Development of the optical electronic setup for carrying out measurements by multicolor Particle Image Velocimetry

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Abstract. The paper is devoted to development of the optical electronic setup for carrying out measurements by multicolor particle image velocimetry. The main advantage of this method is the ability to visualize vector velocity fields in several planes simultaneously. As a result a 3D model of a setup was developed, a laboratory sample was assembled and series of testing experiments were performed. As a test object, vortex structure formed by a chemical stirrer in a cuvette with liquid has been considered. The experimental data were compared with the computer model developed in SolidWorks and FlowVision software.

1. Introduction
Many theoretical and experimental works have already been devoted to the study of swirl flows. Such interest in these phenomena is due to their wide distribution in nature. Some of them even can have a serious impact on human life. For instance, such phenomena as cyclones, tornadoes, and whirlpools can cause natural disasters.

Along with this, highly swirling flows have found broad application in different fields of modern technologies. They are used in cyclone separators for gas and fuel purification, in burner devices for flame stabilization [1]. To optimize the flow mixing process in such devices, it is important to understand mixing mechanism and the flow structure. In relation to rocketry, vortices are realized in centrifugal injectors of liquid engines, combustion chambers, rotating rockets, nozzle blocks cooling systems and control systems of the thrust module [2–4]. Besides, a variety of devices based on swirling flows are used in chemical technologies, metallurgy, agriculture, measuring equipment [5–7].

All this facts determines the extremely relevance of the development of non-invasive flow diagnostics methods. In particular, setups, that can measure three components of a flow velocity and visualize their structure.

To date, one of the widely used flow diagnostic techniques is Particle Image Velocimetry (PIV). This method allows to measure flow distribution velocity and to visualize it in a plane [8]. The PIV operation principle relies on seeding the flow with tracer particles and subsequent capture images of their position at short time intervals. The flow velocity field is extracted from images cross-correlation processing. The possibilities of PIV technique directly grow with the increase in the number of cameras. As a result, the most complete information about the flow structure can be obtained by such PIV modifications as stereo and tomography PIV. However, their application in practice causes a
number of difficulties. These include high-precision calibration of digital cameras, adjusting the optical systems, complicated post-processing and etc. Also one of the significant disadvantages is too high cost of the necessary equipment. This paper discusses developing of an inexpensive flow diagnostics setup, which allows measuring all components of a flow velocity and visualizing its three-dimensional structure.

2. Operation principle of optical-electronic setup

The work principle of developed setup is based on multicolor Particle Image Velocimetry (MPIV). The main MPIV advantage is the ability to visualize vector velocity fields in several planes simultaneously. In addition, practical implementation of this technique is easy and inexpensive. Figure 1 demonstrates MPIV measurement scheme.

![Figure 1. MPIV measurement scheme.](image_url)

It relies on seeding flow with small tracer particles and fixing their position in scattered light at short time intervals. Scattering particles must move at a flow speed and not introduce any kind of disturbance. The investigated region is illuminated by three RGB laser sheets located at a small distance from each other. Positions of tracer particles are recorded by a color digital camera. If laser modules are selected correctly, a signal from each plane will be present only in one of three image color channels. Experimental images will have three main RGB color components. As a result, by applying cross-correlation processing to image pairs for each color channel in PIVview2CDemo, it is possible to obtain velocities distributions in three planes. According to the obtained data, distributions of a vertical or horizontal projection of particle velocities over the selected cross flow sections could be constructed. Further, by constructing in the region of the vertical and horizontal projection particle velocity distributions for the channels of red, blue and green color for each of the sections and applying the approximation procedure of the obtained planes, it is capable to visualize the studied flow three-dimensional velocity field.

The setup main elements are a generating laser sheets unit, a receiving optical system and a computer with specialized software. The generating laser sheets unit includes a set of three laser modules with different wavelengths, system of light intensity normalization and an optical system for forming laser sheets. The receiving optical system consists of a lens and a digital camera with color matrix.

There are a number of factors that can affect MPIV measurements accuracy. The three most important ones are adjustment accuracy, cross-correlation processing accuracy and parameters of an experimental setup. The first factor doesn’t strongly influence the accuracy of experimental data. This technique is quite simple to implement, especially in comparison with other PIV modifications and doesn’t require complex precision adjustment. So it is possible to minimize the adjustment error. The same can be said about the second factor. The processing error in PIVview program is less than 3%. 
However, installation parameters can significantly influence the measurements accuracy. Some of them are wavelengths of radiation sources, radiation intensities of laser sheets, distances between sheets and their thicknesses. To minimize a measurement error, the installation was developed according to next requirements. The system of light intensity normalization must ensure the same response of the receiver for each sheet to the radiation scattered by the same object. The optical system must provide a high power density, uniform energy characteristics, and a small thickness of laser plane in a measurement area. Also, the necessary requirement for setup is the correct separation of a detected scattered radiation along corresponding color channels of matrix.

3. Testing results
Before assembling a laboratory sample of the setup, laser modules were checked. Results are demonstrated in Figure 2. A signal from each module is present to a greater extent only in one of three channels. Thus selection of RGB laser sources has been carried out correctly.

![Figure 2. Experimental image (a), blue channel (a), green channel (b), red channel (c).](image)

During installation tests, a vortex structure was investigated. The vortex was formed by a chemical stirrer in a cuvette with liquid. The medium has been previously seeded with glass spheres 100 μm in diameter. A rotation speed of the stirrer was 300 rpm. Figure 3 shows the cuvette area where turbulences have been created. And this area was chosen for the measurement region.

![Figure 3. Measurement region.](image)
As MPIV measurements result, scattered by glass spheres laser light of RGB sheets was recorded. In turn, each recorded image was contained information about flow velocity distribution in three sheets located in 2 mm from each other. Figure 4 shows the cross-correlation processing result of an experimental images pair. The reconstructed three-dimensional vector field is demonstrated in figure 5.

Figure 4. Vector field in: blue laser sheet (a), green laser sheet (b), red laser sheet (c).

Figure 5. Three-dimensional vector field.
Figure 6 demonstrates vector velocity fields obtained using a computer model of the stirrer operation. The model has been developed in Solid Works and Flow Vision software package [9]. According to the computer model, investigated flow was stationary. But in reality, the vortex had a more complex structure and was changing it over time.

![Figure 6. Modelled vector fields in: blue laser sheet (a), green laser sheet (b), red laser sheet (c).](image)

4. Conclusion
Thus, the laboratory sample of the flow diagnostic optical-electronic setup has been developed and series of testing experiments have been performed. As a test object, vortex structure formed by a chemical stirrer in a cuvette with liquid has been considered. The experimental data were compared with the computer model. The setup allows measuring all components of a flow velocity in range of $47.4 \cdot 10^{-6}$ m/s to $8.58 \cdot 10^{-3}$ m/s and visualizing its three-dimensional structure. The measurement accuracy is 7–10%. It can be widely used to solve problems in the field of aero hydrodynamics, fast-flowing processes visualization and the study of complex vortex structures. The final consumers of the proposed product are various rocket-building enterprises, factories producing cooling systems, enterprises engaged in the development of fuel purification systems, enterprises of aviation engine construction, research institutions.

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