Anisotropy of turbulent fluctuations of velocity and third-order moments in the near wake of a circular cylinder

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Abstract. Turbulent structure of the near wake behind a circular cylinder in a cross flow at Re = 3900 was studied experimentally. Instantaneous velocity vector fields in the wake were measured using Smoke Image Velocimetry (SIV). The profiles of velocity components, their RMS fluctuations and Reynolds stresses were compared with direct numerical simulation and experimental data obtained by other authors. The anisotropy of turbulent fluctuations in different zones of the wake was analyzed. Third-order moments of velocity fluctuations in the near wake behind the cylinder were measured for the first time ever.

1. Introduction

Numerical methods that resolve eddies in turbulent separated flows are rapidly developing. They include, first of all, Direct Numerical Simulation (DNS), Large-Eddy Simulation (LES) and relatively new Detached-Eddy Simulation technique (DES), which is a hybrid RANS/LES method proposed by Spalart et al. [1] in 1997. The researchers employ these methods because the results of RANS and URANS simulation of separated flows are unsatisfactory. However, it should be noted that certain progress in the development of RANS and URANS when applied to such flows has been achieved with non-linear closure models (so-called Reynolds stress transport models). Their advanced versions are successfully employed for simulation of many types of complex turbulent flows [2]. All the above listed simulation methods require thorough testing against reliable experimental data.

Cross flow past a circular cylinder is a classic case of flow with global separation. Despite numerous experimental and numerical studies of such flows, they are not yet well understood. This is particularly true for the near wake behind the cylinder (up to 10 cylinder diameters downstream of the cylinder). The near wake is the region where Karman vortices form, reverse flow is observed, high-level turbulent fluctuations and turbulent structures of different scales are present.

The majority of experimental results and numerical data on the near wake behind the cylinder currently available in the literature were obtained for the Reynolds number of 3900 [e.g. 3 – 5]. These papers primarily aimed at testing and refinement of numerical methods (LES and DNS) by comparison against experiments. However, there are obviously not enough experimental data with detailed description of experimental conditions. Moreover, these data are limited to mean velocity components, RMS fluctuations of instantaneous velocity components and Reynolds shear stresses. The anisotropy of turbulent fluctuations in the cylinder wake has been barely analyzed, and there is almost no information available on the third-order moments of velocity fluctuations in the wake, while such
estimations are crucial, as it is noted by Townsend [6]. Third-order moments are, in particular, included in diffusion terms of Reynolds stress transport equations (Reynolds Stress Models – RSM). Measurements of third-order moments of velocity fluctuations in separated flows are extremely scarce. Some information on triple correlations of streamwise component of velocity in the cylinder wake was provided by Müller [7] for $x/d = 20$ and $30$.

The present paper deals with experimental studies of the instantaneous velocity vector fields in the near wake of a circular cylinder in a cross flow. These measurements allowed us to estimate the anisotropy of turbulent fluctuations of velocity and distributions of triple correlations of velocity fluctuations in different wake zones.

2. Experimental setup and procedure

The experimental setup is schematically shown in fig. 1. The 300-mm long rectangular test section had the following dimensions: height $H = 115$ mm, width $B = 150$ mm. The cylinder (diameter $d = 15$ mm, length $L_z = 150$ mm) was installed at a distance of 60 mm from the test section inlet. Measurements were performed at six stations along the wake in the $x y$ plane: $x/d = 0.58; 1.06; 1.54; 2.02; 4.0$ and $7$, as well as in the $x z$ plane, which was parallel to the cylinder generatrix at $y/d = 0$ and $0.5$. The Reynolds number based on the cylinder diameter and velocity of the approaching flow was $Re = 3900$. Free-stream turbulence intensity at the test section inlet during the measurements was 1%. Smoke Image Velocimetry technique (SIV) was employed as a measurement tool. Its detailed description can be found in [8, 9]. The flow was seeded with small (1-5 µm) suspended tracer particles of water solution of glycerin. High-speed monochrome camera recorded the videos of flow pattern in a light sheet generated by a 5W continuous laser.

The frame size was $43 \times 975$ pix, scale factor was 0.045 mm/pix, framing frequency was $f = 12800$ Hz, duration of video 2.0 s.

![Figure 1. Schematic of experimental setup: 1 – smoke preparation chamber; 2 – honeycomb; 3 – nozzle; 4 – test section; 5 – receiver; 6 – sealed baffle with critical flow nozzles; 7 – axial blower; 8 – cylinder](image)

3. Results and discussion

The profiles of velocity components, their RMS fluctuations and Reynolds stresses were obtained at the above mentioned stations of the wake (in the $x y$ plane) and compared with experimental and DNS results available in the literature. SIV measurements agree well with PIV data reported by Parnaudeau [4] and DNS results obtained by Wissink and Rodi [5] on a refined grid (1206×406×1024 cells) for the width of the interrogation window $L_z/d = 8$.

As our measurements demonstrated, non-uniformity of averaged streamwise component of velocity in the near wake of the cylinder along the transverse coordinate did not exceed $5 – 7\%$ of the approaching flow velocity at the wake axis and $3 – 5\%$ near the wake boundary.
Distributions of velocity fluctuations, $<u'^2>$, $<v'^2>$, as well as the Reynolds stresses, $<u'v'>$, at the above mentioned stations of the near wake are shown in fig.2. Their analysis yielded the estimation of anisotropy of turbulent fluctuations in different wake zones. Near the cylinder ($x/d = 1.06 - 1.54$) at the wake axis, the ratio between fluctuations of streamwise and transverse components of velocity was $<u'^2>/<v'^2> = 0.7 - 1.5$. In the region where Karman vortices formed ($x/d \approx 2.02$), the level of fluctuations $<v'^2>$ at the wake axis was already 4.5...5 times higher than the respective level of $<u'^2>$. In the vicinity of the wake boundary (at $y/d = 0.5$) near the cylinder, $<u'^2>$ fluctuations were approximately 5 times higher than $<v'^2>$. This difference diminished with the distance from the cylinder and finally disappeared at $x/d = 2.02$ (at the wake boundary) where the level of fluctuations of both components was approximately identical. Then, at $x/d > 2.02$ the transverse fluctuations were approximately 2 times the streamwise fluctuations. At the wake axis, starting from $x/d > 4$, $<w'^2>$ fluctuations were of the same order as $<u'^2>$ fluctuations. The difference between them did not exceed 1.2 – 1.3. In this wake zone $<v'^2>/<w'^2> = 3$.

Thus, the maximum anisotropy of turbulent fluctuations of velocity components at the wake axis was observed starting from the region where Karman vortices formed.
Examples of triple correlations of velocity fluctuations obtained in the near wake are plotted in fig. 3. It should be noted that the order of $<u'^3>/<U_0^3$ at $x/d = 7$ was close to the above mentioned results [7]. In the immediate vicinity of the cylinder, the maximum normalized level of triple correlations $<u'^3>/<U_0^3$ at the wake boundary did not exceed 0.002 and increased significantly in the region where Karman vortices formed (fig. 3). Similar trend was also observed for other third-order moments of velocity fluctuations. Remarkably, the transverse gradient $<u'^2v'>$ near the wake axis at $x/d = 1.5 – 2$ (region where Karman vortices formed) changed its sign from positive to negative, i.e. turbulent transport of $<u'^2>$ in transverse direction (along $y$-axis) first aimed to reduce $<u'^2>$ at the wake axis, and then to increase it far from the cylinder. Transverse gradient $<u'^2v'>$ near the wake axis was always negative, and hence turbulent transport of Reynolds stresses in transverse direction aimed to increase these stresses at the wake axis.

The above measurements estimated turbulent fluctuations and third-order moments of velocity components throughout the whole range of frequencies (scales), including the shedding frequency of Karman vortices.

**Figure 3.** Triple correlations of velocity fluctuations in the near wake of the cylinder

**Conclusions**

SIV measurements of the instantaneous velocity vector fields were performed in the near wake behind the circular cylinder in the cross flow at the Reynolds number of 3900. Distributions of velocity components, their RMS fluctuations and Reynolds stresses are in good agreement with direct numerical simulation on a refined grid [5] and PIV measurements [4]. Anisotropy of turbulent fluctuations of velocity was estimated. The maximum anisotropy of fluctuations in the vicinity of the wake boundary was observed close to the cylinder: the level of fluctuations of streamwise component of velocity vector, $<u'^2>$, was 5 – 14 times higher than the respective level of the transverse component, $<v'^2>$. The maximum anisotropy of turbulent fluctuations at the wake axis was documented at $1.5 < x/d < 4$. 
The third-order moments of turbulent fluctuations in the cylinder wake was estimated. The level of \( \langle u'^3 \rangle/\langle U_0 \rangle^3 \), \( \langle u'^2 v' \rangle/\langle U_0 \rangle^3 \), \( \langle u'v'^2 \rangle/\langle U_0 \rangle^3 \) and \( \langle v'^3 \rangle/\langle U_0 \rangle^3 \) increase significantly in the wake zone, where large regular vortices (Karman vortices) formed.

The obtained data can be employed for verification of numerical methods as well as for the development and modification of turbulence models used in Reynolds-averaged Navier-Stokes equations in simulation of separated flows.

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