Capabilities of optical SIV technique in measurements of flow velocity vector field dynamics

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Abstract. The main difference between Smoke Image Velocimetry (SIV) technique and the conventional PIV is that higher concentration of tracer particles typical of smoke visualization techniques is used in SIV. Not separate particles but smoke structures with continuous pixel intensity are visible in the recorded images. Owing to better smoke reflectivity, higher spatial and temporal resolution is obtained in the case when relatively simple equipment (camera and laser) is used. It is simple enough to perform SIV measurements of velocity vector field dynamics at the frequency exceeding 15000 Hz, which offers new opportunities in unsteady flow examination. The paper describes fundamentals of SIV technique and gives some new results obtained using this method for the measurements that require high spatial and temporal resolution. The latter include frequency spectra of turbulent velocity fluctuations, turbulence dissipation profiles in the boundary layer and higher-order moments of velocity fluctuations. It has been shown that SIV technique considerably extends the potential of experimental studies of turbulence and flow structure in high-speed processes.

1. Introduction
Particle Image Velocimetry (PIV) technique has become the most widespread optical method [1-3]. The conventional PIV estimates the flow velocity from the displacement of tracer particle groups moving with the flow over the time between two consecutive frames. This approach has proved to be reliable in the studies of steady flows and large vortices formed in the flows. However, PIV measurements of flow velocity field dynamics in unsteady and fast processes are seriously restricted in terms of temporal resolution due to the camera and laser capabilities. The frame rate is mainly limited by the pumping time of double-pulse lasers [4, 5] involved in conventional PIV measurements. The same reason accounts for the limitation on frequency spectra of turbulent velocity fluctuations obtained by PIV.

The range of linear scales resolved by PIV is limited by the requirement to maximum seeding density [6-8]. If the resolved scale in PIV is reduced to less than acceptable, random errors which appear as white noise in the instantaneous velocity oscillograms [11] sharply increase [9, 10]. For this very reason PIV is still unable to reliably measure the terms of transport equation of turbulent kinetic energy as well as triple and higher-order correlations of flow velocity fluctuations. To estimate these parameters, small-scale turbulence comparable to Kolmogorov scale should be measured in low noise conditions.
significant progress in small-scale measurements of the velocity gradient tensor components was made by PIV combined with other methods like PTV, Tomo-3D-PTV, LPT, STB, VIC+ [12-20].

Another approach to the improvement of spatial and temporal resolution was implemented in the recently developed Smoke Image Velocimetry technique (SIV) [21, 22]. Unlike the conventional PIV, SIV deals with high particle concentrations and hence the images exhibiting not separate particles but fields of continuous pixel intensity. Owing to better reflectivity of smoke, higher spatial and temporal resolution is obtained in the case of light sheet generated by a relatively low-power (of the order of 5 mW) continuous laser at high frame rate. Obviously, 2D SIV measurement limits the applicability of this approach to the class of flows isotropic in transversal plane, but on the other hand it allows reasonably accurate measurement of the fields of small-scale turbulent characteristics in the light sheet.

2. SIV fundamentals

SIV [21, 22] is a relatively new technique that has not become widely known yet. So, here we provide a brief description of the method. It is based on digital processing of smoke visualization videos recorded in a light sheet. Flows are seeded by aerosol generators which are the same as in PIV. Seeding particles follow the gas flow as closely as in PIV, but due to higher concentration they look like not illuminated separate particles but smoke with continuous intensity in the image (Figure 1). Owing to better reflectivity of smoke compared with separate particles, it is possible to obtain a processable image intensity using a high-speed camera with regular sensitivity even at high frame rate and in a light sheet generated by a low-power continuous laser. SIV therefore allows employment of relatively primitive equipment for measurements of dynamics of two-component velocity vector fields with the frequency of about 10 kHz. Allowing for such reasonable time resolution, high seeding density contributes to better spatial resolution and reduction in measurement noise.

The algorithm for estimation of velocity vector field dynamics from smoke visualization is in many ways similar to that used in PIV. But large dimensions of smoke patches, if compared with separate particles, enable SIV to allow significantly larger displacement of tracers between two frames. Instead of searching for the cross-correlation function maximum performed in PIV algorithm, SIV searches for similarity between two windows based on minimization of absolute differences (Sum of Absolute Differences—SAD). The latter appeared to be more stable to large displacements. A reference $N_x \times N_y$ pixels interrogation window is chosen in the vicinity of grid nodes (Figure 1). 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:

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

where $I_{k,i}$ is the grayscale intensity 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 displacement $(\Delta i, \Delta j)$ variation 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. Then the location of the minimum is refined. To that end, values of $\Phi$ at nine points around the previously defined minimum point are used, which are located according to $3 \times 3$ point arrangement scheme with deviation from the center $\pm 1$ pixel along each coordinate. Using these values of function at nine points, the functional $\Phi (\Delta i, \Delta j)$ is approximated by a second-order surface. 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 a second-order surface. Further search for the minimum is performed using the obtained coefficients of the functional approximation by the second-order surface. The experimental verification [21] showed that SIV technique allows large tracer displacement between two consecutive frames up to the reference window size.

3. SIV measurements of flow velocity vector field dynamics and small-scale turbulence

Authors [21] compared SIV results to hot-wire measurements in the turbulent flow with forced velocity pulsations. Almost identical velocity fluctuation spectra were obtained (Figure 2) up to the frequency of 1 kHz, which testifies to the reliability of measurements including the high-frequency range of flow velocity fluctuations.

Figure 1. Interrogation window displacement: 1 – grid node; 2 – reference interrogation window.

SIV potential in measurements of small-scale turbulence is demonstrated here in application to the turbulent boundary layer on the channel wall (Figure 2). The rectangular 75×150 mm$^2$ test section 1 had the length of 1 m. A smooth inlet 10 with the contraction ratio of 6:1 was attached to the test section. Turbulence generating grid 9 was mounted downstream of the smooth inlet. The cell size of the grid was 5 mm, the steel wire diameter was 1.2 mm and the grid solidity was 36%. The flow rate was measured by an ultrasonic IRVIS-RS4-Ultra flowmeter 3 mounted downstream of the receiver. 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 5) was supplied from the preparation chamber 4 to the channel inlet. The measurement area 6 was illuminated by a continuous diode-pumped solid-state laser KLM-532/5000-h 7. The flow pattern in the channel symmetry plane at the distance $L = 0.7$ m from the channel inlet was recorded by a monochrome high-speed camera Fastec HiSpec 8 with the frame resolution of $665 \times 110$ pixel (scaling factor of 0.0625 mm/pixel), frame rate $f = 7083$ 1/s.

When estimating velocity vectors, 16×6, 16×10 and 16×16 pixel interrogation windows were used in SIV. The results obtained for 16×16 pixel interrogation window are given in this paper. The spacing

Figure 3. Schematic of experimental setup: 1 – test section, 2 – receiver tank, 3 – flowmeter, 4 – air-aerosol mixture preparation chamber, 5 – aerosol generator, 6 – SIV measurement area, 7 – continuous laser, 8 – high-speed camera, 9 – turbulence generating grid, 10 – smooth inlet, 11 – regulating gate, 12 – abrasive.
between the nodes at which the velocity vectors were estimated was 2 pixels along both coordinates. Maximum displacement of smoke between two consecutive frames was 10 pixels. The image resolution in Y+ coordinates was 1 pixel = 0.8 Y+.

Profiles of turbulent fluctuation intensity, third-order moments of velocity fluctuations and turbulent energy dissipation are written in wall coordinates:

\[
y' = \frac{\mu_i}{\nu}, \quad u_j^3 = \frac{u_i u_j}{u_e^2}, \quad u_i u_j v_j = \frac{u_i u_j v_j}{u_e^2}, \quad \varepsilon = \frac{\varepsilon}{u_e^2}.
\]

The spectrum of turbulent fluctuations of streamwise velocity component for two \( y' \) coordinates across the boundary layer thickness is plotted in Figure 4. It should be noted that the spectrum was obtained from relatively short video (3.5 s) recorded with the frame rate of 7083 Hz. For this reason, considerable amplitude oscillations are observed in low-frequency spectrum range. In the high-frequency range, for the frequencies exceeding 1000 Hz, variation of the pulsation amplitude becomes unusual for turbulence, which results from the measurement noise. Authors [23] showed that one of the main reasons for such noise is the camera’s limited (8-bit) resolution of image intensity. The measurement noise characteristics are close to the white noise ones and in the considered case the amplitude of such noise is no more than 0.002 m/s. In medium-frequency and low-frequency spectrum ranges this noise is 1-2 orders lower than the turbulent fluctuation amplitude, so it cannot be observed in Figure 3. The white noise in PIV measurements of velocity was mentioned in [11, 24]. But in the case of time-resolved SIV measurements the noise can be filtered out of the high-frequency spectral range. It was realized 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. At the dynamic velocity \( u_e = 0.204 \) m/s considered as the velocity scale in the boundary layer, the cutoff frequency corresponded to the lineal scale of 0.2 mm, i.e. no more than 1.6 of Kolmogorov scale, \( \lambda_k \), for the outer edge of the boundary layer and no more than 2.9\( \lambda_k \) close to the wall. In other words, in the experimental conditions implemented during SIV measurements, the white noise becomes visible only outside the frequency range of the maximum energy of turbulent fluctuations.

Figure 5 compares the profiles of turbulent fluctuations obtained by SIV technique to the ones obtained at equivalent Reynolds numbers, \( \text{Re}_b \), by [25-27]. The components of Reynolds stress tensor, \( <u'_i u'_j>^r \), agree well with the results obtained by other measurement techniques. Subtle discrepancy in \( <u'_i u'_j>^r \) profiles outside the viscous sublayer apparently results from different values of low Reynolds numbers, free-stream turbulence intensity and the channel cross-sectional shape [28, 29].

Estimates of triple and higher-order correlations of velocity fluctuations and turbulence characteristics obtained from the measured spatial derivatives of velocity components are the most sensitive to spatial resolution and measurement noise. The available scarce experimental data on these parameters were obtained by multi-sensor hot wire anemometers. Limitations on spatial resolution and the measurement noise inherent in PIV do not allow reliable estimation of such characteristics for small-scale turbulence in the boundary layer. At present, in the case of relatively low Reynolds numbers, these characteristics are usually estimated from DNS. The profile of \( <u'_i u'_j v'_j>^r \) (Figure 6) measured by SIV agrees well with the one calculated from DNS. Moreover, the dissipation profile measured by SIV (Figure 7) agrees well with the one obtained by the most advanced and promising optical technique VIC+ [20].

**Conclusions**

SIV technique allows the employment of relatively simple equipment for high-speed measurement of dynamics of two-component velocity vector fields with high spatial resolution offering new opportunities for the research of unsteady processes and small-scale turbulence.
SIV measurements of profiles of turbulent characteristics in the boundary layer are in good agreement with the reliable experimental data and DNS results.

![Figure 4. Spectrum of streamwise velocity fluctuations.](image1)

![Figure 5. Profiles of turbulent fluctuations, \(\langle u'u'\rangle^+\):](image2)

- DNS (Re\(\theta\)=590; [27]);
- hot wire (Re\(\theta\)=502; [25]);
- PIV (Re\(\theta\)=518; [26]);
- SIV (Re\(\theta\)=425).

![Figure 6. Profiles of triple correlations:](image3)

- DNS (Re\(\tau\)=180; [30]);
- hot wire (Re\(\theta\)=706; [31]);
- SIV (Re\(\tau\)=214, Re\(\theta\)=425).

![Figure 7. Turbulent energy dissipation:](image4)

- DNS (Re\(\tau\)=782; [32]);
- VIC+ (Re\(\tau\)=782; [20]);
- PIV (Re\(\tau\)=2300; [33]);
- PIV (Re\(\tau\)=782; [20]);
- nine-sensor hot wire (Re\(\theta\)=2790; [34]);
- SIV (Re\(\tau\)=214).
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