PIV noise estimation derived from spectrum analyses

C. Cuvier* and J.-M. Foucaut

Univ. Lille, CNRS, ONERA, Arts et Métiers ParisTech, Centrale Lille, FRE CNRS 2017-LMFL-Laboratoire de Mécanique des Fluides de Lille-Kampé de Fériet F-59000, Lille, France

*christophe.cuvier@centralelille.fr

Abstract

A new method to estimate and suppress the PIV random noise in the turbulent intensity profiles is proposed based on the PIV transfer function. The method consists in processing the images recorded two times with two different interrogation window sizes at the final pass. The proposed method was validated on two different PIV experiments conducted in the LMFL boundary layer wind-tunnel, a 2C2D and a stereo set-ups. For both experiments, several sizes of final interrogation window size were used to determine the noise of both PIV experiments with the suggested procedure. All the estimation were the same even for interrogation windows up to 1.6 times bigger showing the robustness of the proposed method. Finally, for the stereo case, the noise predicted is in very good agreement with the noise estimated thanks to the common region of the two stereo-PIV set-ups composing the 3C2D test case.

1 Introduction

Particle Image Velocimetry (PIV) is nowadays a reliable tool to study turbulent flows. However for turbulent boundary layer (TBL) statistical characterization, hot-wire anemometry is generally preferred probably due to larger bandwidth and a smaller noise than PIV. Recently, Willert et al. (2017) have shown that high magnification PIV can over-performed hot-wire for obtaining Reynolds stresses profiles in turbulent pipe flow up to Re_τ = 40000. However, the profiles suffer from PIV random error which overestimate by up to 2.5% the streamwise Reynolds stress profile which is partly compensated by the filtering effects (Atkinson, et al. 2014). To obtain accurate turbulent intensity profiles from PIV, an estimation of both the random noise and filtering effects has to be obtained. For random noise estimation, some methods have been proposed for 2D2C set-ups (for example image matching Sciacchitano et al. (2013), comparison with a higher dynamical range system, Sciacchitano et al. (2014) among other). When two set-ups are used with a common region, Kostas et al. (2015) were also able to estimate the noise even for stereo PIV but only in the common region.

In the present contribution, an alternative method to estimate and remove PIV noise in the Reynolds stresses statistics is proposed based on PIV transfer function and 1D spectrum in the continuity of the work proposed by Foucaut et al. (2004).

2 PIV transfer function and noise estimation

Based on the 3D transfer function of PIV given by Atkinson et al. (2014), the 3D energy spectrum $E(k_x, k_y, k_z)$ obtained by PIV follow equation (1), where E_{true} is the true 3D energy spectrum and E_n a 3D white noise and where the filtering effects due to the time separation between two frames dt is neglected as it corresponds to smaller displacements than the interrogation window size IW_x along x, or IW_y along y or IW_z along z (consider here as the light sheet thickness).

$$E(k_x,k_y,k_z) = (E_{true} + E_n).sinc^2\left(\frac{k_x.IW_x}{2}\right).sinc^2\left(\frac{k_y.IW_y}{2}\right).sinc^2\left(\frac{k_z.IW_z}{2}\right) \quad (1)$$

The 1D PIV energy spectrum E_{11}^1in streamwise direction can then be obtained by integrating the 3D energy spectrum given by PIV (equation (1)) on all k_y and k_z wavenumbers. This leads to equation (2).

$$E_{11}^1 = \iint_{k_y,k_z}(E_{true} + E_n).sinc^2\left(\frac{k_x.IW_x}{2}\right).sinc^2\left(\frac{k_y.IW_y}{2}\right).sinc^2\left(\frac{k_z.IW_z}{2}\right)dk_y.dk_z \quad (2)$$

Manipulating equation (2) leads to equation (3) where $E_{11_{y,z}}^1$ is the 1D energy spectrum affected by the filtering due to interrogation window size along y and light sheet thickness along z for a streamwise PIV plane and $I = \int_{-\infty}^{+\infty} sinc^2(u)du$. The streamwise Reynolds stress $\overline{u'^2}$ is obtained by integrating equation (3) for all k_x wavenumbers, resulting to equation (4) with $\overline{u'^2}_{true_{x,y,z}}$ the noise free variance attenuated by the filtering of PIV in the three directions and σ_{noise} the PIV random noise.

$$E_{11}^1 = \left(E_{11_{y,z}}^1 + \frac{E_n.4.I^2}{IW_y.IW_z}\right).sinc^2\left(\frac{k_x.IW_x}{2}\right) \quad (3)$$

$$\overline{u'^2} = \int_{-\infty}^{+\infty} E_{11_{y,z}}^1.sinc^2\left(\frac{k_x.IW_x}{2}\right)dk_x + \frac{E_n.8.I^3}{IW_x.IW_y.IW_z} = \overline{u'^2}_{true_{x,y,z}} + \sigma_{noise}^2 \quad (4)$$

Processing all the PIV fields recorded with two different final interrogation window sizes with same IW_x but slightly different IW_y (i.e. IW_y and IW_y' with IW_y' close to IW_y so that the filtering can be consider to be nearly the same) allows then the estimation of the noise (i.e. the $\overline{u'^2}$ computed on the two sets have the same $\overline{u'^2}_{true_{x,y,z}}$ but differs due to different σ_{noise}^2). As equation (4) shows that the PIV noise which overestimates the variance is of the form k/IW_y with k a constant ($k = \frac{E_n.8.I^3}{IW_x.IW_z}$ with IW_z and IW_x fixed), the difference between $\overline{u'^2}_{IW_y}$ and $\overline{u'^2}_{IW_y'}$ is $k.(1/IW_y - 1/IW_y')$. With this determination of k values, the noise profile can be estimated and then subtracted from the variances. The white noise E_n can also be extracted from k and depends only on the experiment characteristics (size of particle images, concentration, out-of-plane motion, velocity gradient, etc.).

3 Experimental set-ups for the validation

For validating the method, two different PIV experiments were carried out in the LMFL boundary layer wind tunnel at 6.8 m from wind tunnel entrance and at a free-stream velocity U_∞ = 9 m/s. This facility has a 20 m long test section fully transparent 2 m wide and 1 m in height which allows the generation and study of a thick boundary layer (about 24 cm at the end of the test section) at high Reynolds number. This facility is designed for intensive use of optical metrology. In the following, x is the streamwise axis, y the wall normal one and z is spanwise. The first experiment is a streamwise wall-normal 2C2D set-up composed of a sCMOS camera equipped with a 300 mm lens to obtain a magnification of 0.43 (field of view of 32 mm along x and 33 mm along y) at 1.03 m working distance (extension tube of 140 mm). The f# number was set at 8 to obtain particle of about 2 px to optimize the accuracy (Foucaut, et al. 2003) and a displacement of about 20 px in the upper part of the field of view was selected to obtain good turbulence statistics. Also, to be sure of good convergence statistics, 10000 fields were recorded. The light sheet thickness was 0.3 mm. Figure 1 gives a picture of the experiments. The images were processing with the modified version of MatPIV at LMFL. The analysis was done with a multipass approach ((Willert et Gharib 1991), (Soria

1998)) ending with 24 x 24 interrogation window size (corresponding to 0.36 mm x 0.36 mm or about 8 wall-units) which was found as good compromise between noise and filtering. Before the final pass, image deformation was used to improve the quality of the data ((Scarano 2002), (Lecordier et Trinité 2004)).

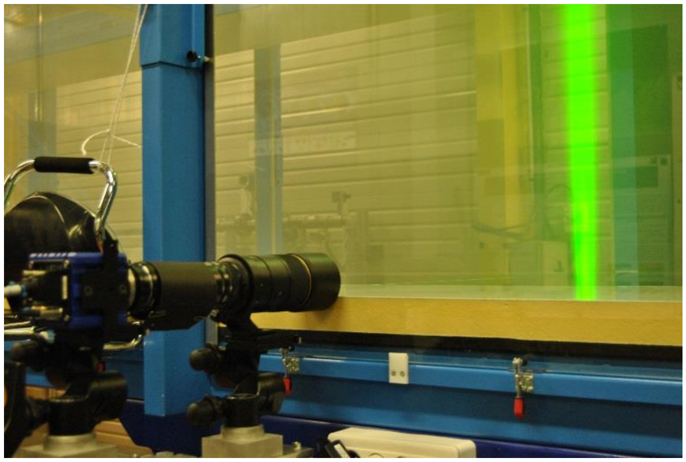

Figure 1 : Picture of the 2C2D set-up

The second experiment was a double stereo PIV systems (3C2D) one on the top of the other and composed of four sCMOS cameras equipped with a 135 mm lens at f# 8. The field of view obtained is 26.5 cm in streamwise direction and 32 cm in wall normal one in order to obtain the full boundary layer properties (magnification of 0.083). The displacement was set at about 13 px at the top of the field of view and 10000 fields were also recorded to unsure good turbulence statistics. The light sheet thickness was 0.6 mm. The reconstruction used is the one proposed by Soloff et al. (1997) and a self-calibration similar to Wieneke (2005) was applied. The analysis was done with MatPIV again with a multipass approach. The final interrogation window size was 18 x 24 (corresponding to 1.9 mm x 1.9 mm or about 45 wall-units) which was found to be a good compromise between noise and filtering. Before the final pass, image deformation was also used to improve the quality of the data. Figure 2 shows a picture of the set-up.

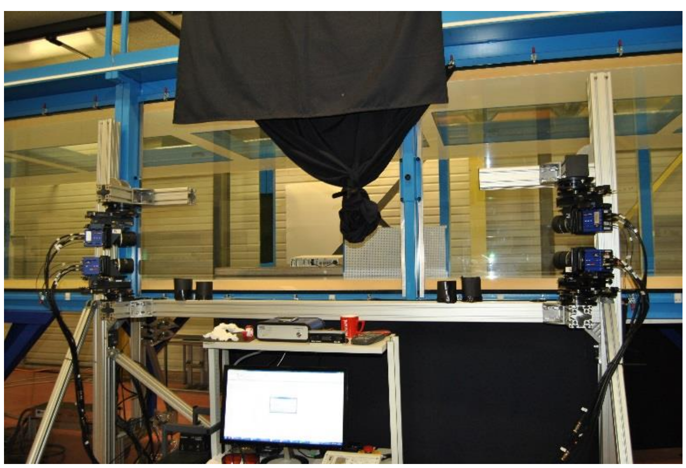

Figure 2 : Picture of the 3C2D experiment

4 Results

For the two experiments, several PIV processing were realized with only changing the final interrogation window size in wall-normal direction at the final pass. For the 2C2D set-up, data with interrogation windows of 24 pixels in streamwise direction and 20, 24, 26 and 32 pixels in wall-normal one were then generated to test the proposed method. For the 3C2D one, the data available are 18 pixels in streamwise direction and 18, 24, 26, 28 and 32 pixels in wall-normal one. For every set, the Reynolds stresses were computed and the corresponding profiles were obtained by averaging all the profiles in the streamwise direction supposing homogeneity to improve the convergence. From two sets with different interrogation window sizes (IW_y and $IW_{y\prime}$), the noise on the streamwise Reynolds stress is then computed with the proposed model by computed the difference between $\overline{u'^2}_{IW_y}$ and $\overline{u'^2}_{IW_{y'}}$. The method shows, if we neglect the difference in filtering due to very close interrogation windows, that the obtained difference profile can be modeled by $\mathrm{k}.\left(\frac{1}{IW_y}-\frac{1}{IW_y'}\right)$, with k a constant when the interrogation window size in x and z (light sheet thickness) are fixed. This allows the computation of the profiles for the parameter k. The noise of $\overline{u'^2}_{IW_y}$ is then obtained by $\frac{\mathrm{k}}{IW_y}$ and the streamwise random PIV noise with it square root. Figure 3 shows the streamwise PIV noise estimated for both set-ups and for various interrogation window sizes in wall normal direction. The good match of every curves demonstrates the validity of the proposed model to estimate PIV noise in Reynolds stresses. For the two first points the curves differ probably linked to the proximity of the wall which can introduce spurious behaviors due to laser reflection which are not took into account in the present method. To also support the method, the estimated noise in Figure 3 b) is compared for the 3C2D case with the noise estimation in the common region as proposed by Kostas et al. (2015). The agreement is again very good.

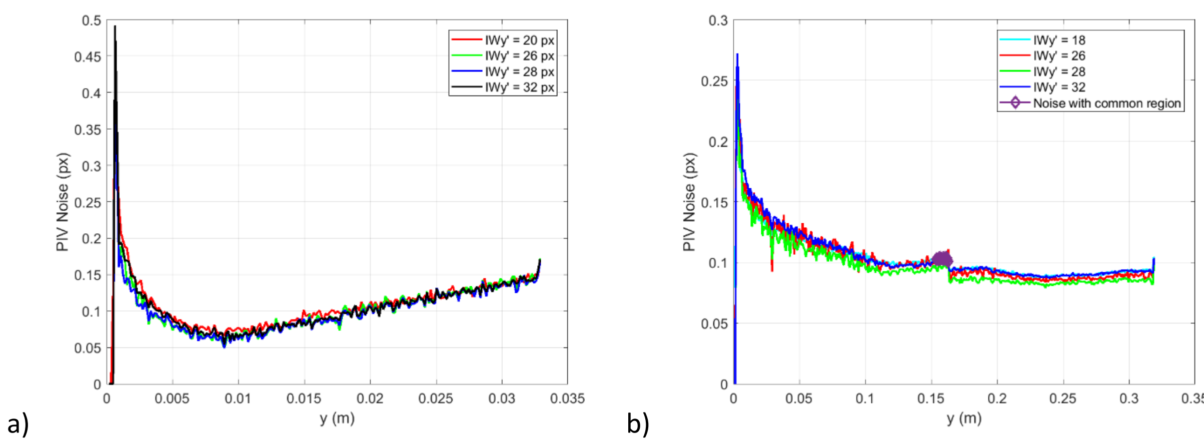

Figure 3: Streamwise PIV noise profile estimated with several IWy' for a) the 2C2D set-up with 24*24 interrogation windows and b) the 3C2D set-up with 18*24 ones.

Finally, Figure 4 gives the streamwise and wall-normal Reynolds stresses profiles obtained with both set-ups in wall units with and without noise. The good agreement at the end of the field of view of the 2C2D case with the 3C2D one, especially on the wall-normal component, becomes bad when the noise is removed indicating that the noise was compensating the filtering effects (for the 2C2D the interrogation window size is 8^+ so the filtering is very weak compared to the 45^+ of the 3C2D). The proposed method is then necessary to avoid these biased conclusions in order to evidence only the filtering effect in the Reynolds stresses profiles provided. The noise provided in Figure 3 for both set-ups is of the order of 0.1 pixel which corresponds to good PIV measurements (Foucaut, et al. 2003). In Figure 4, for 2C2D case, the difference is less marked between the raw profiles and the de-noised ones than for the 3C2D set-up. This can be explained by the higher dynamics range of the 2C2D set-up where the noise corresponds 0.1 to 0.8 % for the streamwise Reynolds stress and 1 to 2.5 % for the wall-normal component, compared to 2 to 4 % (or more of course when $\overline{u'^2}$ goes to zero) for the streamwise Reynolds stress of 3C2D case and 4 to 9 % for the wall-normal one. The higher relative noise for the wall-normal component is explained by the fact that this quantity is about 3-4 times smaller than the streamwise one $\overline{u'^2}$. This quantity is then difficult to measure accurately as it is more sensible to noise and then require more care in noise estimation for judging the data quality.

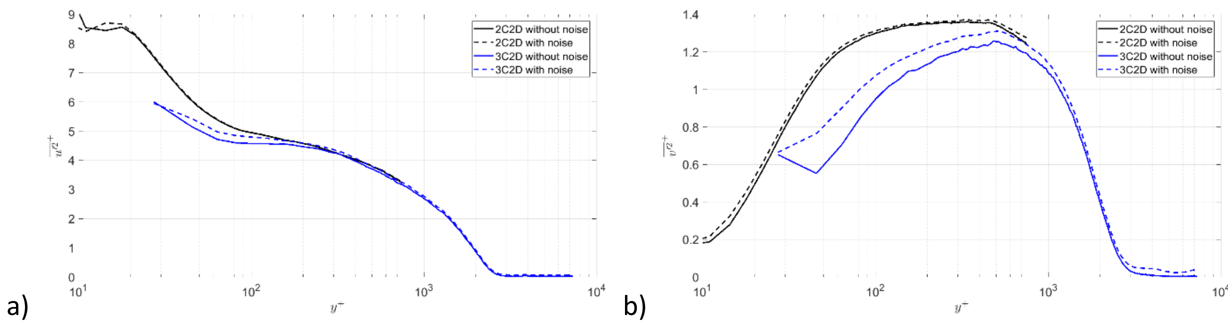

Figure 4: Reynolds stresses profiles in wall units of both set-ups with and without noise a) streamwise component and b) wall-normal one

5 Conclusion

A new method to estimate and suppress the PIV random noise in the turbulent intensity profiles is proposed based on the PIV transfer function. The method consists in processing the images recorded two times with two different interrogation window sizes at the final pass. The proposed method was validated with two different PIV experiments, a 2C2D and a stereo ones. For the stereo case, the noise predicted by this new procedure is perfectly in agreement with the noise estimated thanks to the common region of the two 3C2D set-ups. Now focus will be set when there is a homogenous direction to obtained noise free spectrum and to estimate the filtering effect thanks to the PIV transfer function. Also the method have to be tested with very small interrogation windows to see if it is robust against spurious vectors so that the effects of filtering can be attenuated by the use of small interrogation windows.

Acknowledgements

This work was carried out within the framework of the CNRS Research Foundation on Ground Transport and Mobility, in articulation with the ELSAT2020 project supported by the European Community, the French Ministry of Higher Education and Research, and the Hauts de France Regional Council.

References

Atkinson, C., N. Buchmann, O Amili, and J Soria. "On the appropriate filtering of PIV measurements of turbulent shear flows." *Exp. Fluids*, 2014: 55:1654.

Foucaut, J.M., B. Milliat, N. Perenne, and M Stanislas. "Characterisation of different PIV algorithm using the europiv synthetic image generator and real images from a turbulent boundary layer." EUROPIV2 workshop, Zaragoza, Spain: Springer, 2003.

Foucaut, J.-M., J Carlier, and M Stanislas. "PIV optimization for the study of turbulent flow using spectral analysis." *Meas. Sci. Technol.*, 2004: 15:1046-1058.

Kostas, J, Foucaut, J.-M and Stanislas, M. "Application of double SPIV on the near wall turbulence structure of an adverse pressure gradient turbulent boundary layer." *6th International Symposium on Particle Image Velocimetry.* Pasadena,California, September 21-23, 2015.

Lecordier, B., and M. Trinité. "Advanced PIV algorithms with Image Distortion Validation and Comparison using Synthetic Images of Turbulent Flow." Edited by Springer. Proceedings of the EuroPIV 2 Workshop, March 31 - April 1, Zaragoza, 2004. 115-132.

Scarano, F. "Iterative image deformation methods in PIV." *Measurement Science and Technology* 13 (2002): 1-19.

Sciacchitano, A, B Wieneke, and F Scarano. "PIV uncertainty quantification by image matching." *Meas. Sci. Technol.* , 2013: 24.

Sciacchitano, A, et al. "Collaborative framework for PIV uncertainty quantification: comparative assessment of methods." *17th International Symposium on Applications of Laser Techniques to Fluid Mechanics.* Lisbon, Portugal, 07-10 July, 2014.

Soloff, S. M., R. J. Adrian, and Z. C. Liu. "Distortion compensation for generalized stereoscopic particle image velocimetry." *Meas. Sci. and Technol.* 8 (1997): 1441–1454.

Soria, J. "Multigrid approach to digital cross-correlation digital PIV and HPIV analysis." Melbourne: 13th australasian fluid mechanics conference, 1998.

Wieneke, B. "Stereo-PIV using self-calibration on particle images." *Exp. In Fluids* 39 (2005): 267–280.

Willert, C, et al. "Near-wall statistics of a turbulent pipe flow at shear Reynolds numbers up to 40 000." *J. Fluid Mech.*, 2017: Vol. 826, R5.

Willert, C.E., and M. Gharib. "Digital particle image velocimetry." *Experiments in Fluids* 10 (1991): 181-193.