Development of the method of laser Doppler anemometry for diagnostics of turbulent flows at high speed

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Abstract. The aim of the work was to develop a laser Doppler anemometry method for high-speed turbulent aerodynamic flow diagnostic. As a result, this allowed us to measure two projections of the velocity vector in the range of 0.1 - 400 m/s with a relative error not exceeding 0.5%. The measurement area was 0.1x0.1x0.5mm. The positioning device moved the measuring unit in the area of 250 x 250 x 250 mm with an accuracy of 0.1 mm. This method also provides the ability to measure local flow rate fluctuations.

1. Introduction
The problem of verifying the turbulent flow calculations is important in a few scientific and practical applications. Often, measurements of the velocity fields are carried out in the sections of experimental setups to verify numerical calculations. The velocity measurement at a high speed is important in many practical applications. For example, in the wind energy the air velocity near a tip of the blade can reach high velocities of up 200 m/s or even higher. The physical modeling of such event can require high air velocity measurements. So, the development of an adequate velocity measurement technique is quite desirable. Optical methods are especially convenient for measuring such kinematic characteristics, including the method of laser Doppler anemometry. The LDA method does not disturb the flow and has a small measurement error. Measurement of the kinematic parameters of turbulent flows at a high speed is a difficult task [1].

The aim of this work was to develop a laser Doppler anemometry method for high speed turbulent aerodynamic flow diagnostic and to implement it in the LAD-07 meter. The LAD-07 meter was developed and manufactured at the Institute of Thermophysics SB RAS.

2. The method
The laser Doppler anemometry method is based on measuring the frequency of laser radiation, scattered from moving objects. A laser beam, characterized by frequency $\omega_0$ falls on an object moving with speed $v$ and is scattered in different directions. In this case, the scattered wave is characterized by frequency $\omega_s$. The relationship between the optical frequencies $\omega_0$ and $\omega_s$ is determined by the expression:

$$\omega_s = \omega_0 \frac{[1 - (v/c) \cos \theta]}{[1 - (v/c) \cos \vartheta]},$$

where $\theta$ is the angle between the direction of laser beam propagation and the direction of object movement, $\vartheta$ is the angle between the directions of wave registration and object movement. This relationship forms the basis of the Doppler method for measuring velocities [2]. It allows you to
determine the speed of an object by the measured frequency of the scattered wave with known parameters $\omega_0$, $\theta$, and $\phi$.

Since it is difficult to measure directly the frequency of scattered radiation in the optical range ($\omega_0 \approx 1.5 \times 10^{15}$ [rad/s]), heterodyne methods are used to measure the frequency difference between laser and scattered radiation. Taking into account (1), it is possible to determine the frequency shift of the scattered radiation caused by the Doppler effect:

$$\omega_D = \omega_0 - \omega_0 = \omega_0 (v/c)(\cos \theta - \cos \phi).$$

3. The implementation of the method in LAD-07 meter and its development

The LAD-07 meter contains an optoelectronic module, a computer, a coordinate-moving device, and software. The internal structure of the product is shown in Fig. 1. In the functional diagram, the following elements are shown in numbers: 1 – laser source with pump current source; 2 – acousto-optic Y-channel modulator; 3 – acousto-optic X-channel modulator; 4. – rotary prism; 5 – thermometer DS1822; 6 – optics and plate thermometer; 7 – X-channel acousto-optics thermometer; 8 – Y-channel acousto-optics thermometer; 9 – shaping lens; 10 – optical plate; 11 – swivel mirror; 12 – rotary prism; 13 – photomultiplier unit; 14 – reference generator; 15 – Y-channel amplifier switch; 16 – X-channel amplifier switch; 17 – signal preprocessor; 18 – quadrature mixer; 19 – photomultiplier unit power supply; 20 – power supply.

The meter works as follows. The beam of an injection semiconductor laser 1, after passing through matching optical elements, hits acousto-optic modulators 2, 3, to which the traveling ultrasonic waves are directed, respectively, along the X and Y axes. At the outputs of the modulators operating in the Bragg diffraction mode, three light beams are formed, diffracted into zero, X-minus and Y-minus first orders. The split beams pass sequentially through the rotary prisms 4, 12, the dielectric mirror with the shaped coating 11 and the objective 9 are directed into the investigated region of the flow, whose velocity must be measured.

Crossing in the flow, the laser beams form an interference field with a known periodic structure. Its image in scattered light is formed by optical elements on the light-sensitive surface of the photodetector 13. The image size is limited by the field diaphragm, which determines the degree of spatial filtration in the receiving path.

When the scattering particle crosses the probing optical field at the output of the photodetector, a radio pulse of the photoelectric signal appears, whose frequency is a known linear function of the Doppler frequency shift, and the duration is equal to the time of passage of the light diffuser through the interference field.

Amplifiers-commutators 15 and 16 include modulators 2 and 3, and also connect synchronously the quadrature mixer 18 and the Doppler signal preprocessor 17 to the photodetector 13 after N signal pulses arrive at its input. As N decreases, information sampling frequency for each velocity component increases, reaching a maximum value at N = 2.

Switching of optical channels occurs at times when there are no strobe signals and the processor does not accumulate information. This eliminates the effect of switching noise and the mutual influence of optoelectronic measuring channels.

Signal preprocessor LDIS LAD-07 is designed for complex demodulation of the Doppler radio signal. The preprocessor module implements the method of time selection and provides control over the selection of the optical measuring channel. In combination with a computer software signal processor, it provides automatic adaptive switching the optical measurement channels and measurement of two orthogonal components of the velocity vector.

LDIS LAD-07 implements effective optoelectronic methods for selecting the velocity vector of light scatterers in an orthogonal coordinate basis, providing a significant increase in sensitivity and expansion of functionality. The orientation of LDISs towards the use of semiconductor injection lasers seems to be very promising. This is due to their compactness, mechanical strength, high efficiency, low noise level, and significant output radiation power, which exceeds the radiation power of helium-neon lasers.
Figure 1. The scheme of laser Doppler anemometer LAD-07.

The optical scheme of the laser Doppler meter LAD-07 is based on a combination of a diffractive beam splitter and a shaping lens. After passing through the anamorphic transducer, the laser beam hits the diffractive splitter. A dynamic phase diffraction grating is used as a beam splitter, which is implemented, for example, in an acousto-optic traveling wave modulator (AOM). In acousto-optic frequency modulators, the phenomenon of laser beam diffraction on a moving phase grating, formed by a periodic change in the refractive index of a photoelastic medium under the action of an acoustic wave, is used. The diffractive splitter operates in the Bragg mode. A feature of Bragg diffraction is that the powers of all diffracted beams, except for the first, become negligible, i.e., after phase grating,
only two beams are obtained: zero and first. The period of the interference pattern formed by the achromatic objective on the surface under study does not depend on the wavelength of the laser emitter [see 1,2]. It is determined only by the period of diffraction grating in the beam splitter and the angular magnification of the optical system. The image of the probing field in the light scattered by the moving surface of the measured object is formed on the photodetector 13. The measurement result does not depend on the spectral emission band of the semiconductor laser. Consequently, when organizing the optical scheme of a laser Doppler meter with a diffractive beam splitter, the requirements for the stability of the laser radiation wavelength are significantly reduced, and the corresponding technical solutions become simpler and more efficient.

In LAD-07, the following operations of generation and conversion of optical and electronic signals are sequentially performed. Laser beams are directed into the investigated medium, forming coherent probing fields with given sensitivity vectors. The scattered light beams are separated and quadratic photoelectric conversion of the optical signals is performed. The components of electrical signals, whose frequencies correspond to the projections of the velocity vector onto the given directions of the sensitivity vectors, are selected. Synchronous adaptive switching of laser measuring channels is performed. The frequencies of the selected signals are transformed into the values of the corresponding components of the velocity vector by means of known linear transformations determined by the spatial configuration of the sensitivity vectors.

In LAD-07 a lot of new and original technical solutions are applied. Among them are the following. For the first time, a new anamorphic scheme of a laser anemometer was developed, which allowed application of modern high-power semiconductor lasers with a low degree of spatial and temporal coherence, which significantly improved the characteristics of the anemometer. For the first time a built-in signal processing system based on parallel programmable logic structures "Field Programmable Gate Array" was developed as well as a new method of adaptive Doppler frequency extraction.

The orthogonal pairs of velocity vector components in the LAD-07 are measured by combining transformations of the Doppler signal frequencies corresponding to the projections of the velocity vector onto the sensitivity vectors in the selected basis. This ensures the selection of the orthogonal components of the velocity vector in configurations with a smaller number of probing and scattered light beams than in known optical schemes, and a significant gain in stability and reliability of operation is achieved.

Realizability at small solid angles is another advantage of the developed optical configurations. This circumstance is especially important, since it allows one to reduce significantly the requirements for the quality and cost of optical elements of experimental physical installations. Rotary prisms and lenses, mirror and antireflection coatings are optimized for laser anemometer applications. Thus, the quality of the probing coherent beams is optimized. The device contains elements of passive aerodynamic protection of external optical surfaces from dust and atmospheric aerosol.

Optical elements were tested for compliance and preservation of parameters when the external temperature conditions changed, as well as when the level of concentration of the radiation energy on the optical part itself was changed. The mechanical parts of the assemblies provide rigid fixation of the optical elements and do not allow deviations under mechanical stress and temperature extremes.

Here we present the improvement of LAD-07 meter for near wall velocity measurements. The device is modified for measuring one velocity component. This improvement gives an ability to adjust laser beam for enhancement the interferometry pattern and enlargement of bands number in a reflected signal which allows an increase in the device sensitivity and enlargement of the frequency peak measurement precision. Also, it allows an increase in the laser power density. The laser and photomultiplier are modified for better signal achievement.

4. Experimental demonstration
For demonstration, measurements were performed in a transparent Ranque-Hilsh vortex tube [3]. The Ranque vortex tube is an aerodynamic device which separates the aerodynamic inlet flow into two
flows; one of them is cooled and another is heated. The main characteristics of the flow is the inlet pressure $P_{in}$ and the ratio of cooled flow rate to inlet flow rate $\mu = G_c/G_{in}$. Here $G_c$ is the cooled flow rate, and the $G_{in}$ is the inlet flow rate. The experimental Ranque tube (Figure 2) includes the accelerating vortex chamber with the guiding apparatus with transparent windows. The side of rectangular working channel with the square cross-section is 34 mm. The more detailed explanation can be seen in [3]. The vortex tube is equipped with the swirler with transparent windows. Windows are made of optical glass which allows precise optical diagnostics inside the swirler [4].

![Figure 2. The vortex tube with square cross-section.](image1)

![Figure 3. 3D model of the swirler with transparent windows.](image2)

The circumferential velocity component (fig. 4, 5) is measured in the transparent vortex swirler at $\mu = 0.3$ and inlet pressure values ranging from 2 to 5 bar. On the Oy axis this velocity component can be considered as a tangential velocity component in the polar coordinate system. The assymetry is connected to slit placement according to the OY axis. The velocity profiles in the upper flow area of vortex chamber in the central plane are shown in fig. 5 for absolute pressures from $P_{in} = 2$ to 5 bar. The module of $V_X$ velocity component increases from the periphery to the center up to the reverse flow boundary at $Y/D = 0.2$. The velocity profiles of a similar shape tend to close with an increase in the $P_{in}$ value.

![Figure 4. The velocity “circumferential” component measurement scheme (front view).](image3)

![Figure 5. The tangential velocity profiles at inlet pressure $P_{in}$ =1-4 bar.](image4)
Conclusion
This work is aimed at developing a laser Doppler anemometry method for diagnosing turbulent aerodynamic flows at high speed. The device is modified for measuring one velocity component. This improvement gives an ability to adjust laser beam for enhancement of the interferometry pattern and enlargement of band number in a reflected signal which allows an increase in the device sensitivity and enlargement of the frequency peak measurement precision. As a result, this allows the measurement of two projections of the velocity vector in the range of 0.001 - 400 m/s with a relative error not exceeding 0.5%. The measurement area is 0.1x0.1x0.5 mm. The positioning device allows measuring unit movement in the area of 250 x 250 x 250 mm with an accuracy of 0.1 mm. This method also provides the ability to measure local flow rate fluctuations. For demonstration, the measurements are performed in a transparent Ranque-Hilsh vortex tube. The circumferential velocity component is measured in the transparent vortex swirler at $\mu = 0.3$ and inlet pressure values ranging from 1 to 4 bar. The maximum velocity component can reach the value of 150 m/s.

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