Technique for velocity vector field dynamics measurement on the basis of smoke visualization of flow

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Abstract. The main difference between Smoke Image Velocimetry (SIV) technique and traditional PIV is that the smoke with continuous intensity in the image is seeded into the flow instead of separate particles. Owing to better smoke reflectivity, relatively primitive equipment is enough to measure the dynamics of velocity vector fields with the frequency of 25 kHz and higher. The image processing algorithm is adapted to high tracer concentration and relatively large displacement of smoke patches between two consecutive frames. The results of SIV testing are presented, including the estimations of the most measurement noise sensitive characteristics of turbulence calculated from spatial derivatives of fluctuations of small-scale turbulence. The measurement results have been shown to agree well with the data obtained by other methods. Application of SIV technique opens new possibilities in the research of flow pattern and turbulence in unsteady and fast processes.

1. Introduction

PIV has become the most widespread optical measurement method so far [1-3]. Traditional PIV has shown good results in the investigation of steady flows. However, when the dynamics of velocity vector fields is measured in unsteady and fast processes, this method has significant limitations in time resolution due to the characteristics of cameras and lasers involved in the measurements. Frame rate is mainly limited by the pumping time of high-power dual pulsed lasers [4, 5]. Efforts to overcome these limitations have been made recently [6, 7]. The main point here is replacement of dual pulsed lasers with a continuous light source, e.g. DPSS laser [6] or LED [8], and employment of high-speed cameras for flow pattern recording. Moreover, DPSS lasers are approximately 100 times cheaper than pulse lasers, and LEDs are even more affordable. Despite obvious advantages of such an approach, there are some major shortcomings associated with short exposure time typical of high-speed cameras and relatively low power of continuous light sources. This reduces the intensity of light scattered by particles and leads to poor illumination of the camera’s sensor. Authors [6] note that further improvement of the mentioned time resolved PIV is associated with employment of more powerful continuous light sources and cameras equipped with sensors of increased sensitivity to light.

Another approach to spatial and temporal resolution refinement has been implemented in Smoke Image Velocimetry (SIV) technique [9]. The present paper briefly describes the technique and provides new test results.
2. SIV foundations

The main difference between Smoke Image Velocimetry (SIV) technique and traditional PIV is that the former employs many times higher concentration of tracer particles. This makes the tracer images look like not separate particles but smoke with continuous intensity (figure 1). Owing to better reflectivity of smoke compared to separate particles, it is possible to obtain a processable image intensity even in a light sheet generated by a low-power continuous laser at the camera exposure time of 40 µs. Therefore, SIV allows employment of relatively primitive equipment for measurements of dynamics of two-component velocity vector fields with the frequency of about 25 kHz. This opens new possibilities for the research of unsteady processes. Besides, high seeding density contributes to better spatial resolution and measurement noise reduction.

The algorithm for estimation of velocity vector field dynamics from smoke visualization is in many ways similar to those used in PIV. However, large dimensions of smoke patches, if compared with separate particles, enable SIV to allow significantly larger displacement of particles between two frames. Instead of searching for the cross-correlation function maximum as is the case with PIV algorithm, SIV searches for similarity between two windows based on minimization of absolute differences of pixel intensities (Sum of Absolute Differences – SAD). This algorithm appeared to be more stable to large displacements. A reference interrogation window is chosen in the vicinity of grid nodes (figure 1). Its dimensions are $N_x \times N_y$ pixel$^2$. Then each window in the frame $k$ is compared to windows of the same shape and size in the frame $k+1$ around the same grid node. Similarity between the windows at the displacements of $\Delta i$ and $\Delta j$ is calculated from the functional:

$$
\Phi_{\Delta i, \Delta j} = \frac{1}{N_x N_y} \sum_{i=1}^{N_x} \sum_{j=1}^{N_y} |I_{k,i,j} - I_{k+1,i+\Delta i,j+\Delta j}| 
$$

(1)

where $I_{k,i,j}$ are grayscale intensities of the pixel with coordinates $(i, j)$ in the frame $k$; $I_{k+1,i+\Delta i,j+\Delta j}$ is the grayscale intensity of the pixel with coordinates $(i+\Delta i, j+\Delta j)$ in the frame $k+1$; $\Delta i$, $\Delta j$ are the displacements of interrogation window coordinates in the frame $k+1$ relative to the frame $k$. Coordinates $(i, j)$ are counted from the origin of the considered window.

To speed up the procedure of image processing, a search area is specified around each grid node, which restricts the range of the window displacements, $\Delta i$ and $\Delta j$, in the frame $k+1$. The search area is specified arbitrarily and can allow for dominating displacement direction at each grid node. The displacements, $\Delta i$ and $\Delta j$, at which the functional $\Phi$ is minimal, are determined in the search area. These integer displacements define the position of the window, which is the most similar to the reference one with accuracy up to one pixel.

Further search for the minimum is performed using the approximation of the functional in the vicinity of its minimum. Authors [9] showed that the functional has a sharp minimum, and the shape of $\Phi(\Delta i, \Delta j)$ surface near the minimum is nearly conical, i.e. it is nearly a second-order surface. Therefore, to refine the minimum location, values of $\Phi$ at nine points closest to the integer approximation are used. These points are located according to $3 \times 3$-point arrangement and are displaced from the center by $\pm 1$ pixel along each coordinate. The approximating relationship is the following:

$$
a_0 + a_1 \Delta i + a_2 \Delta j + a_{12} \Delta i \Delta j + a_{11} \Delta i^2 + a_{22} \Delta j^2 = \Phi^2 
$$

(2)
Coefficients $a_0$, $a_1$, $a_2$, $a_{12}$, $a_{11}$, $a_{22}$ are estimated by the least-squares method from values of the functional around the minimum. The relationship (2) describes variation of $\Phi$ between the grid nodes as well, i.e. $\Delta$, $\Delta$ values can be non-integer. The minimum value of the functional and coordinates of the reference interrogation window displacement with subpixel accuracy are estimated from (2) with the obtained coefficients.

3. Testing of SIV
Some experimental testing of SIV measurements of velocity vectors was performed in [9]. It showed that SIV allows large (up to the reference window size) displacements of tracer particles between two consecutive frames. Comparison of SIV results to hot-wire measurements in the turbulent flow with forced velocity pulsations demonstrated almost identical velocity pulsation spectra up to the frequency of 1 kHz, which confirms the reliability of SIV results including the measurements of high-frequency velocity pulsations.

Synthetic images are often used for quantitative estimation of PIV accuracy [1]. The accuracy of submitted SIV technique was also estimated using this approach [5]. To simulate smoke visualization images, images of particles with the diameter of 10 pixels and concentration of $C = 0.01014$, $0.02027$ and $0.04054$ particle/pixel$^3$ were used in [5]. It was shown that employment of SIV for such particle concentrations reduces the random error 44, 31 and 12 times compared with the corresponding PIV results, while the bias error of SIV-SAD algorithm is reduced 9, 6 and 7 times, respectively.

Estimation of turbulence characteristics in the turbulent boundary layer is one of the most representative ways to test an optical method. The development of 2D methods for instantaneous velocity measurements enabled to allow for the turbulence anisotropy when estimating small-scale flow parameters. However, a problem with resolved spatial scales arose at the same time. Unlike the Reynolds stress tensor components, which are defined by large-scale vortex motion [10-12], turbulent energy dissipation is governed by the scales of the order of two Kolmogorov scales [13]. There are also difficulties in estimation of spatial derivatives of flow velocity pulsations that result from their sensitivity to the noise of the measurement method.

Nevertheless, despite constant improvement of 2D and 3D optical methods during more than 20 years, the experimental estimation of dissipation is still complicated by limitations in resolution of PIV technique [10, 11, 13-17]. Measurement volume that is significantly larger than the Kolmogorov scale obviously leads to underestimation of dissipation as the energy of small-scale turbulent pulsations is neglected [14-16]. Spatial resolution of PIV technique has limitations due to maximum allowed seeding density [13, 18]. Refinement of resolved scales in PIV down to less than allowable values leads to abrupt increase in random errors [10, 16], which are observed as the white noise in the instantaneous velocity oscillograms [19].

Major progress in small-scale measurements of velocity gradient tensor components was achieved by combination of PIV with other methods. PTV allows smaller interrogation windows if compared with PIV, but it has limitations on maximum seeding density, which prevents it from being used for experimental estimation of components of the above mentioned tensor [12, 20]. The combination of these two methods (Tomo-3D-PTV [20]) allowed spatially resolved low-error 3D measurements of not only velocity gradient tensor components but also a 3D pressure field. Authors [12] obtained more accurate estimation of dissipation in the range of $25 < y^+ < 140$ in the case of Tomo-3D-PTV with VIC + if compared with Tomo-PIV alone. Nevertheless, Tomo-3D-PTV with VIC + overestimated near-wall dissipation just as Tomo-PIV.

Air flow in a smooth plane channel was considered in test experiments. To study the flow pattern using SIV, the experimental setup schematically shown in figure 2 was employed. The test section $I$ was a rectangular 1-meter long channel with a cross section of $75 \times 150$ mm$^2$ and a smooth inlet 10 attached to it. The latter had a contraction ratio of 6:1. A turbulence generating grid 9 was installed downstream of the smooth inlet. The grid had the cell size of 5 mm, steel wire diameter of 1.2 mm and 36% solidity. Flow rate was measured by an ultrasonic flowmeter 3 IRVIS RS4-Ultra mounted downstream of the receiver tank. The relative error in flow rate did not exceed 1%.
To visualize the flow pattern, the air-aerosol mixture (MT-Gravity fluid with medium fog density; Safex aerosol generator) was supplied from the smoke conditioning chamber 4 to the channel inlet. The measurement area 6 was illuminated by a DPSS laser KLM-532/5000-h. 7. The flow pattern in the channel symmetry plane at the distance of \( L = 0.7 \) m from the channel inlet was recorded by a monochrome high-speed camera Fastec HiSpec 8 with the frame resolution of 665×110 pixel (scaling factor of 0.0625 mm/pixel), frame rate \( f = 7083 \) 1/s. The light sheet thickness was 1 mm (16 pixel).

Velocity vector fields were estimated using \( 16 \times 6 \) pixel\(^2 \) interrogation windows. The window size was chosen according to recommendations of [9]. The spacing between grid nodes at which velocity vectors were obtained was two pixels along both coordinates. When estimating dissipation, to reduce the random errors, the interrogation window size was increased up to \( 16 \times 16 \) pixel. Maximum displacement of smoke between two consecutive frames was 10 pixels. Image resolution in Y+ coordinates was 1 pixel = 0.8 \( Y^+ \).

Profiles of velocity, turbulent fluctuation intensity, vorticity fluctuations and turbulent energy dissipation were written in wall coordinates (3)

\[
y^+ = \frac{yu}{v}, \quad U^+ = \frac{U}{u_\tau}, \quad \overline{u' u'} = \frac{\overline{u' u'}}{u_\tau^2}, \quad \omega^+ = \frac{\omega \overline{u' v'}}{u_\tau v}, \quad \varepsilon^+ = \frac{\varepsilon v}{u_\tau}.
\]

Vorticity of the vector field, \( \omega_{ij} \), was estimated by Stokes’ theorem with approximation of circulation, \( \Gamma \), by a first-order central difference scheme [1]. Friction velocity, \( u_\tau \), was estimated as \( u_\tau = 0.204 \) m/s from velocity measurements at a point in viscous sublayer using the relation \( u_\tau = \sqrt{v \frac{\partial U}{\partial y}} \big|_{y=0} \). Turbulent energy dissipation was calculated from [16]:

\[
\varepsilon = 3
\left[ \frac{\bar{u'}^2}{\delta u_{ij} / \delta x_j} + \frac{\bar{u'}^2}{\delta u_{ij} / \delta x_i} + \frac{\bar{u'}^2}{\delta u_{ij} / \delta x_k} \right] + 6 \frac{\bar{u'} v'}{\delta u_{ij} / \delta x_j}.
\]

Figures 3-5 compare the profiles of velocity, Reynolds stress and RMS vorticity fluctuations measured by SIV to the ones obtained at the same Re\(_0\) in [8, 21, 22]. The velocity profile agrees well with the theory and other measurement methods across the whole turbulent boundary layer. Larger inclination in the logarithmic region of the velocity profiles obtained by DNS, PIV and SIV is attributed to the streamwise pressure gradient typical of channel flows, while theoretical profile (line) and hot-wire measurements were obtained in the case of free flow over a plate.

Components of Reynolds stress tensor, \( <u' u' > \), (figure 4) also agree well with the results obtained by other measurement techniques. Subtle discrepancy in \( <u' u' > \) profiles outside the viscous sublayer apparently results from different values of low Reynolds numbers, free-stream turbulence intensity and the channel cross-section shape [23, 24].

The root-mean-square distribution of the wall-parallel vorticity component, figure 5, obtained by SIV is in fairly good agreement with DNS and PIV profiles. The dissipation profile measured by SIV (figure 6) agrees well with the one obtained by an advanced method of VIC+ [12].

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**Figure 2.** Experimental setup: 1 – test section, 2 – receiver tank, 3 - flowmeter, 4 – smoke conditioning chamber, 5 – smoke generator, 6 - measurement area, 7 – DPSS laser, 8 – high-speed camera, 9 – turbulence generating grid, 10 – smooth inlet, 11 – regulating gate, 12 – abrasive.
SIV allows estimation of the dynamics of flow velocity fields with time resolution that depends on the frame rate of videos. Figure 7 presents the spectra of turbulent fluctuations of two components of flow velocity for the coordinate $y^+=20$. It should be noted that the spectrum was obtained from relatively short video with the duration of 3 seconds. It caused substantial oscillations of amplitude in the low-frequency part of the spectrum. Apart from that, the spectrum was typical of the developed turbulence excluding its high-frequency part with the frequencies exceeding 1000 Hz. In the latter range the measurement noise was pronounced, which in our case had the amplitude of no more than 0.001 m/s. At the friction velocity $u_\tau=0.204$ m/s adopted as a velocity scale in the boundary layer, the linear scale of 0.2 mm corresponded to this frequency. It is comparable to the estimate of Kolmogorov scale $\lambda_K=0.15$ mm obtained from the measurement of $<\varepsilon>$ in the region of $y^+=20$. In other words, the white noise of measurement became visible only outside the frequency range of the maximum energy of turbulent fluctuations. Among the main reasons for such noise was the camera’s limited (8-bit) resolution of image intensity [26]. The white noise in PIV measurements of velocity was observed in [19]. However, in the case of time-resolved SIV measurements the noise can be filtered out of the high-frequency spectral range. It was implemented by filtering high-frequency white noise out of velocity component oscillograms. The cutoff frequency was defined from the oscillogram of streamwise component; specifically, it corresponded to the indicative transition from the typical of turbulence pulsation amplitude (decreasing with frequency growth) to approximately constant amplitude (white noise) in high-frequency spectrum range.

**Figure 3.** Velocity profile in the boundary layer of turbulent flow: --- logarithmic law; - - - DNS [22]; ▲ hot wire [21]; □ PIV [8]; SIV.

**Figure 4.** Profiles of turbulent fluctuations: - - - DNS [22]; ▲ hot wire [21]; □ PIV [8]; SIV.

**Figure 5.** Root-mean-square distribution of the wall-parallel vorticity component: --- DNS [22]; □ PIV [8]; SIV.

**Figure 6.** Turbulent energy dissipation: --- DNS [22]; ▾▼▼▼ VIC+ [12]; □ PIV [12]); ◇ PIV [12]; ▲ nine-sensor hot wire [25]; ▲ SIV.

**Figure 7.** Velocity fluctuation spectra at $y^+=20$. 

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Conclusions
SIV technique allows employment of relatively primitive equipment for measurements of dynamics of two-component velocity vector fields with the frequency of about 25 kHz. This opens new possibilities for the research of unsteady processes.

Image processing algorithm embedded in SIV is adapted to high tracer concentration and relatively large displacement of smoke between two consecutive video frames.

The profiles of velocity and turbulent fluctuations as well as the profiles of vorticity fluctuations and turbulent energy dissipation estimated from SIV measurements agree well with experimental data obtained by multi-sensor hot-wire anemometers, stereo PIV, 3D-PTV with VIC+ and DNS results.

Acknowledgments
This work was supported by the Russian Science Foundation (Project no.16-19-10336).

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