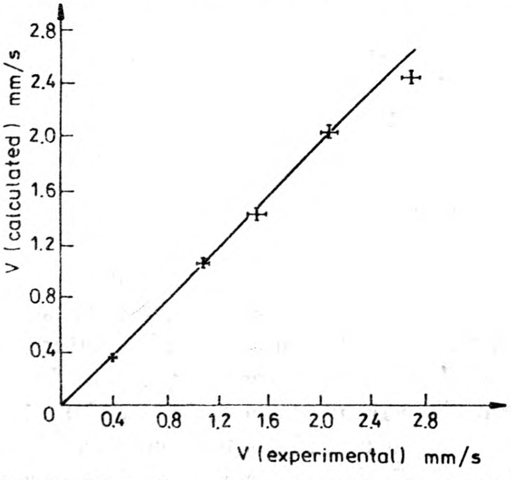

Fig. 4. Comparison of experimental and calculated velocities for moving mirror

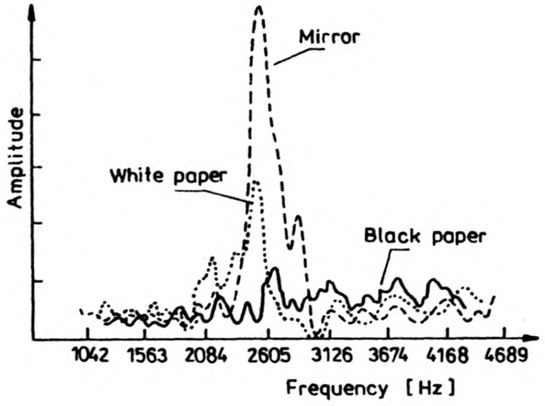

Fig. 5. Shift frequency obtained for different reflectors

Good linearity was obtained with the maximum error of 6.1% and the slope of 0.986, while the theoretical value of the latter is 1.00. This means that the experimental results are in a good agreement with the calculated values and LDV has a good response for the moving mirror. To confirm the usefulness of LDV, another experiment was conducted to see the performance of the equipment in the case of colour reflectors as shown in Fig. 5. The reflecting bodies were subsequently a mirror, white and black papers. The surface to be measured was fixed on a movable stand, which was moving at the same velocity for all the measured surfaces. The reflector position was set at the same distance and the starting point for the motion was the same. The shift frequencies were expected to be equal for all the different surfaces being moved with the same velocities, but the amplitudes were not the same, depending on the reflectivity of the moving surface. Figure 6 shows the results for red paper as a reflector surface moving with different velocities ranging

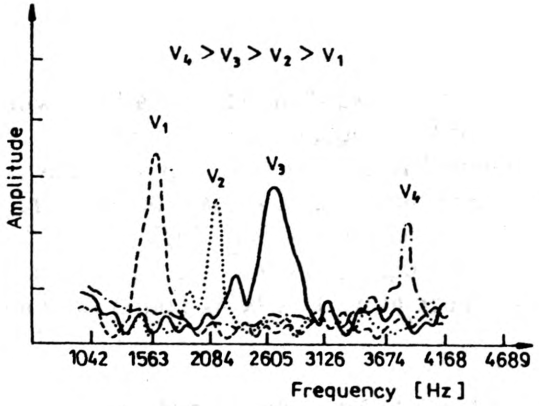

Fig. 6. Shift frequency obtained for different velocities (red paper as a reflector)

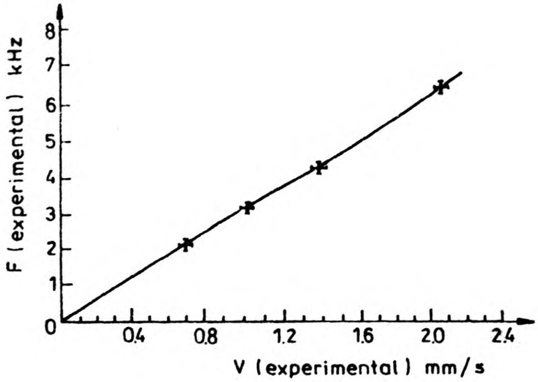

Fig. 7. Experimental result for shift frequency against velocity (red paper as a reflector)

from 0.816 to 2.0 mm/s. In Figure 7, we plot the experimental results of Δf versus V. Clearly, the relationship is quite linear. The coefficient of proportionality, i.e., $2/\lambda$ was found to be 3181.8 cm^{-1}. In our experimental situation, the wavelength value was $\lambda =$ 632.8 nm and then we theoretically obtained $2/\lambda = 3160.5$ cm^{-1}. Considering the simplicity of our equipment this agreement was quite satisfactory. The correlation factor was found to be 0.999, with error not greater than 3.6%.

5. Conclusions

In the present study, our efforts have been directed towards developing a LDV with an optical fiber capable of measuring the velocity of moving bodies, which is based on optical heterodyning. However, experimental results using known velocities of moving bodies demonstrated that the blood flow velocity may be measured accurately by using FFT programme. We conclude that the LDV using the technique of optical mixing spectroscopy may simply provide quick and accurate values of moving body velocities. The experimental work is being continued, and new results will be reported later.

Acknowledgements — We would like to express our thanks to Mr Krzysztof Kołodziejczyk for his preparation of the FFT programme.

References

[1] TANAKA T., Science **186** (1974), 830.
[2] JACOBS S. F., Am J. Phys. **56** (1988), 235.
[3] NILSSON G. E., TENLAND T., OBERG A., IEEE Trans. Biomed. Eng. BME **27** (1980), 12.
[4] OWCZAREK G., *Measurement of the velocity of blood cells using a technique of optical heterodyning*, Thesis for M.Sc. Degree, Technical University of Łódź, Poland, 1988 (in Polish).
[5] SRIRAM P., HANAGUD S., CRAIG J., KOMERATH N. M., Appl. Opt. **29** (1990), 2409.
[6] BATES G. J., J. Phys. E **10** (1977), 669.
[7] NISHIHARA H., KOYAMA J., HOKI N., KAJIYA F., HIRONAGA M., KANO M., Appl. Opt. **21** (1982), 1785.

[8] Tanaka T., Benedek G. B., Appl. Opt. **14** (1975), 189.
[9] Wakins D., Holloway G. A., IEEE Trans. Biomed. Eng. BME **25** (1978), 28.
[10] Riva C., Ross B., Benedek G. B., Invest. Ophtalmol. **11** (1972), 936.
[11] Duteil L., Bernengo J. C., Schalla W., IEEE Trans. Biomed. Eng. BME **32** (1985), 439.
[12] Wilson J., Hawkes J. F. B., *Optoelectronics. An Introduction*, Prentice-Hall Internat. 1983, Chapt. 9.
[13] Abdullah A., Drobnik A., Owczarek G., Wolf L., *Velocity measurement using heterodyning effect* (to be published).

Received January 21, 1992,
in revised form May 27, 1992