Comparison of PIV and Hot-Wire Statistics of Turbulent Boundary Layer

A Dróżdż¹, V Uruba²

¹ Czestochowa University of Technology, Armii Krajowej 21, Czestochowa, PL
² Academy of Science of the Czech Republic, Dolejskova 5, 182 00 Prague 8, CR

E-mail: arturdr@imc.pcz.czest.pl

Abstract. The paper shows a cross checking of turbulent boundary layer measurements using large field of view PIV and hot-wire anemometry techniques. The time-resolved PIV method was used for the experiments. The measuring plane was oriented perpendicularly to the wall and parallel to the mean flow. Hot wire measurement has been performed using the special probe with perpendicular hot wire. The HW point measurements were performed in the same place as PIV experiments. The hot-wire probe has the wire length of \( l' < 20 \) in considered range of Reynolds numbers. Various evaluation methods were applied on PIV data. The profiles of statistical characteristics of streamwise velocity components were evaluated from the data. Mean values, standard deviations as well as skewness and kurtosis coefficients were compared for a few values of \( Re_\theta \). Reynolds number ranges from 1000 to 5500. The result shows that with the increasing Reynolds number the attenuation of fluctuations maximum in PIV measurements occurs with respect to Hot-Wire measurements, however representation of velocity fluctuations using the PIV method is satisfactory. The influence of wall-normal fluctuation component on Hot-Wire near wall peak was also investigated.

1. Introduction

The measurements of small-scale turbulence are highly challenging due to the insufficient spatial resolution especially in high Reynolds number flows. According to the common opinion, a hot-wire anemometry using a single-wire probe is sufficient to resolve the streamwise \( u \) velocity component [1]. The comparison of \( u' \) fluctuation distributions obtained with DNS (Direct Numerical Simulation) and from a single-wire probe revealed self-similarity in shape, and some differences in levels are attributed to the uncertainty error [2,3]. Averaging due to a large measuring volume is known to reduce the near-wall peak of turbulence intensity [4], but also it could falsify higher order moments, like the skewness and flatness factors [5]. It could also reduce the frequency of detected burst events as documented by Johansson and Alfredsson [6]. Ligrani and Bradshaw [4] found two key recommendations for accurate measurements, both became standards for hot-wire design i.e. \( l' < 20 \) and \( l/d > 200 \), where \( l \) is length of a wire (in the viscous units\( l' \)), while \( d \) is wire diameter. There is no such clear recommendation for PIV measurements. However it is know that the spatial averaging occur in PIV results, however it is masked by noise present in PIV results [7]. However

¹ To whom any correspondence should be addressed.
comparing the PIV results with hot-wire techniques one should be also aware that a single-wire probe does not measure the $u$ component, but the resultant velocity fluctuations, composed of the streamwise $u$ and wall-normal $v$ fluctuation components. It is worth to note that $v$ component is of the smaller scale than the streamwise component therefore is more sensitive to spatial averaging. Dróżdż and Elsner [8] showed energy spectra comparison of single and X-wire probe and concluded that using single-wire probe the near-wall peak have an elevated value caused by the influence of the $v$ component in single wire readings. It could results from the near-wall vortical structures inducing strong $v$ component in the case, where the mean velocity $U$ is the lowest [8]. They concluded also that that the criteria for the wire length, i.e. $L^* \lesssim 20$, could not be sufficient to properly estimate the streamwise and wall-normal fluctuations.

The paper shows a comparison of turbulent boundary layer measurements using large field of view PIV and well resolved hot-wire anemometry technique that fulfil the Ligrani and Bradshaw [4] recommendation. In case of PIV the fluctuating components are sensitive on vector estimation method and the interrogation area.

2. Test rig and experimental setup

The existing blow-down test rig was modified for experiments with the boundary layer flow. The tunnel has rectangular cross-section with filled corners within the contraction (to suppress corner vortices), honeycomb and a system of damping screens followed by contraction with contraction ratio 16. The area of the test section input is 0.25 m in height and 0.1 m in width, the channel is 3 m long. The time mean velocity departures from homogeneity in planes perpendicular to the tunnel axis are of order tenth of per cent with the exception of corners, where corner vortex starters could be detected. The natural turbulence level was about 0.1 % in the working section input. Application of the 2mm cylindrical wire or the strip of coarse-grained sandpaper to the channel wall at different positions from the leading edge allowed for obtaining a value of the Reynolds number, based on the momentum thickness, up to $Re_\theta \approx 5500$.

The boundary layer was studied close to the channel end, 2700 mm downstream from the inlet, in the middle of the wider wall. The time-resolved PIV method was used for the experiments. The measuring system DANTEC consists of a double-pulse laser with cylindrical optics and CMOS camera. The software Dynamics Studio 3.4 was used for velocity-fields evaluation. Laser New Wave Pegasus Nd:YLF, double head, wavelength 527 nm, maximal frequency 10 kHz, a shot energy is 10 mJ for 1 kHz (corresponding power 10 W per head). Camera Phantom V711 has maximal resolution 1280 x
800 pixels and corresponding maximal frequency 3000 double-snaps per second. For the seeding the SAFEX fog generator was used, which products droplets of about 1 micron in size. The measuring plane was oriented perpendicularly to the wall and parallel to the mean flow. The field of view of PIV camera was of the size of the boundary layer thickness. Hot wire measurement has been performed using the special probe with perpendicular hot wire, 3 μm in diameter and 0.4 mm in length, the DANTEC anemometer StreamLine was used. The HW point measurements were performed in the same place as PIV experiments (see figure 1). Sampling frequency was 75 kHz, signal was low-pass filtered on 30 kHz. The hot-wire probe has the wire length of \( l' < 20 \) in considered range of Reynolds numbers. The wall closest position of the hot-wire probe was determined using the mirrored image. The profiles were evaluated from measurements of statistics. The mean of statistics calculated from \( \frac{1}{2} \) of width in the middle (see figure 2). The time records were 20 s at frequency equal 100 Hz double snaps, time in viscous units was from 0.1 to 0.7.

3. Comparison of statistics for different PIV vector estimation methods.

The error analysis of both HW and PIV method is commonly known. For the HW it is connected with precision of the calibration, accuracy of the cooling law used and wire length, while for PIV it is connected with precision of the particle position determination from the individual snaps and their spatial resolution. The first task was to compare the different estimation methods of vector PIV maps. The methods were also tested on spatial resolution sensitivity. There are substantial differences in spatial resolution of the methods in question: HW and PIV, because of large field of view of PIV camera. The HW method allows for closer position to the wall. The measuring point in the \( x \) and \( y \) direction is much smaller for the HW (the HW dimension was 3 μm), while for the PIV is given by the interrogation area size in table 1. In general, the velocity value evaluated using the PIV method represents itself the spatial mean value over the interrogation area. The PIV data were evaluated by 5 alternative methods (see table 1).

| Table 1. Parameters of PIV interrogation area for PIV methods in question. |
|-----------------|-------|-----------|------|------|
| method          | IA [pxs] | IA [mm] | dy [pxs] | dy [mm] |
| PIV 1         | Adaptive correlation | 16x16 | 0.72x0.72 | 8 | 0.3573 |
| PIV 2         | 2D least square matching | 39x15 | 1.74x0.67 | 6 | 0.2680 |
| PIV 3         | Adaptive correlation | 32x32 | 1.43x1.43 | 16 | 0.7146 |
| PIV 4         | Adaptive PIV | 8x8 | 0.36x0.36 | 4 | 0.1787 |
| PIV 5         | Adaptive PIV | 32x8 | 1.43x0.36 | 4 | 0.1787 |

The first method is the adaptive correlation method, which calculates velocity vectors with an initial interrogation area (IA) of the size \( N \) time the size of the final IA and uses the intermediary results as information for the next IA of smaller size, until the final IA size is reached [10]. The 50% overlap with 2 steps refinement was used for two interrogation areas 0.72x0.72 mm and 1.43x1.43. The second one is the Adaptive PIV method, which is an automatic and adaptive method for calculating velocity vectors based on particle images. The method will iteratively adjust the size and shape of the individual interrogation areas (IA) in order to adapt to local seeding densities and flow gradients. The last one was 2D Least Squares matching (LSM). The method is used for determining 2D velocity fields in highly seeded flows in water and air. The input data consists of double-frame images or of time-resolved single-frame images and the output data are equally spaced vector fields. Interrogation areas from within the image are analyzed to determine local affine transformations. In contrast to correlation based techniques, LSM shifts, rotates and stretches a fluid element. For this purpose, the LSM algorithm iteratively compares gray value information of an interrogation area in the first time step with the gray value information in the second time step. This is an iterative least squares procedure applying a proper transformation on the interrogation areas. In 2D this results in six
transformation parameters. The advantage of LSM is that whilst calculating the zero order translational velocities, the first order terms of motion are simultaneously optimized increasing the accuracy of the velocity field. The resulting displacement gradient tensor includes parameters like rotation, shear and strain of the interrogation area resulting from the particle displacement within the area. 2D LSM performs a geometric and radiometric transformation between two successive states of the same system. In the case of a gray value filled interrogation area its state is a gray value distribution of the pixel elements. For this purpose, the transformation is optimized such that the gray value differences between a template area and a search area reach a minimum. Compared with conventional 2D cross-correlation, LSM considers the deformation of a fluid element for the calculation of the displacements. This results in a more accurate calculation of the velocity field. The velocity gradient tensor and as result the rotation and deformation rate tensor can be calculated without applying central difference schemes. In LSM all this is done without manipulation of the raw particle images.

Figure 2 presents the estimation of the statistics for Reynolds number 1100 using above methods: mean velocity \( U/U_e \) figure 2a), turbulence intensity \( u'/U_e \) and \( v'/U_e \) figure 2b), skewness factor \( S_f = \overline{u^3}/\overline{u^2}^{3/2} \) figure 2c) and flatness factor \( F_f = \overline{u^4}/\overline{u^2}^2 - 3 \) figure 2d). The mean velocity profile is affected substantially by neither the experimental method (HW and PIV) nor by evaluation method resolving the logarithmic region. Even very close to the wall the values obtained using the PIV method are reliable, as in viscous sublayer the instantaneous velocity distribution in the \( y \) direction is supposed to be close to the linear. However, the viscous sublayer itself is far of to be well resolved by the PIV method for the spatial resolution reasons mentioned above.

In the inner region (viscous sublayer, buffer region and logarithmic region \( y < 20 \text{ mm} \)) the fluctuations are captured nearly perfectly using the 2D LSM method. The other PIV evaluation method cause irregularities and artificial oscillations of skewness and kurtosis. However in the wake region ( \( y > 20 \text{ mm} \)) the 2D LSM method fails in capturing big absolute values of both skewness and kurtosis, here the adaptive method offers better results. In this region strong intermittent behaviour of occurrence of the turbulent fluid from the boundary layer and the fluid from the low-turbulent flow.
outside the boundary layer is expected. The adaptive PIV method shows the worse results through all
the profile. The intensity of fluctuations is underestimated by all PIV methods, the underestimation is
proportional to the interrogation area size. The fluctuations amplitudes are the best captured by the
adaptive method with the smallest interrogation area - PIV1. Surprisingly, the adaptive PIV method
with smaller interrogation area PIV4 shows more intense fluctuation attenuation.

4. Statistics comparison of HW with PIV
The profiles of statistical characteristics of streamwise velocity components were evaluated from the
data by the two measuring techniques. The hot-wire data were compared to 2D LSM methods of PIV
vector field estimation. Mean values, standard deviations as well as skewness and kurtosis coefficients
were compared for three cases in Reynolds number from a range 1000 to 5500. The distributions of
mean velocity a), turbulence intensity b), skewness c) and flatness d) factors were presented for
$Re_\theta = 1100$ in the figure 3, for $Re_\theta = 3200$ in figure 4 and for $Re_\theta = 5500$ in figure 5.
The turbulence intensity profiles b) show that with the increase of Reynolds number, the
underestimation of PIV results is more important. The effect of spatial averaging is evident. The
small-scales energy is attenuated because the most of attenuation is present close the wall where
small-scale structures dominate. The result is similar as for attenuation of the near wall peak of
fluctuation when the hot-wire length is growing.
The skewness factor distributions show that with the increase of Reynolds number, the skewness
factor obtained from PIV is increasing. The effect is the same as for the result of Orlu and Alfredsson
[5], where with the decrease of spatial resolution the skewness factor increases. On the other hand the
flatness factor changes are negligible with the Reynolds number.
The mean velocity profile is well captured by the PIV method for all examined Reynolds numbers.
The fluctuations attenuation close to the wall produced by the PIV method, with respect to HW
measurements fulfil Ligrani and Bradshaw [4] recommendation, is of growing importance with
increasing Reynolds number. This effect could be explained by appearance of smaller structures
connected with higher frequencies, which could not be captured by the PIV method, but only by the
HW.

Figure 3. Statistics for Reynolds number 1100: mean velocity a), turbulence intensity
b), skewness factor c) and flatness factor d)
Figure 4. Statistics for Reynolds number 3200: mean velocity a), turbulence intensity b), skewness factor c) and flatness factor d)

Figure 5. Statistics for Reynolds number 5500: mean velocity a), turbulence intensity b), skewness factor c) and flatness factor d)

Inconsistency in streamwise fluctuation between the measuring techniques could results not only from spatial averaging but also from influence of wall-normal component, which is taken into account in the case of hot-wire perpendicular probe. To analyse the problem, the velocity fluctuations from single-
wire probe and PIV was compared for the case where the spatial averaging of PIV is the highest. Because of perpendicular single-wire streamwise fluctuations are influenced by $v$ component, the resultant velocity fluctuations $u'_x = \sqrt{u'^2 + v'^2}$ has to be calculated for PIV results before comparison with HW fluctuations. The comparison was shown in figure 6.

It may be noticed that the distribution of $u'_x$ (see figure 6) obtained by PIV slightly differ in shape in comparison with HW. In the outer zone the values of PIV are slightly overestimated in comparison of HW except the near-wall peak, where values are greatly underestimated. The overestimation of the PIV results in the outer zone could be caused by measurement noise present in PIV results as it was shown by Atkinson [7]. However, the near-wall peak substantial underestimation of resultant $u'_x$ reviles that $v'$ component is much more under resolved than $u'$ in figure 5b. Dróżdż and Elsner [8] showed on the energy spectra that the near-wall peak of single-wire fluctuations consist also the small-scale $v$ fluctuations, which are twice shorter than the scales responsible for near-wall peak of $u$ fluctuations. The fulfilled recommendation of Ligrani and Bradshaw [4] HW measurements resolves small-scales $v$ fluctuations in wider range than PIV methods. The underestimation could be explained by appearance of the smaller structures in the flow, which are far from resolving using large field of view PIV methods. Both methods are more or less inadequate and should be re-compared to DNS properly. Single wire fluctuations should be compared to resultant $u'_x$ calculated for DNS fluctuation components in order verify if upper limit of wire length $l' < 20$ is enough to resolve the smallest scales.

5. Conclusions
The profiles of statistical characteristics of streamwise velocity components were evaluated from the data obtained using the two completely different experimental methods, HW and PIV. The aim of the paper was to check the PIV point statistics reliability and limitations of them in comparison with Hot-Wire technique, which is still the only candidate. The PIV data were evaluated by 5 alternative methods. Mean values, standard deviations as well as skewness and kurtosis coefficients were compared for a few values of momentum thickness-based Reynolds number from the range from 1000 to 5500.

As for the PIV data, the best results were obtained using the 2D Least squares matching evaluation method within the turbulent boundary layer close to the wall, while in the intermittent region on the boundary layer border the adaptive correlation method gives better results. The result shows that with the increasing Reynolds number the attenuation of fluctuations maximum and increase of skewness

Figure 6. Comparison of HW $u'$ with PIV resultant of $u'$ and $v'$ fluctuations.
The factor in PIV measurements occurs with respect to the Hot-Wire measurements that fulfill the Ligrani and Bradshaw [4] recommendation. Special care was devoted to near-wall peak value of fluctuation distribution for both measurement techniques. The wall-normal component influence the single-wire fluctuations, which should not be treated as streamwise fluctuation component but resultant of $u$ and $v$ components, especially in the near-wall region. Therefore, the fluctuations distribution of the single-wire perpendicular probe, which fulfill the Ligrani and Bradshaw [4] recommendation, is not self-similar with the DNS data because of elevated value of near-wall peak caused by $v$ component. However the HW technique resolves small-scales $v$ fluctuations in wider range than PIV methods. It seems that the increase of PIV field of view magnification should increase the range of resolved small-scales as it was shown by De Silva et al. [9]. However, both methods are more or less inadequate that is why it is strong need to perform further study in order to establish new criteria of well resolved measurements of turbulence.

6. References

[1] Hutchins N, Nickels T B, Marusic I and Chong M S 2009 Hot-wire spatial resolution issues in wall-bounded turbulence *J. Fluid Mech.* **635** 103

[2] Monty J P and Chong M S 2009 Turbulent channel flow: comparison of streamwise velocity data from experiments and direct numerical simulation *J. Fluid Mech.* **633** 461

[3] Schlatter P, Örlü R, Li Q, Brethouwer G, Fransson J H M, Johansson A V., Alfredsson P H and Henningson D S 2009 Turbulent boundary layers up to $Re_{\theta}=2500$ studied through simulation and experiment *Phys. Fluids* **21** 051702

[4] Ligrani P M and Bradshaw P 1987 Spatial resolution and measurement of turbulence in the viscous sublayer using subminiature hot-wire probes *Exp. Fluids* **5** 407–17

[5] Örlü R and Alfredsson P H 2010 On spatial resolution issues related to time-averaged quantities using hot-wire anemometry *Exp. Fluids* **49** 101–10

[6] Johansson A V. and Alfredsson P H 1983 Effects of imperfect spatial resolution on measurements of wall-bounded turbulent shear flows *J. Fluid Mech.* **137** 409–21

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

[8] Dróżdż A and Elsner W 2014 Comparison of single and X-wire measurements of streamwise velocity fluctuations in turbulent boundary layer *J. Theor. Appl. Mech.* **52** 499–505

[9] De Silva C M, Gnanamanickam E P, Atkinson C, Buchmann N a., Hutchins N, Soria J and Marusic I 2014 High spatial range velocity measurements in a high Reynolds number turbulent boundary layer *Phys. Fluids* **26** 025117

[10] DynamicStudio v3.4 User's Guide 2013 Dantec Dynamics A/S

Acknowledgements

The investigation was supported by Polish-Czech bilateral project no. 88781/R13/R14/(7AMB13PL003), the statutory funds BS/PB-1-103-3010/2011P and the Grant Agency of the Czech Republic, project No. P101/10/1230.