Reconstruction of the flow structure in a matrix channel based on two-component LDA data

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Abstract. The work is aimed at creating a technique for reconstructing the three-dimensional structure of turbulent flows using data of a two-component laser-Doppler anemometer at the example of a flow in flat coplanar channels. Data of paired measurements by a two-component LDA at two different angles relative to the measurement point are used to obtain information about the three-dimensional structure of the flow. Further, all three components of the velocity vector were calculated using transformations. The developed method is used to measure the velocity field in a coplanar channel.

1. Introduction
The experimental study of complex turbulent flows is one of the most urgent problems of fundamental and applied mechanics. Currently, there are many methods of non-contact measurement of the velocity field based on determination of the displacement of particles illuminated by a laser sheet (PIV, Stereo PIV, PTV, TRPIV, and SIV). For many objects of a complex shape (which include the coplanar channels considered in this paper), such methods are almost inapplicable, and the point methods are most often used [1–7]. One of them is the method of laser-Doppler anemometry (LDA), used in this work.

To date, significant information on the numerical and computational-analytical study of aerodynamics and heat transfer inside the coplanar channel has been accumulated [8–18]. Also, there are a lot of experimental works dealt with the flow parameters [19–25] and heat transfer [24–28]. However, it should be emphasized that experimental works often study only the integral parameters and distribution of pressure and temperature on the walls, and there are almost no data on the flow structure. At the same time, to create effective cooling systems, it is necessary to understand the physics of flow in channels with complex ribbing, which will allow the control of heat transfer, an increase in uniformity of surface cooling, and a reduction in the channel resistance. The main and unsolved question for today is the search for optimal operating and geometric parameters of the systems. Works in this direction are intensively carried out, but due to the complexity of the process, the task is far from being completed.

In the current study, we made an attempt to reconstruct the complete flow structure in such a channel based on several measurements at one point made using a two-component laser-Doppler anemometer.
Figure 1. a – measurement system, b – test section (the investigated cells are indicated by numbers), c – experimental setup (1 – blower, 2 – inlet diffuser, 3 – working channel, 4 – aerosol generator, 5 – compressor, 6 – LDA).
2. Experimental setup
The experimental setup (figure 1(a)) consists of a two-component laser-Doppler anemometer with adaptive time selection of channels, velocity measurement range \( V' = 0 \text{--} 40 \text{ m/s} \), and three-component control unit (a coordinate positioning device). An aerosol formed during condensation of glycerin vapors using a generator created by the authors was used as a source of light-scattering particles. The fan forced the air flow through the diffuser, the rotary elbow and the confuser (Vitoshinsky profile) into the channel (figure 1(c)). The test section (figure 1(b)) was a coplanar channel formed by the ribs crossed at an angle of 2\( \beta \) equal to 90\(^\circ\). The distance between the ribs was 15 mm, the dimensions of the section were \( 400 \times 150 \times 20 \text{ mm}^3 \). The average speed at the channel entrance was 8 m/s. Numbers 1–3 denote the cells in which the experiment was carried out (figure 1(b), (c)).

The LDA used in this experiment (LAD-06C) had a number of advantages and distinctive features over the known devices: increased signal-to-noise ratio due to the use of the full power of laser radiation in each optical measuring channel; real-time visualization of the velocity vector components; no need to adjust the optical-mechanical part of the device during operation. This allowed the measurement of velocity \( V_x \) and \( V_z \) with an accuracy of 2 \%, and measurement of velocity \( V_y \) with an accuracy of 11 \%, which helped us to understand qualitatively the physics of the flow in the considered volume. The measurement rate was approximately 30 seconds per measurement of the full velocity vector at each point.

3. Velocity field recovery method
Let us denote two velocity components measured by LDA along the \( Z \) and \( X \) axes as \( U \) and \( V \), respectively. To cover the maximum cell area, the laser-Doppler anemometer was rotated around the \( Y \)-axis by 45 degrees (figure 2 (a)). Then, to measure the third velocity component, plane \( \beta \) was turned by \( \alpha_1 = 10^\circ \) and \( \alpha_2 = -190^\circ \) by rotating LDA by \( \pm 10^\circ \) and channel by \( 0^\circ \) and \( 180^\circ \) relative to the \( Z \)-axis (figure 2 (a)). Let us denote two velocity components measured by LDA after the turn by \( \alpha_1 = 10^\circ \) and \( \alpha_2 = -190^\circ \)as \( U_{1,2} \) and \( V_{1,2} \), respectively.

![Figure 2. a – Scheme of rotation of the laser-Doppler anemometer, b – scheme of calculation of \( V_x \) and \( V_y \) velocity components.](image)

Let us calculate three velocity components \( (V_x, V_y, V_z) \). It can be seen that in plane \( \beta \) we can find velocity \( V_z \), as well as velocities \( V_{11} \) and \( V_{12} \), which are in plane \( XY \), for angles \( \alpha_1 = 10^\circ \) and \( \alpha_2 = -190^\circ \), respectively (figure 2 (b)). Thus, for angle \( \alpha_1 = 10^\circ \) we obtain

\[
\begin{align*}
V_{11} &= \frac{\sqrt{2}}{2} U_1 + \frac{\sqrt{2}}{2} V_1 \\
V_z &= \frac{\sqrt{2}}{2} U_1 - \frac{\sqrt{2}}{2} V_1 \quad .
\end{align*}
\]

Similarly, for angle \( \alpha_2 = -190^\circ \) we obtain
\[
\begin{align*}
V_{12} &= \frac{\sqrt{2}}{2} U_2 + \frac{\sqrt{2}}{2} V_2, \\
V_z &= \frac{\sqrt{2}}{2} U_2 - \frac{\sqrt{2}}{2} V_2.
\end{align*}
\] (2)

Now, let us turn to plane \(XY\) and obtain velocities \(V_x\) and \(V_y\) from velocities \(V_{11}\) and \(V_{12}\)
\[
\begin{align*}
V_x &= \frac{1}{2 \cos 10} (V_{11} - V_{12}) \\
V_y &= \frac{1}{2 \sin 10} (V_{11} + V_{12}).
\end{align*}
\] (3)

Finally, we obtain three velocity components
\[
\begin{align*}
V_x &= \frac{1}{2\sqrt{2} \cos 10} (U_1 + V_1 - U_2 + V_2) \\
V_y &= \frac{1}{2\sqrt{2} \sin 10} (U_1 + V_1 + U_2 + V_2) \\
V_z &= \frac{\sqrt{2}}{2} U_1 - \frac{\sqrt{2}}{2} V_1 = \frac{\sqrt{2}}{2} U_2 - \frac{\sqrt{2}}{2} V_2.
\end{align*}
\] (4)

The study was carried out in three cells of the coplanar channel, as it is shown in figure 3(a). With the help of a three-component coordinate positioning device (CPD), an area of \(8 \times 8 \times 20\) mm\(^3\) was covered at two angles of LDA rotation \(\alpha_{1,2}\) (figure 3(b)). As a result, the field of the full velocity vector was obtained in this region.

![Figure 3](image.png)

**Figure 3.** a – measured cells in the coplanar channel, b – studied region in each cell.

4. Experimental results

**Cell 1**

Let us consider cell 1 (figure 3(a), 4). As it is shown in [9], a flow turn occurs in the extreme cell because a wall prevents the further movement of liquid. This flow is shown schematically in figure 4(e). Indeed, as it is shown in figure 4(a), (c), a flow turns in the extreme cell. The maximum flow velocity \(V_y \geq 5\) m/s is shifted towards \(y < 0\) (figure 4(a)), since a part of the flow (figure 4(d)) goes into the upper half-cell. Maximum velocities are \(V_z = 6\) m/s and \(V_x = 6\) m/s. As a result, there is indeed a flow turn in the side cell, which is consistent with [10].

**Cell 2**

Let us consider cell 2 (figure 3(a), 5). In [25], the method of visualizing the instantaneous flow at different Reynolds numbers for channels with crossed and parallel ribs was used to show the vorticity inside each channel cell, and it was also assumed that the cells represent a kind of vortex generators, and that the size of the averaged vortex is comparable to the size of the cell. In [8], using numerical simulations, it is clearly demonstrated that the overflow occurs not only in the extreme cell. Let us
Figure 4. Cell 1: a – streamlines and surfaces of constant velocities $V_y = -5, 0, 5$ m/s, b – streamlines and velocity $V_y$ in plane $XZ$ at $Y = 0$, c – streamlines and velocity $V_x$ in plane $XY$ at $Z = 0$, d – streamlines and velocity $V_z$ in plane $YZ$ at $X = 0$, e – scheme of the flow in cell 1 (indicated with +).
Figure 5. Cell 2: a – streamlines and surfaces of constant velocities $V_y = -5, 0, 5 \text{ m/s}$, b – streamlines and velocity $V_y$ in plane $XZ$ at $Y = 0$, c – streamlines and velocity $V_x$ in plane $XY$ at $Z = 0$, d – streamlines and velocity $V_z$ in plane $YZ$ at $X = 0$, e – scheme of the flow in cell 2 (indicated with +).
Figure 6. Cell 3: a – streamlines and surfaces of constant velocities $V_y = -5, 0, 5$ m/s, b – streamlines and velocity $V_y$ in plane $XZ$ at $Y = 0$, c – streamlines and velocity $V_x$ in plane $XY$ at $Z = 0$, d – streamlines and velocity $V_z$ in plane $YZ$ at $X = 0$, e – scheme of the flow in cell 3 (indicated with +).
analyze the results obtained by the authors of this paper (figure 5). As it can be seen from figure 5(a), (c), velocity $V_y$ has positive values in almost the entire volume and on the entire XZ plane at $Y = 0$, exceeding $V_y$ by the modules in the extreme cell (figure 4(a), (c)). The maximum modules of velocities $V_x$ and $V_y$ are 2 times higher than the similar velocity components in the extreme cell (figure 4(c), (d), 5(c), (d)). This means that only a part of the flow reaches the end cell. Figure 5(c) shows that the streamlines are directed to the turn in the cell, and figure 5(d) shows that the streamlines are directed to the offset towards the front side of the cell. According to this, we can assume that inside cell 2, the main flow goes upwards along a spiral trajectory (this flow allows a simple movement around the ribs), as it is schematically shown in figure 5(e).

Cell 3
Let us consider cell 3 (figure 3(a), 6). As we can see, the flow has a structure similar to cell 2. However, velocity $V_y$ (figure 6(b)) in cell 3 is greater than the velocity $V_y$ (figure 5(b)) in cell 2. This is due to the fact that part of the velocity from the cell 2 flows to the extreme cell where the turn occurs. In cell 3, almost all the flow goes up by a spiral trajectory.

5. Conclusion
The paper demonstrates an experimental approach to reconstruct the structure of three-dimensional flows using laser Doppler anemometry at the example of the flow in flat coplanar channels. It is shown that using the two-component LDA, this method allows us to visualize the complete picture of the flow in a channel of complex geometry. The results of the study in the coplanar channel showed that a significant flow of a cooler occurs in the boundary cell, which was previously discussed in [9]. We should also note that the main flow in the cells located at some distance from the lateral surface has a spiral character, which correlates with the results of [8, 25].

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