Developing the laser doppler anemometry method for the diagnostics of kinematic parameters of a turbulent flow in the near wall region

V G Meledin, S V Dvoinishnikov, I K Kabardin, A S Chubov, G V Bakakin, A K Kabardin, V A Pavlov, M Kn Pravdina and N I Yavorsky
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk

E-mail: ivankabardin@gmail.com

Abstract. The aim of the work is to develop a laser Doppler anemometry method for diagnosing turbulent aerodynamic flows in the near wall region. This will enable measuring two projections of the velocity vector in the range of 0.001 … 400 m/s with a relative error not exceeding 0.1%. The measurement area is 0.1×0.1x0.5mm. The positioning device allows moving the measuring unit in the area of 250×250x250 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 calculations of turbulent flows is important in a number of scientific and practical applications. Often, measurements of the velocity fields are carried out in the sections of experimental setups to validate numerical calculations. Optical methods, including the method of laser Doppler anemometry, are especially convenient for measuring the kinematic characteristics. The LDA method does not disturb the flow and has small measurement error. Measurements of the kinematic parameters of turbulent flows near the wall are much more difficult than measurements in the flow core, since in this region a number of incoming tracer particles is much smaller, there are reflections from the wall and large velocity gradients [1].

The aim of the work is to develop a laser Doppler anemometry method for diagnosing turbulent aerodynamic flows in the near wall region and to implement it in the LAD-07 meter. The LAD-07 meter is developed and manufactured at the Institute of Thermophysics SB RAS.

2. The method

The laser Doppler anemometry method is based on the laser radiation frequency measurement which is scattered from moving objects. A laser beam, characterized by a frequency $\omega_0$ falls on an object moving with a speed $v$ and is scattered in different directions. In this case, the scattered wave is characterized by a frequency $\omega_s$.

The relationship between the optical frequencies $\omega_0$ and $\omega_s$ is determined by the expression:

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

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

Since it is difficult to directly measure the frequency of the scattered radiation in the optical range ($\omega_0=1.5\times10^{15}$ [rad/sec]), 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:

$$\omega_0 = \omega_k - \omega_0 = \omega_0 (v/c)(\cos \vartheta - \cos \theta). \quad (2)$$

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 – Laser thermometer DS1822; 6 – Optics and plate thermometer DS1822; 7 – X-channel acousto-optics thermometer DS1822; 8 – Y-channel acousto-optics thermometer DS1822; 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 “FRONTEND”; 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, in 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, the velocity of which 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, the frequency of which 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 synchronously connect 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, the 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 of 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 of optical measurement channels and measurement of two orthogonal components of the velocity vector.

The measurement system 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 LDAs 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.

Semiconductor lasers have some special properties that complicate their direct application in optical measurement technology. These properties include: wide directional diagram of the laser beam, for the conversion of which it is necessary to use anamorphic optical systems based on cylindrical lenses; strong dependence of the mode composition and spectral band of radiation on the pump current.
and temperature; narrow working range of pump current; significant scatter of parameters of semiconductor laser diodes even within the same batch.

In most of the known circuit solutions of laser Doppler meters, the spatial period of the probing optical field is determined by the wavelength of the laser emitter. Therefore, very stringent requirements are imposed on the stability of the wavelength of the laser emitter. They are designed to work with gas lasers with high radiation coherence.

As it is known, for semiconductor laser diodes, the wavelength drift from temperature is 3–5 Å/°C. The same jump occurs in the radiation of a laser diode due to a rearrangement of the mode composition, for example, upon repeated switching on or upon a change in the pump current.

In this case, for the LAD-07 meter, the contribution of the instability of a given wavelength (λ = 684 nm) to the relative measurement error will be 0.5 %, which exceeds the permissible measurement error. Therefore, the optical scheme of a semiconductor laser LDA should be designed so that the result of measuring the Doppler frequency shift is not critical to the stability of the laser wavelength.

For this reason, 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). AOM use the phenomenon of diffraction of a laser beam 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. 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 the 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 the 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 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 a quadratic photoelectric conversion of the optical signals is performed. The components of electrical signals are selected; their frequencies correspond to the projections of the velocity vector onto the given directions of the sensitivity vectors. 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, the following new and original technical solutions are applied. A new anamorphic scheme of a laser anemometer has been developed for the first time. It allows using modern high-power semiconductor lasers with a low degree of spatial and temporal coherence, which significantly improves the characteristics of the anemometer. A built-in signal processing system based on parallel programmable logic structures “Field Programmable Gate Array” and a new method of adaptive Doppler frequency extraction have been developed for the first time.

Measurement of orthogonal pairs of velocity vector components in the LAD-07 is performed 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 one more advantage of the developed optical configurations. It is especially important, since, as a result, the requirements for the quality and cost of optical elements of experimental physical installations are significantly reduced.

Rotary prisms and lenses, mirror and antireflection coatings are optimized for laser anemometer applications. Thus, the quality of the probing coherent beams is improved.

The device contains elements of passive aerodynamic protection of external optical surfaces from dust and atmospheric aerosol.

Optical elements are tested for compliance and preservation of parameters at changes in the external temperature conditions, as well as when the level of concentration of the radiation energy on the optical part itself changes. The mechanical parts of the assemblies provide rigid fixation of the optical elements and prevent from deviations under mechanical stress and temperature extremes.

Here improvement of LAD-07 meter for near wall velocity measurements are presented. The device was modified for measurement of one velocity component measurements. This improvement gave an ability to adjust laser beam for enhancement the interference pattern and for the enlargement of bands number in a reflected signal which allowed us to increase the device sensitivity and to enlarge frequency peak measurement precision

4. Experimental demonstration

Figure 2 illustrates the near-wall measurements. The LDA measurements are used to justify the choice of the most appropriate inlet boundary conditions for better modeling of a gas flow in turning-and-expanding devices. The choice of boundary conditions is done based on the comparison of calculation results and experimental data [3]. The detailed description of the experimental setup is presented in [3]. Measurements of average and pulsation values of flow velocity are carried out by the method of laser Doppler anemometry. The precise measurement of axial velocity component is required for better comparison of experimental and modeling results. The numerical modeling is performed on the basis of the known modern turbulence models: k-ε model and Reynolds stress transfer model. A comparative analysis of the models is done. The comparison is made for the surfaces of the axial velocity component in a cross section. The data obtained may be useful for determining the limits of applicability of various turbulence models and for verifying CFD codes.

![Figure 2](image2.png)

**Figure 2.** An example of axial velocity measurement in a cross-section before the turn section.

![Figure 3](image3.png)

**Figure 3.** An example of axial velocity measurement in a cross-section after the turn section.

For more detailed comparison of LDA system before and after modification the figures 4 and 5 are presented. In figure 4 the comparison of velocity in near wall region at the mean velocity of 12 m/s before and after modification are presented. The characteristic velocity scale for the sub-layers was \( u^* = 0.16 \) m/s and a characteristic wall length scale \( l^* \) was 50 um. The velocity and scales were
presented in dimensionless form $U^+ = U/\nu^*$, $y^+ = y/l^*$. It can be seen that before modification the LDA meter did not measure near the wall at $y^+<18$ that equals 0.9 mm. Figure 5 represent the comparison of samples rate per minute in near wall region at the mean velocity of 12 m/s before and after modification. It can be seen that before the modification the sample rate was almost 10 times lower than after the modification.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** The comparison of velocity in near wall region at the mean velocity of 12 m/s before and after the modification.  
**Figure 5.** The comparison of samples rate per minute in near wall region at the mean velocity of 12 m/s before and after the modification.

**Conclusions**
The aim of the work was to develop a laser Doppler anemometry method for diagnosing turbulent aerodynamic flows in the near-wall region. The device was modified to measure one velocity component. This improvement gave an ability to adjust laser beam for enhancement the interference pattern and for the enlargement of bands number in a reflected signal which allowed us to increase the device sensitivity and to enlarge frequency peak measurement precision. As a result, it has become possible to measure 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 was $0.1 \times 0.1 \times 0.5$ mm. The positioning device allowed moving the measuring unit in the area of $250 \times 250 \times 250$ mm with an accuracy of 0.1 mm. This method may also serve to measure the local flow rate fluctuations. The LDA meter modification allowed to make measurement closer to the wall (0.1 mm instead of 0.9 mm) and increased the sample rate almost in 10 times.

**Acknowledgments**
The work was carried out within the framework of the state contract with the IT SB RAS (121032200034-4 and AAAA-A19-119052190039-8).

**References**
[1] Meledin V G 2008 Informatics of optoelectronic measurements: science and innovative industrial technologies (Novosibirsk: Publishing house of IT SB RAS) 75
[2] Basov N G, Bill B M and Popov Yu M 1959 Journal of experimental and technical physics 37 587–8.
[3] Kabardin I K, Klimonov I A, Usov E V, Yavorsky N I, KabardinA K, Kakaulin S V, Ezendeeva D P, Gordienko M R, Polyakova V I and Pravdina M H 2020 Journal of Engineering Thermophysics 29(3) 1–9