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Testing of the SIV method for measuring the average flow characteristics in the wake of a transverse circular cylinder

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Abstract. The results of testing the SIV method (Smoke Image Velocimetry) for two-dimensional instantaneous flow velocity vector fields measurements were presented for the case of flow in the near wake of a cross circular cylinder at Reynolds number of 3900. Measured profiles of the streamwise and transverse flow velocity components in the near wake of the cylinder at different distances were compared with the direct numerical simulation and experiments of other authors. The capabilities of SIV method were confirmed.

Introduction

A reliable prediction of the wide range of turbulent characteristics, including those which have the practical interest for different technical applications, is one of the most difficult problems in fluid mechanics. When employing the numerical modeling of complex turbulent flows, the main tool is still the method based on the solution of the Reynolds-averaged Navier-Stokes equations (RANS), which requires the use of various semi-empirical models of turbulence. Despite the continuing improvement of these models, the simulation results of separated flows and flows in the wake of bluff bodies using RANS models are still insufficient. To develop methods of numerical simulation of turbulent flows, as well as to improve turbulence models in RANS methods, reliable experimental data is needed. The most used hot-wire anemometric methods of measuring the flow velocity are contact and allow to obtain only local characteristics of the flow. The use of the PIV method and its variations makes it possible to derive the components of the flow velocity vector and their correlation characteristics in complex flows. However, they have limitations on the spatial scale.

In present paper, the results of testing the capability of the new optical SIV method for predicting the profiles of the streamwise and transverse components of the average flow velocity in the near wake of a bluff body (transverse circular cylinder) are presented. This type of flow is often used as a test to estimate the efficiency of numerical methods for modeling separated flows, testing and verification of computational codes. The largest number of studies on the cross-flow in the near wake of a circular cylinder has been performed for the Reynolds number Re = 3900. The SIV measurement results obtained in this paper are mainly compared with the available data of direct numerical simulation (DNS) and experiments. The results of the large-eddy simulation (LES) method are used in the case when there are no above-mentioned data.

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Experimental setup and procedure

The wind channel and the setup arrangement used in the experiments is shown in figure 1. The fan 7 operates on the suction and drives the air in the setup. The set value of the average flow velocity in the test section is provided by the defined set of critical nozzles 6. The test section is 300-mm long 115×150 mm^2 rectangular channel. The turbulence level in the inlet of the test section does not exceed 1%.

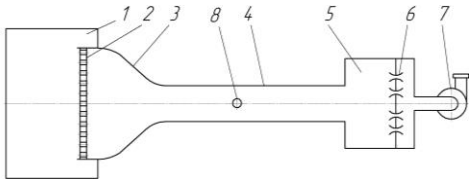


Figure 1. Schematic of the experimental setup: 1 – air-aerosol mixture preparation chamber; 2 – honeycomb; 3 – nozzle; 4 – measurement section; 5 – receiver tank; 6 – sealed baffle with set of critical nozzles; 7 – suction fan; 8 – cylinder

A circular cylinder with a diameter d = 15 mm and a length L = 150 mm was mounted horizontally on the axis of the test section at a distance of 60 mm from its inlet section. The measurements were carried out at Reynolds number Re = U d/ν = 3900 calculated by the average flow velocity U in front of the cylinder and its diameter d. The profiles of the streamwise velocity component U along the central line of the wake behind the cylinder (x-axis), as well as the profiles of the streamwise U and transverse V velocity components at distances x/d = 0.54; 1.06; 2.02; 4.0 and 10.0 from the cylinder were measured. The range of measurements for the y coordinate was y/d = -3.0 to y/d = 3.0. The velocity components in the near wake of the cylinder were measured using the SIV technique (smoke image velocimetry). A detailed description of the SIV method is given in [1, 2]. The frame resolution in the experiments was 43 × 975 pixel with the scaling factor of 0.045 mm/pixel, frame rate f = 12800 Hz and recording time of 2.0 s. The minimum interrogation window size of 11×11 pixel was used in the present measurements. Node-to-node spacing along both coordinates was equal to 4 pixels. The maximum displacement of turbulent structures between two consecutive frames was 9 pixels along the x-axis and 6 pixels along the y-axis.

Results

The profile of the streamwise velocity vector component along the central line of the near wake behind the cylinder obtained experimentally by the SIV method agrees quite well with the experimental data available in the literature and DNS results (figure 2).

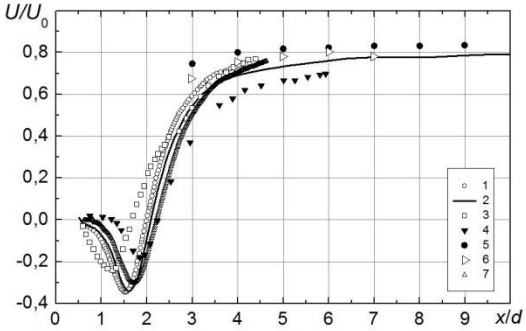


Figure 2. Streamwise velocity component along the central line of the wake behind the cylinder at Re = 3900: 1 – PIV [3]; 2 – DNS [4]; 3 – PIV [5] (private communication); 4 – PIV ((private communication, из [6]); 5 – HWA [3]; 6 – HWA [7]; 7 – present SIV measurements

The profiles of the streamwise and transverse velocity components obtained from SIV mneasurements are also in sufficient agreement with DNS profiles. Examples of respective comparisons are given in figures 3 - 8.

The profiles of the streamwise velocity component at $x/d = 0.58$ have a pronounced U-shape(figure 3), which is confirmed both by the results of the present SIV measurements and by numerical simulation using LES (Beaudan, P. & Moin, P. [9], Kravchenko AG, Moin P. [8] and the experiments of Lourenco, Shih [4]).

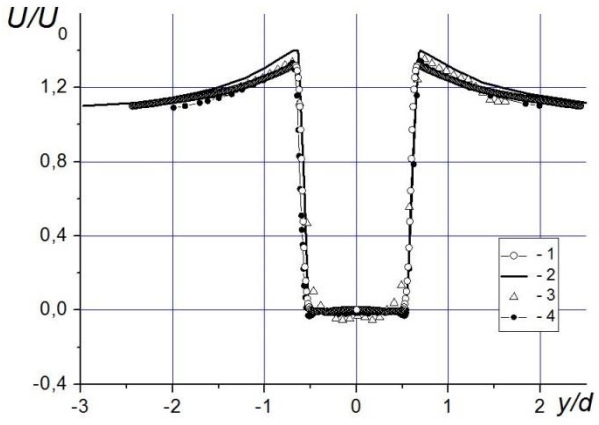


Figure 3. Profiles of the streamwise velocity component behind the cylinder at $x/d = 0.58$: 1 – SIV; 2 – LES [8]; 3 – PIV [4]; 4 – LES [9]

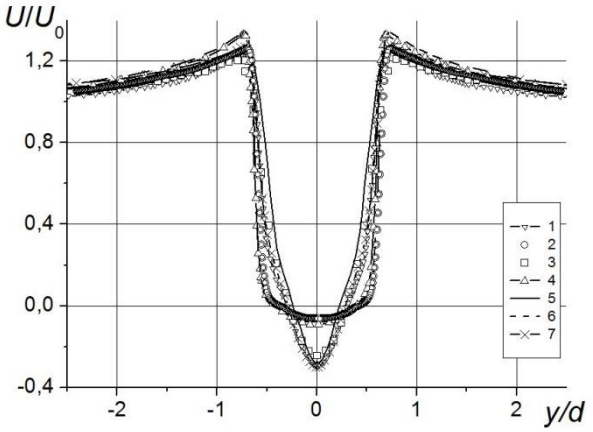


Figure 4. Profiles of the streamwise velocity component behind the cylinder at $x/d = 1.06$: 1 – DNS [6], (case I); 2 – SIV; 3 – PIV [4]); 4 – DNS [6], (case II); 5 – DNS [5] (simulation A); 6 – DNS [5] (simulation E); 7 – DNS [5] (simulation E +)

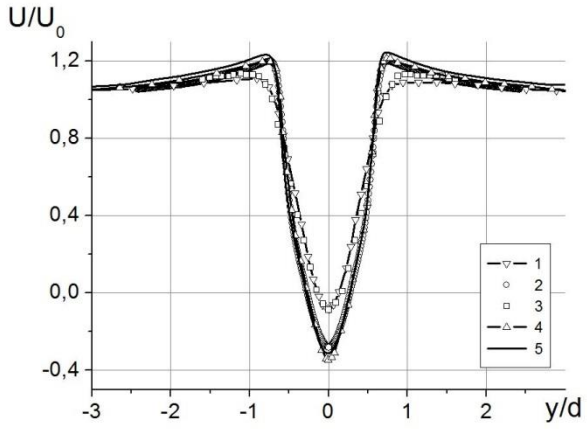


Figure 5. Profiles of the streamwise velocity component behind the cylinder at $x/d = 1.54$: 1 – DNS [6] (case I); 2 – SIV; 3 – PIV [4]; 4 – DNS [6] (case II); 5 – DNS [5] (simulation E)

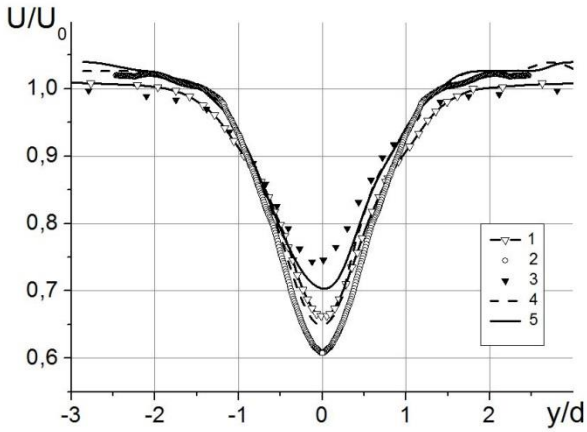


Figure 6. Profiles of the streamwise velocity component behind the cylinder at $x/d = 4.0$: 1 – DNS [6] (case I); 2 – HWA [7]; 3 – DNS [5] (simulation A); 4 – DNS [5] (simulation E); 5 – SIV

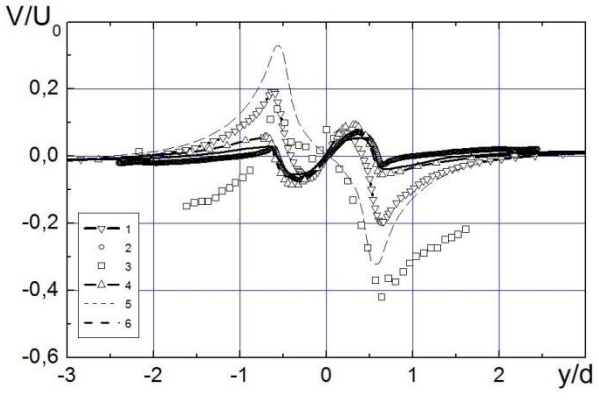


Figure 7. Profiles of the transverse velocity component behind the cylinder at $x/d = 1.06$: 1 – DNS [6] (case I); 2 – SIV; 3 – PIV [4]; 4 – DNS [6] (simulation II); 5 – DNS [5] (simulation A); 6 – DNS [5] (simulation E)

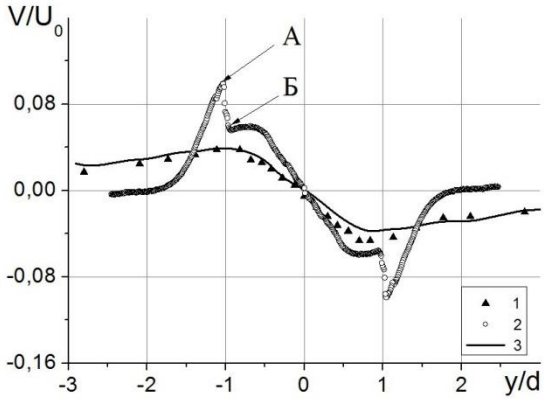


Figure 8. Profiles of the transverse velocity component behind the cylinder at $x/d = 4.0$: 1 – HWA [7]); 2 – SIV; 3 – DNS [6] (case II)

The gradual transformation from the U-shaped profile of the streamwise velocity component to the V-shape occurs (figures 3 - 5) as the distance from the cylinder increased in the range $x/d = 0.54 – 1.54$. The transition from a stagnant zone with close to zero values of the streamwise velocity component to a zone with the largest (on average) velocity of the reverse flow near the wake axis is observed right in this area of the wake, and, as the data of the flow visualization showed, the Karman vortices are generated here. The position of this area appears to be related to the size of the flow separation region behind the cylinder, which, in turn, is affected by the turbulence level of the free-stream flow, the aspect ratio (the ratio of cylinder length to its diameter), and the blockage ratio (the ratio of the cylinder diameter to the channel height). Subtle discrepancy in the values of U between DNS and experimental data using PIV and HWA and the present data (SIV measurements) results from the effect of above-mentioned factors.

The features of the distribution of the transverse velocity component at $x/d = 4.0$ obtained from the SIV data are revealed. In the vicinity of $y/d = \pm 1.0$, a sharp change in the average value of the transverse flow velocity is observed (figure 8). As some estimates show, this change corresponds to the rotation of the average velocity vector by an angle of approximately 2.5° in a section of the order of 0.1 cylinder diameter along the transverse coordinate.

An analysis of the vortex structure dynamics of the wake behind the cylinder performed using the flow visualization showed the following. In addition to moving in the direction of the free-stream flow, the large-scale vortex structures (Karman vortices) in the process of its formation shift perpendicular to this direction toward the wake axis. According to the visualization data, largest displacement is observed at a distance of about $4d$ downstream of the cylinder. The bound of the vortex forming on the lower surface of the cylinder (see figure 1) corresponds to transverse coordinate of about $y/d = +1.0$. And the vortex shedding from the upper side of the cylinder reaches the coordinate $y/d = –1.0$. The vortex periodically induces relatively large transverse velocities in this region due to the displacement across the flow. The direction of these velocities is opposite to the direction of the transverse velocity component near the bound of the wake, which causes the sharp change in the distribution of $V(y)$ (figure 8). The described feature is confirmed by oscillograms of the transverse velocity component at points A and B of the wake (marked on figure 1): the negative values of the velocity with its oscillations at the frequency of vortex formation are much greater at point B than at point A located farther from the wake axis. The average value of the transverse velocity at point B is lower than at point A due to these oscillations.

Conclusions

The SIV method was tested to study the structure of the averaged flow in the near wake of a transverse circular cylinder at Reynolds number Re = 3900. Flow velocity components were obtained at relative distances x/d = 0.54; 1.06; 2.02; 4.0 and 10.0 downstream of the cylinder axis. It is shown that the distributions of the flow velocity components derived from the SIV measurements are in sufficient agreement with DNS data.

It is established that the profile of the streamwise velocity component along the transverse coordinate with increasing distance from the cylinder smoothly changes from U-shaped to V-shaped. The U-shaped profile is typical for a stagnant zone in the immediate vicinity of the cylinder (x/d = 0.54) with a value of the streamwise velocity component close to zero. The velocity profile assumes the V-shape from the region where the velocity of the reverse flow is close to the maximum and this shape is maintained throughout the near wake.

It was found from the SIV measurements that at x/d = 4.0 in the vicinity of y/d = ±1.0, a sharp change in the average direction of the vector of streamwise velocity component by about 2.5° is observed in a section with a length of about 0.1 cylinder diameter along the transverse coordinate. This change is due to the displacement of the Karman vortices in the transverse to the wake axis direction. Also it occurs in the region of the critical (along the transverse coordinate) displacement of the vortices formed on the opposite side of the cylinder and is caused by the dynamics of this process.

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