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A laser method for measuring the three-dimensional velocity vector

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***Abstract*.** **A laser method for three-dimensional measuring the velocity vector is discussed. In this method, a three-beam configuration of the probing field is used to form a 3-D orthogonal coordinate basis. The method has been realised in an operating prototype of the measuring system that employs temporal selection of the velocity components. It has been tested experimentally in a study of a swirling flow.**

***Keywords*:** *velocity measurement, three-dimensional method, laser anemometer.*

1. Introduction

In the modern 3-D laser measurement technology, the problem of measuring the full velocity vector is one of the most important. It arises, for example, in laser diagnostics of gas and condensed-matter flows [1, 2] and is important for research and industry fields where nonperturbing monitoring of kinematic parameters is necessary.

The known methods for selecting the velocity vector (see, for example, [3]) are based on constructing a multichannel optical measurement system. Each channel of the system forms a probing field whose sensitivity vector $\boldsymbol{K}_i$ specifies the direction of one axis of an orthogonal coordinate basis:

$$\boldsymbol{V} = \sum_{i=1}^{3} \boldsymbol{V}_i = \sum_{i=1}^{3} V \frac{\boldsymbol{K}_i}{K_i}.$$

The sensitivity vector $\boldsymbol{K}_i$ is the vector of an amplitude or phase periodic structure (grating) that is formed by the probing field. The magnitude K_i of this vector is inversely proportional to the spatial period Λ: $K_i = 2\pi/\Lambda_i$. Therefore, the Doppler frequency shift of the light scattered by a moving optical inhomogeneity is determined by the projection of its velocity vector $\boldsymbol{V}$ on the vector $\boldsymbol{K}_i$:

$$\omega_{\mathrm{D}i} = \boldsymbol{V}\boldsymbol{K}_i = 2\pi \frac{V_i}{\Lambda_i}, \tag{1}$$

where $V_i = V\cos\varphi_i$ and φ_i is the angle between $\boldsymbol{V}$ and $\boldsymbol{K}_i$. By selecting and measuring the Doppler frequency shift $\omega_{\mathrm{D}i}$, the i-th component of the velocity is obtained in the direction of $\boldsymbol{K}_i$. The vector $\boldsymbol{K}_i$ is determined by the configuration of light beams in the optical measurement scheme.

In heterodyne schemes of laser Doppler anemometry (LDA), the sensitivity vector is determined by the difference between the wave vectors of the incident ($\boldsymbol{k}_{\mathrm{i}}$) and scattered ($\boldsymbol{k}_{\mathrm{s}}$) beams:

$$\boldsymbol{K} = \boldsymbol{k}_{\mathrm{s}} - \boldsymbol{k}_{\mathrm{i}}. \tag{2}$$

In differential schemes, the sensitivity vector is equal to the difference between the wave vectors of the laser beams that form the probing interference field:

$$\boldsymbol{K} = \boldsymbol{k}_1 - \boldsymbol{k}_2. \tag{3}$$

In LDA schemes with photomixing of sidebands of the Fourier spectrum of an optical signal, the sensitivity vector is determined by the difference of the wave vectors of scatterred beams:

$$\boldsymbol{K} = \boldsymbol{k}_{\mathrm{s}1} - \boldsymbol{k}_{\mathrm{s}2}. \tag{4}$$

The problem of measuring the 3-D velocity vector consists in producing a probing field whose sensitivity vectors $\boldsymbol{K}_i$ $(i = 1, 2, 3)$ are adequate to an orthogonal coordinate basis, selecting optical signals, and separating and measuring the Doppler frequency shifts $\omega_{\mathrm{D}i}$, which are related to their respective velocity components $\boldsymbol{V}_i$ by well-known equations that follow from Eqn (1) [4]:

$$V_i = \frac{1}{2\pi}\omega_{\mathrm{D}i}\Lambda_i. \tag{5}$$

The multiplication of optical channels used in the known methods for selecting the 3-D velocity vector complicates the measurement system, degrades its reliability, and restricts its functionality. In particular, it complicates measurements in dispersive media, spatially confined flows, near-wall regions, etc. This is a consequence of the larger number of laser beams that form the probing field (in the known systems, there are five beams, subtending a solid angle of ~ 0.5 sr). The conventional chromatic selection of optical signals greatly complicates or even prohibits measurements in dispersive media.

Another problem is that of increasing the measurement sensitivity, which, as follows from Eqn (1), is proportional

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to the magnitude K of the sensitivity vector. An obvious way to tackle this problem is to find a configuration of the probing field that has the maximum K_i. In the known methods, the ability to perform 2-D and 3-D measurements of the velocity vector entails the price of a reduced sensitivity [3].

In [5], new methods for selecting the velocity vector in an orthogonal coordinate basis were described, which are based on linear sum-difference transformations of sensitivity vectors. A special feature of these methods is the possibility to measure the 3-D velocity vector in configurations with a lower number of probing laser beams, which increases the measurement sensitivity. For example, a three-beam configuration, usually used in 2-D measurements, is sufficient to select of the 3-D velocity vector. In this work, we discuss the realisation of a laser measurement system which employs adaptive temporal selection of the full velocity vector in an orthogonal coordinate basis formed by a three-beam configuration of the probing field.

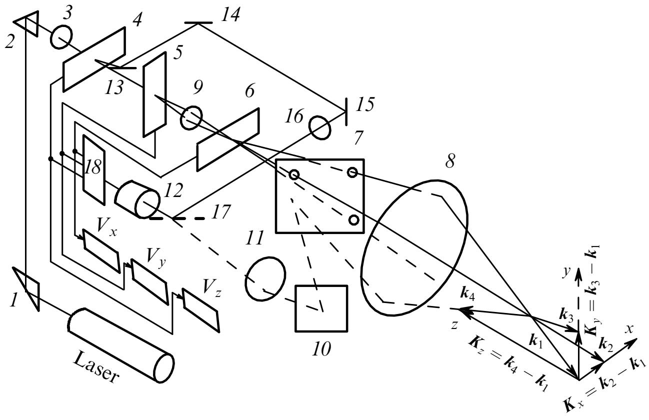

Figure 1. Functional scheme of the laser Doppler meter for measuring the 3-D velocity vector: (*1, 2*) deflecting prisms; (*3*) lens; (*4–6*) travelling–wave acoustooptical modulators; (*7*) mirror with apertures; (*8*) objective; (*9*) matching objective; (*10*) deflecting mirror; (*11*) microobjective; (*12*) photodetector; (*13–15*) mirrors; (*16*) matching objective; (*17*) semitransparent mirror; (*18*) switching processor.

2. Description of the method

Fig. 1 shows the functional scheme of the measurement system. The orthogonal coordinate basis is formed by the sensitivity vectors $\boldsymbol{K}_x, \boldsymbol{K}_y$, and $\boldsymbol{K}_z$ obtained in the three-beam geometry

$$\begin{aligned} \boldsymbol{K}_x &= \boldsymbol{k}_2 - \boldsymbol{k}_1, \\ \boldsymbol{K}_y &= \boldsymbol{k}_3 - \boldsymbol{k}_1, \\ \boldsymbol{K}_z &= \boldsymbol{k}_4 - \boldsymbol{k}_1, \end{aligned} \tag{6}$$

where $\boldsymbol{k}_1, \boldsymbol{k}_2$ and $\boldsymbol{k}_3$ are the wave vectors of the incident beams and $\boldsymbol{k}_4$ is the wave vector of the separated scattered beam. To perform 3-D measurements, the wave vectors of the laser beams should satisfy the conditions

$$(\boldsymbol{k}_2 - \boldsymbol{k}_1)^2 + (\boldsymbol{k}_3 - \boldsymbol{k}_1)^2 = (\boldsymbol{k}_3 - \boldsymbol{k}_2)^2,$$

$$(\boldsymbol{k}_4 - \boldsymbol{k}_1)^2 + (\boldsymbol{k}_3 - \boldsymbol{k}_1)^2 = (\boldsymbol{k}_4 - \boldsymbol{k}_3)^2,$$

$$(\boldsymbol{k}_4 - \boldsymbol{k}_1)^2 + (\boldsymbol{k}_2 - \boldsymbol{k}_1)^2 = (\boldsymbol{k}_4 - \boldsymbol{k}_2)^2$$

or

$$\boldsymbol{K}_x^2 + \boldsymbol{K}_y^2 = (\boldsymbol{K}_y - \boldsymbol{K}_x)^2,$$

$$\boldsymbol{K}_z^2 + \boldsymbol{K}_y^2 = (\boldsymbol{K}_z - \boldsymbol{K}_y)^2,$$

$$\boldsymbol{K}_z^2 + \boldsymbol{K}_x^2 = (\boldsymbol{K}_z - \boldsymbol{K}_x)^2,$$

which implies that $\boldsymbol{K}_x\boldsymbol{K}_y = 0$, $\boldsymbol{K}_z\boldsymbol{K}_y = 0$, $\boldsymbol{K}_z\boldsymbol{K}_x = 0$.

The measurement system includes a laser and the following optical elements, sequentially arranged on the path of the laser beam: deflecting prisms *1* and *2*, a lens *3*, orthogonally oriented travelling-wave acoustooptical modulators *4–6*, a mirror *7* with apertures, and an objective *8*. A matching objective *9* is placed between acoustooptical modulators *5* and *6*. A deflecting mirror *10*, a microobjective *11*, and a photodetector *12* are placed on the path of the scattered beam, which is limited by the aperture of objective *8* and reflected by mirror *7*.

Ultrasonic waves propagate in modulators *5* and *6* in the directions that correspond to the orientations of the measured velocity components V_x and V_y. The modulators operate in the Bragg regime; the apertures made in mirror *7* limit the diffracted light beams. The first-order diffracted beam, coming from modulator *4* is deflected by a sequence of mirrors (*13–15*). After passing through a matching objective *16*, it is directed by semitransparent mirror *17* to photodetector *12*.

The photodetector is connected to a switching processor *18*, which contains a logic switch whose output is connected to three velocimeters V_x, V_y, and V_z in pairs and to corresponding acoustooptical modulators *4–6*.

The 3-D measurement system employs temporal selection of the orthogonal components of the velocity vector. Unlike the laser anemometer employing adaptive temporal selection and visualisation of the 2-D velocity vector, described in Ref. [6], the 3-D measurement system contains a channel that measures the z-component of the velocity vector in a given coordinate basis.

After passing through optical elements *1–4*, the laser beam falls on an acoustooptical modulator *5*, the ultrasonic wave travelling in it along the y axis. Under the action of the controlling voltage of frequency Ω, the zero-order and minus first-order diffracted beams appear at the modulator output. The separated beams pass through matching objective *9*, modulator *6*, and the apertures of mirror *7*. After that, the beams are focused by objective *8* to the flow region under study.

Intersecting in the flow, the beams, which have wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_3$, form an interference field with the lattice vector $\boldsymbol{K}_y$ (6). The image of this interference field in the light scattered by particles moving in the flow is formed by optical elements *7, 8, 10*, and *11* on the photosensitive surface of a photodetector *12*. When a scattering particle crosses the probing optical field, a radio pulse of the photocurrent appears at the photodetector output. The carrier frequency of this pulse is a known linear function of the Doppler frequency shift:

$$\omega_y = \Omega + \omega_{\mathrm{D}y} = \Omega + \boldsymbol{V}\boldsymbol{K}_y,$$

and its duration equals the time during which the particle crosses the interference field. The switching processor *18* feeds the output signal to the meter of the velocity component V_y.

Upon completion of a single or a given number (N) of photocurrent radio pulses, the switching processor turns off modulator *5* and activates modulator *6*, at the same time feeding the output signal to the meter of the velocity component V_x. The travelling ultrasonic wave in modulator *6* is parallel to the x axis in the measurement coordinate basis. This axis is parallel to the lattice vector K_x formed by the interfering laser beams with wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ diffracted by the ultrasonic wave in modulator *6*.

As the scattering particle moves in the probing field, a radio pulse of the photocurrent appears at the photodetector output. The frequency of this pulse is a known linear function of the Doppler frequency shift ω_{Dx}:

$$\omega_x = \Omega + \omega_{Dx} = \Omega + \boldsymbol{V}\boldsymbol{K}_x.$$

Upon completion of a single or a given number (N) of radio pulses, the switching processor activates acousto-optical modulator *4* and velocimeter V_z, thereby switching the optical and electronic systems over to the mode for measuring the velocity projection V_z. In this case, the probing field is formed by the laser beam with the wave vector $\boldsymbol{k}_1$.

The light beam with the wave vector $\boldsymbol{k}_4$, scattered by a particle moving in the probing field, represents a signal beam, which is directed by the sequence of optical elements *7, 8, 10, 11* on the photosensitive surface of the photodetector. The signal and reference beams are made coincident on semitransparent mirror *17*. The reference beam is the result of the first-order diffraction from the ultrasonic wave in modulator *4*; it is directed by the sequence of elements *13 – 17* on the photosensitive surface of the photodetector *12*. The optical mixing of the signal and reference beams produces a radio pulse, whose frequency is a known linear function of the z-component of the velocity:

$$\omega_z = \Omega + \omega_{Dz} = \Omega + \boldsymbol{V}\boldsymbol{K}_z.$$

By measuring ω_z, one obtains information about the z projection of the velocity.

Upon completion of a single or a given number (N) of radio pulses, the switching processor repeats the measurement cycle by switching the optical and electronic measurement channels. The optical channels are switched over in time instants when there is no Doppler signal, which prevents switching noise. The data sampling frequency is determined by the channel switching frequency f_c. It increases with decreasing N for each velocity component, reaching the maximum at $N = 1$.

The switching frequency is determined by the dynamics of the process under study and the concentration of scattering particles. In the case of regular sampling, the velocity component measurements can be considered simultaneous for spectral frequencies of the process under study not exceeding $(1/6)f_c$. In the case of random sampling, this boundary frequency is approximately $0.1f_c$. As compared to the known systems, the energy sensitivity gain is much better in our case because the total laser power is used for measuring each velocity component, which increases the signal-to-noise ratio and, accordingly, the accuracy.

Upon the velocity measurement, the process under study is discretised by moving scattering particles. The time used for averaging (accumulating) the results of measurements of components of the velocity vector is determined by the time during which a moving particle crosses the probing field formed by the activation of the corresponding measurement channel. In this situation, the power of the probing light field is three times higher in the regime of temporal separation than in the case of the simultaneous measurements in all three channels. As a result, the signal-to-noise ratio increases (for example, in the case of shot noise, the signal-to-noise ratio increases by a factor of $\sqrt{3}$); the energy sensitivity and the accuracy characteristics increase as well.

In the case of backscattering, the intensity of the light signal is 2 – 3 orders of magnitude lower than in the case of forward scattering. Therefore, the possibility of increasing the signal-to-noise ratio is crucial for enhancing the functional and accuracy characteristics of the measuring device. The measurement channels are commutated when there is no signal, in the time interval between the end of a signal from one particle and the beginning of a signal from the next particle. Therefore, the radio pulse signal formed by a particle moving through the probing field is not gated by the channel switching. The accumulation time remains equal to the radio pulse duration, and the switching noise does not arise.

In laser Doppler anemometry, the range of scattering particle dimensions usually corresponds to the Mie scattering conditions. The scattering indicatrix of macroparticles is extremely irregular. During the measurements, the scattered light is filtered in the angular spectrum band that corresponds, on average, to a single order of diffraction. If the solid angle that limits the scattered beam spans several diffraction maxima, the useful signal is suppressed due to phase mismatch between light beams. This means that the band of the angular spectrum used for filtering the scattered light field in the x and y measurement channels is not very different from the band used for measuring the velocity component V_z. In addition, the amplitude of the variable component of the photocurrent signal increases in the z measurement channel due to the heterodyne transformation of the corresponding scattered light beam.

3. Experimental results

We measured the 3-D velocity vector of a swirling water flow in a 12 cm × 12 cm × 13 cm cell (Fig. 2). The flow was induced by a disk rotating above the water surface. The y

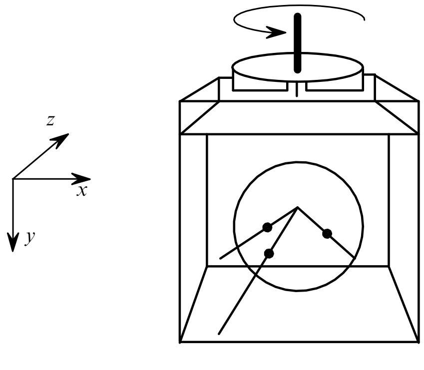

Figure 2. Cell with a swirling flow.

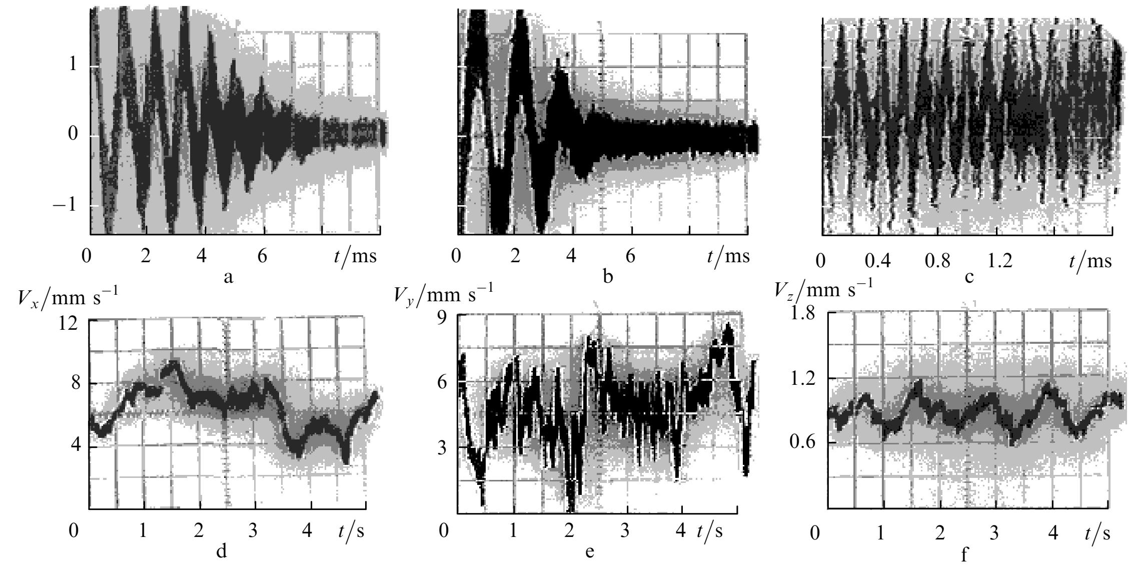

Figure 3. Doppler (a–c) and analogue (d–f) signals corresponding to the components V_x (a,d), V_y (b,e), and V_z (c,f) of the 3-D velocity vector.

axis of the orthogonal coordinate basis formed by the probing field was parallel the rotation axis.

Fig. 3 shows examples of Doppler signals and corresponding analogue signals proportional to the V_x, V_y and V_z components of the 3-D velocity vector.

Fig. 4 shows the stereoscopic projection of the reconstructed 3-D velocity vectors at two different points of the swirling flow separated by 17.5 and 31.5 mm from the swirl axis and by 86 mm from the cell bottom. To perceive Fig. 4

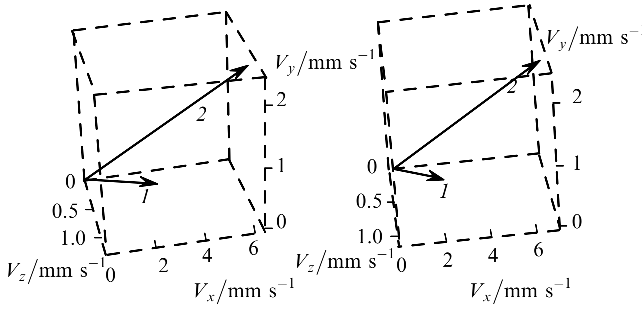

Figure 4. Stereoscopic projection of the 3-D velocity vectors measured in two different radial points of the swirling flow, separated by 17.5 (*1*) and 31.5 mm (*2*) from the swirl axis and by 86 mm from the flow bottom.

stereoscopically, one should accommodate the eye to infinity.

The provided examples demonstrate that the laser method for measuring the 3-D velocity vector with a three-beam configuration of the probing optical field is indeed feasible and applicable to practical studies of swirling flows.

4. Conclusions

We have considered a laser method for measuring the flow velocity vector in an orthogonal coordinate basis with a three-beam probing field configuration and implemented it in an operating prototype of a laser anemometer that employs temporal selection of the 3-D velocity components. This method features high energy sensitivity that was achieved by employing the total laser power to measure each velocity component in the case of adaptive or forced switching between the measurement channels. This method may find applications in research and industrial technologies where nonperturbing measurements of kinematic parameters of gas and condensed media are necessary.

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