Turbulent boundary layer high-order moments: uncertainty analysis for PIV measurements

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Abstract. *High-order moments are quantities of extreme importance for the understanding of the structure of turbulent flow. In particular, structural information can be extracted without ambiguity from third- and forth-moments. For example, for flow over a smooth wall, the longitudinal skewness, S_u, is positive in the near wall region and negative in the external. Flow regions where S_u is positive are associated with acceleration-dominated velocity fluctuations resulting from the arrival of external high-speed fluid (sweep events). The objective of the present work is to show how particle image velocimetry can be used to determine the high-order moments of near wall flow. In particular, the work assesses the minimum number of samples that are required to achieve a faithful characterization of third- and forth-moments. The experiments are conducted over a rough wall in a low turbulence wind tunnel.*

Keywords: *PIV, uncertainty analysis, skewness, flatness.*

1. Introduction

Particle image velocimetry (PIV) is quickly becoming a dominating measuring technique in experimental fluid mechanics. The unique capability of PIV of simultaneously resolving the spatial and time scales of the flow has made it a favorite choice for the experimental characterization of complex turbulent flows. For this reason, data on mean velocity and high-order moments can now be routinely found in literature.

The purpose of the present work is to discuss in great detail the usefulness of PIV to find higher-order moments in boundary layer flow. Some previous works have remarked that in flow configurations devoided of regions of high shear and reverse flow, mean velocity profiles can be obtained from the processing of only 40 images (Cenedese et al. 1994). Others have used as many as 1800 PIV frames to achieve good agreement between LDA and PIV measurement statistics in open channel flows. Comparison between LDA and PIV measurements for the assessment of second-order moments in flow over a wavy wall with a small number of images, 37, was made in Nakagawa and Hanratty (2001); the discrepancies were large. Romano (1992) conducted the same type of investigation but considered 1000 PIV images and 20000 LDA samples. The deviations remained large. On a special note, authors remarked that deviations were greater in the wall-normal components.

The detailed turbulent structure and budgets behind permeable ribs have been studied by Panigrahi et al. (2008). The detailed features of mean and rms velocity, higher-order moments, quadrant decomposition of turbulent shear stress producing terms, skewness and components of the turbulent kinetic energy budgets have been determined through PIV. The flow statistics have been evaluated from 1200 image pairs.

The effects of PIV interrogation area (IA) on the higher-order turbulent statistics in flow over smooth and rough walls have been investigated by Shah et al. (2008). The Reynolds shear stress was found to be essentially independent of IA sizes whereas greater IA sizes tend to increase the correlation coefficient. Triple correlations, skewness (S) and flatness (F) factors and production terms were also observed to be independent of IA sizes. The conclusion was that IA sizes of 32x16x50 and 32x32x50 are sufficient for the adequate measurement of turbulent statistics up to the 4th-order moments. The adequacy of sample size was evaluated from sets of 500, 1000, 1500, 2000 and 2500 image pairs. The authors claim that all mean and turbulent quantities – with the exception of v_3, S_v and F_v – converge reasonably well for N $\geq$ 1000. For this reason all quantities were computed from 2500 pairs of image.

In the present work, sets of 1000, 2500, 5000, 7500 and 10000 PIV images are used to investigate the convergence of mean and turbulent quantities. Estimated quantities include both components of mean velocity profile as well as Reynolds stresses, skewness and flatness factors. Contrary to other works, the present results indicate that a minimum of 5000 samples are required to assure statistic convergence of the results.

2. Experimental procedure

2.1 Wind tunnel

The experiments were performed in a low-turbulence wind tunnel in the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ. The tunnel is an open circuit tunnel with a test section of dimensions 300x300x4000 mm. The test section is divided into two sections of equal length which can be fitted with surfaces having different types of roughness. In the present experiment, all four meters were fitted with the rough surface shown in Fig. 2. A general view of the wind tunnel is presented in Fig. 1.

Figure 1: General view of the wind tunnel.

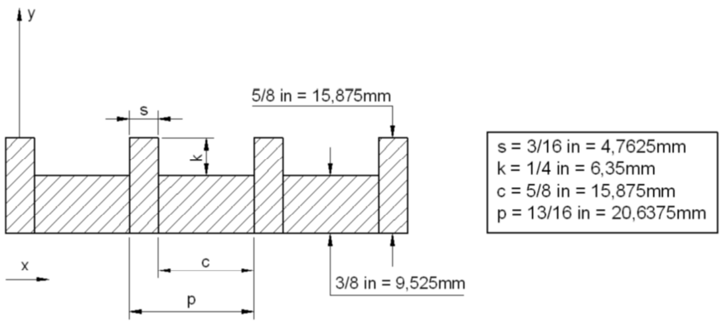

Figure 2: Geometry of the rough wall.

The measurements were performed for values of the free-stream velocity of 8 m/s; the free stream-level of turbulence was about 0.2%.

2.2 PIV system

The PIV measurements were performed with a two-dimensional Dantec system. The light source was furnished by a double pulsed Nd:YAG laser that produced short duration (10 ns) high energy (120 mJ) pulses of green light (532 nm). The collimated laser beam was transmitted through a cylindrical (15 mm) and a spherical (500 mm) lens to generate a 1 mm thick lightsheet. The reflected light was recorded at 15 Hz by a CCD camera with 1280x1024 pixels and 12-bit resolution. The camera was fitted with a Nikkor 105 mm f/2.8D lens. The air was seeded through a smoke generator that burned a mixture of water and glycerin. Image calibration was made by taking pictures of a reference target specially designed for the present purpose.

For all the measurements, the velocity vectors computational conditions were fixed. Adaptive correlation has been processed through FlowManager software on 32x32 pixels-size final interrogation spots, with 50% overlap, which gives a 64x64 vectors grid. The pixel resolution is 6.45 x 6.45 μm. Particle image treatment consists in using subpixel cell shifting and deformation, allowing bias and random error reduction. A widely accepted estimation of the absolute displacement error using these algorithms is 0.05 pixels. Different thresholds including signal-to-noise ratio and velocity vector magnitude were used as post-processing steps. Residual spurious vectors have been detected using a comparison with the local median of eight neighbour vectors for each grid points. No further filtering has been applied to the velocity fields in order to keep the whole measurement information.

3. Results

The determination of mean flow quantities normally has been known to require the use of about 500 pairs of images. Measurements of the second-order moments with an increasing number of pairs of images are shown in Figs. 3 to 5.

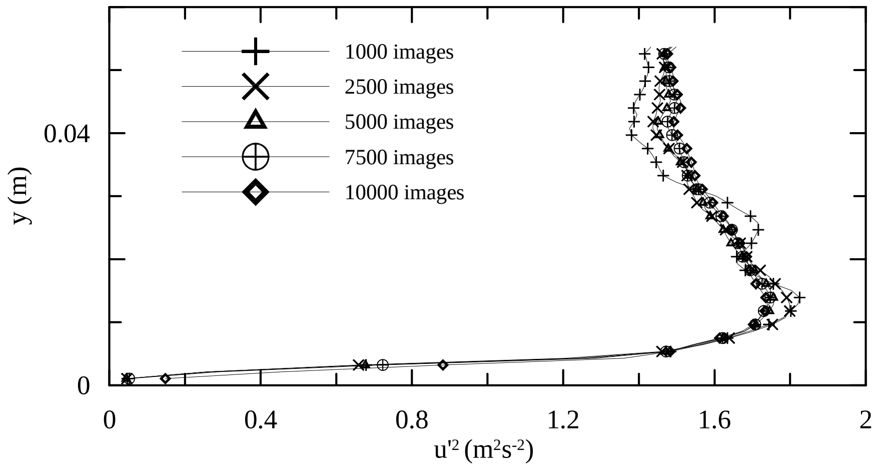

Figure 3: Results for the Reynolds longitudinal stress.

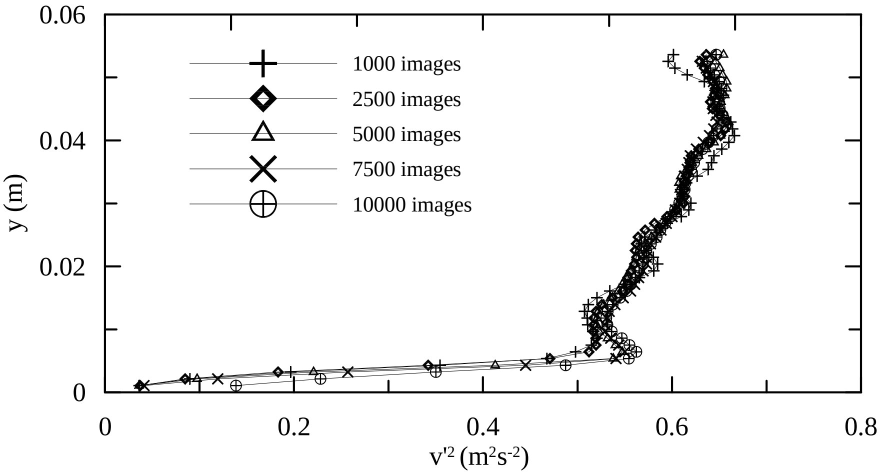

Figure 4: Results for the Reynolds transversal stress.

The changes in turbulent second moments or Reynolds stresses are particularly important to understand the behaviour of turbulence. They are crucial to characterize important concepts including local equilibrium, rapid distortion and turbulence memory. In fact, the reaction of the Reynolds stresses to combinations of basic strains related to flow acceleration, curvature determines the level of turbulent stress present at any point in the flow.

From the present findings, 1000 or even 2500 samples are shown to be completely inadequate for the characterization of the second-order moments. Measurements with 5000, 7500 and 10000 pairs of image cluster together for most of the profiles, including the regions of peak value of $\overline{u'u'}$, $\overline{v'v'}$ and $\overline{u'v'}$. The two sets with a small number of images – 1000 and 2500 – cannot reproduce the near wall peaks. In addition, the sets with 1000 samples oscillate largely in the external region, specially the $\overline{u'v'}$-profile.

Important aspects of flow turbulence can be understood from the analysis of the higher order moments of the fluctuating velocities. In particular, structural information can be extracted without ambiguity from third and fourth moments (Gad-el-Hak and Bandyopadhyay 1994). The third-order velocity products are particularly helpful to understand the diffusion process of the Reynolds stresses.

The skewness and flatness factors for the longitudinal velocity fluctuations are defined by

$$S_u = \overline{u'^3}/\left(\overline{u'^2}\right)^{3/2}, \tag{1}$$

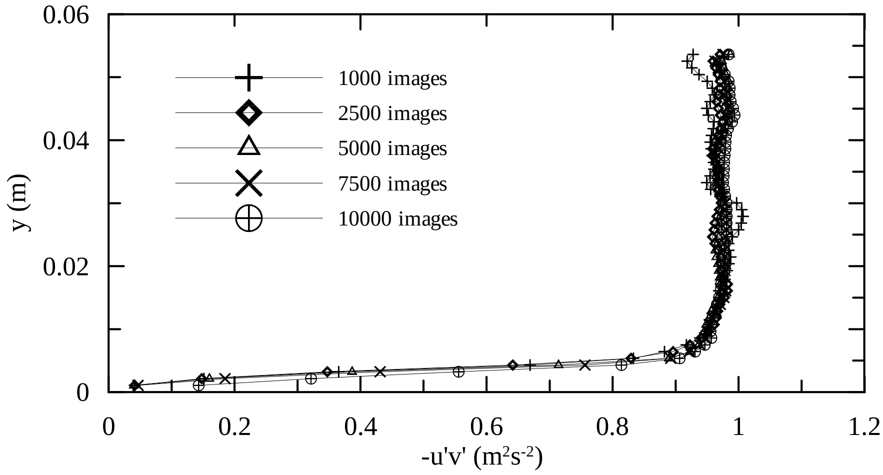

Figure 5: Results for the Reynolds shear stress.

$$F_u = \overline{u'^4}/\left(\overline{u'^2}\right)^2. \quad (2)$$

Equivalent expressions can be written for the other flow properties. A signal with a Gaussian distribution satisfies S_u = 0 and F_u = 3.

Results for S_u and S_v are shown in Figs. 6 and 7. As reported by previous authors, for flow over a smooth wall, S_u must be positive in the near wall region and negative in the external. Flow regions where S_u is positive are associated with acceleration-dominated velocity fluctuations resulting from the arrival of external high-speed fluid (sweep events) (Gad-el-Hak and Bandyopadhyay 1994). For flow over rough surfaces very high values of S_u are observed for the near wall region. The results obtained with 1000 and 2500 samples definitively do not follow this trend. The smallest set of samples yields a S_u-profile that is always positive and much higher than the other results. Measurements with 2500 samples are also mostly positive. In fact, in the wall region of the flow, even for the 5000 and 7500 results are not satisfactory. These profiles are clearly distinct from the 10000 samples profile. For heights above y = 80 mm, the 5000, 7500 and 10000 samples profiles coincide almost exactly.

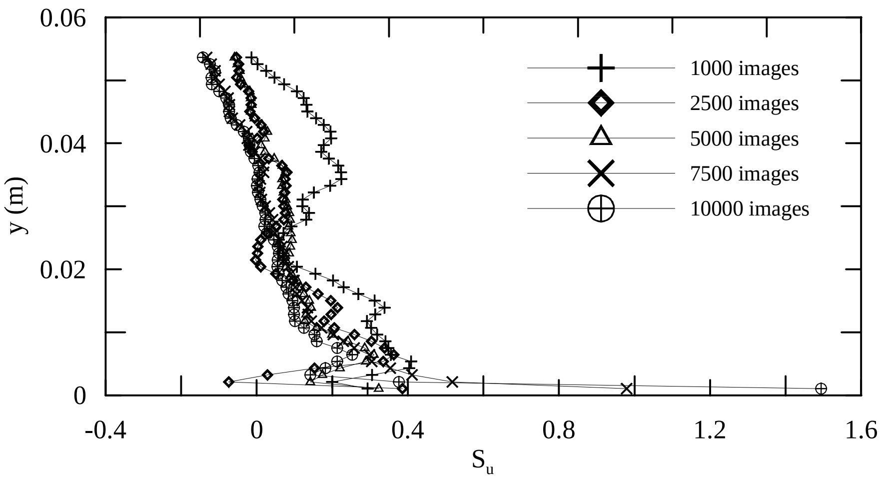

Figure 6: Results for S_u.

For the present data, the peak values of $\overline{u'u'}$ lies in the range 0.01 m $\leq y \leq$ 0.015 m so that the extremal values for S_u and F_u should also occur in this interval. This is observed to hold in the present work. In the log region, 0.02 m $\leq y \leq$ 0.04 m, S_u and F_u take on the nearly constant values 0 and 2.8 respectively. The implication is that over a large flow region the velocity fluctuations should follow nearly a Gaussian distribution. Bandyopadhyay and Watson (1988) claim that the general qualitative distributions of S and F are the same for flows over smooth and rough walls, the only significant change being the lower values of S_v (the skewness of the vertical velocity fluctuations) for all rough surfaces.

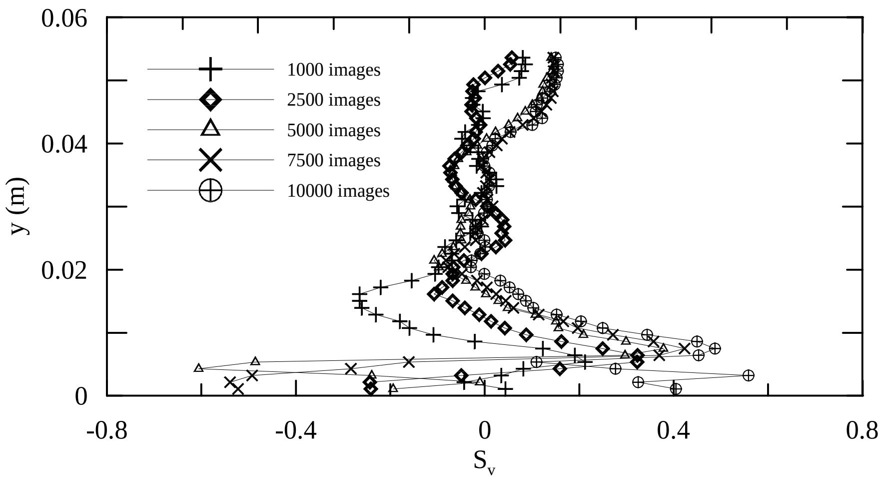

Figure 7: Results for S_v.

The present data show that for the 5000, 7500 and 10000 samples profiles, S_u follows the canonical behaviour (Fig. 6). Intense fluctuations are recorded positive near to the wall (≈ 0.5 to 1.2) and negative in the external region (≈ -0.75). It is also apparent that the point of cross-over from positive to negative S_u is identically predicted by all three profiles ($\approx 0.03m$). Regions of $S_u \approx 0$ can be identified for 0.02 m $\leq y \leq$ 0.04 m.

Measurements of S_v have been presented by some authors for flow over smooth surfaces. Difficulties related to the spatial and temporal resolution of probes and their large measurement uncertainties make these results differ greatly between each other (Gad-el-Hak and Bandyopadhyay 1994). However, most works agree that the value of S_v is negative near the wall and positive in the outer region. For flow over rough wall, large and positive values of S_v occur in the near wall region. In the log-region, S_v remains positive and about zero (≈ 0.1), that is, near to a Gaussian distribution. Bandyopadhyay and Watson (1988) find only positive values of S_v over their entire measurement range, for flows over smooth and rough walls.

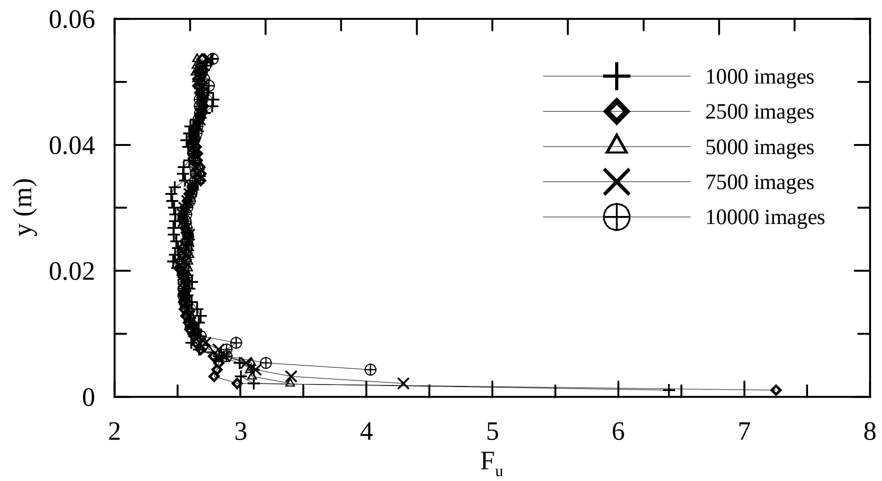

Figure 8: Results for F_u.

Here, the difficulties in determining S_v are clear. The near wall region cannot be resolved even with 5000 or 7500 pairs of images. The calculations with 5000 and 7500 pairs of images give negative values of S_v in the near wall region. The profile with 10000 samples, however, gives positive S_v throughout the vertical domain. This is in agreement with the expected trend. For y $\geq$ 0.01 profiles taken with 5000, 7500 and 10000 samples coincide well.

In the logarithmic region all profiles oscillate around zero. In the external region they assume slightly positive values. The general conclusion is that ideally 10000 samples should be considered for the evaluation of S_v in the region around the crest of the roughness elements.

Profiles for the flatness in a boundary layer show very high values near the wall and in the outer layer, where turbulence is highly intermittent. In the log-region, F_u should approach 2.8.

Profiles of F_u are show in Fig. 8. Far away from the wall, F_u approaches 2.6. In the wall region F_u is as high as 27

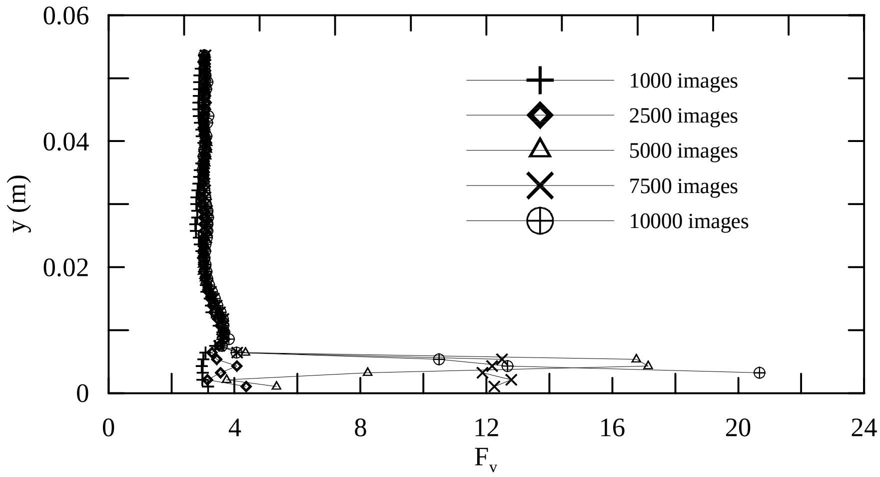

Figure 9: Results for F_v.

according with results obtained with 10000 samples. This value is not shown in Fig. 8 to keep the axis limits restricted to adequate values. The use of 1000 and 7500 samples gives F_u = 6.4 and 12 respectively. Thus, it is clear that the large degree of intermittent flow near the roughness elements needs a very large number of pairs of image to be determined.

Table 1: Computational effort.

Samples	Time
1000	14 m 25 s
2500	37 m 43 s
5000	64 m 8 s
7500	90 m 17 s
10000	112 m 20 s

The same pattern can be observed for the predictions of F_v (Fig. 9). At least 5000 samples are required to characterize the near wall flow.

The net computing time to obtain the present results is shown in Table 1.

4. Final remarks

The present work analyzes PIV results on two-component mean flow quantities and higher-order statistical quantities. Data for the shear and normal components of the Reynolds stress tensor and the distributions of skewness and flatness factors for the streamwise and vertical velocity fluctuations were thoroughly investigated.

Contrary to what is commonly stated in literature, less than 5000 pairs of image were shown to be completely insufficient for a good characterization of the high-order moments. Ideally, at least 10000 samples should be used to determine the skewness and flatness coefficients. Such a comprehensive assessment of the use of PIV to evaluate S and F cannot be found in literature. In special, an analysis of near wall measurements was carried out.

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