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COMPARISON OF SINGLE AND X-WIRE MEASUREMENTS OF STREAMWISE VELOCITY FLUCTUATIONS IN TURBULENT BOUNDARY LAYER

Artur Dróżdż, Witold Elsner
Czestochowa University of Technology, Institute of Thermal Machinery, Częstochowa, Poland
e-mail: welsner@imc.pcz.czest.pl

The paper discusses the problem of measuring velocity fluctuations of a turbulent boundary layer using single and X-wire probes. It seems that the difference between the streamwise fluctuating component of these two probes results not only from spatial resolution, but also from influence of the wall-normal fluctuating component, which is usually not considered. It was shown that the vector summing these two components obtained from X-wire probe gives the shape of fluctuation distribution obtained from a single-wire probe. It implies that the underestimation of the near-wall peak of streamwise fluctuating component in X-wire measurements results from disregarded wall-normal fluctuations, which is obviously taken in the case of a single-wire probe. Moreover, it was shown that the criteria for wire length i.e. $l^+ \leqslant 20$ could not be sufficient to properly estimate the streamwise and wall-normal fluctuations.

Keywords: turbulent boundary layer, energy spectra, hot-wire spatial resolution

1. Introduction

The measurements of small-scale turbulence are highly challenging due to the insufficient spatial resolution of the probes 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_x velocity component (Hutchins *et al.*, 2009), however, influence of the wall-normal u_y component on a single-wire probe readings is not throughly discussed. One should be aware that a single-wire probe does not measure the u_x component, but the resultant velocity, composed of the streamwise u_x and wall-normal u_y fluctuation components.

Most researchers who do measurements in the turbulent boundary layer believe that the influence of u_y component is insignificant and can be ignored, but it is only a simplifying assumption. The comparison of u_x 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 (Monty and Chong, 2009; Schlatter *et al.*, 2009). However, from the physical point of view, the negligible small influence of the u_y component in a single-wire readings is not so convincing. Despite the predominant motion of the streamwise direction, the vortical structure that is present in a turbulent boundary layer acts on the probe wire inducing the u_y velocity component.

DNS study of Lenaers *et al.* (2012) confirms the presence of the high value of wall-normal velocity fluctuations, which occasionally occur in the near-wall region and have the magnitude larger than their local standard deviation. Since the high values were initially observed only in direct numerical simulations and not in experiments, it was thought that this effect was not a physical, but rather numerical artifact. The results of research performed by Hutchins *et al.* (2009) concerning spatial resolution effects of a single-wire probe on the energy spectra, are consistent with the study of Lenaers *et al.* (2012). The authors show that the calculated "missing energy" (difference in energy between a shorter and longer wire), due to increase of the probe wire length, is observed on the viscous length scale $\lambda^+ \approx 600$ and viscous time scale $\tau^+ \approx 60$. This time scale is close to the characteristic single event occurrence ($\tau^+ \approx 20$) of the wall-normal component noticed by Lenaers *et al.* (2012). Marusic *et al.* (2010) showed that the maximum of u_y energy spectrum for the same scale ($\lambda^+ \approx 600$, $\tau^+ \approx 60$) occurs close to the wall. However, this coincidence of energy maximum of u_y with missing energy of u_x measured by a single-wire probe was not noticed by the Melbourne group (Marusic *et al.*, 2010; Hutchins *et al.*, 2009). This coincidence mentioned above could result from small scale vortices, which produce a strong wall-normal component and transfer the energy to the streamwise component by the mean shear in the near-wall region.

The paper, based on the measurements of the turbulent boundary layer with single and X-wire probes, tries to explain the effect of the wall-normal component in the readings of the single-wire probe. In particular, we consider comparison of fluctuation profiles and time scales energy spectra of velocity components.

2. Facility and instrumentation

The experiment was performed in an open-circuit wind tunnel, where the turbulent boundary layer was developed along the flat plate, which was 2807 mm long, 250 mm wide and 155 mm high, with a boundary layer thickness of up to 25 mm. The test section had two pairs of suction gaps, located in the channel upstream the test section, aimed to control the two-dimensionality of the flow. To avoid separation, the leading edge of the flat plate had an elliptical shape. The tripping of boundary layer, after the leading edge of the flat plate was used in order to obtain a fully developed turbulence. It was resolved using 2 mm cylindrical wire fastened to the plate at 210 mm from the leading edge, which allowed one to obtain a value of the Reynolds number, based on the friction velocity u_τ, equal $\mathrm{Re}_\tau \approx 1000$. To accelerate further the breakdown of the large-scale vortex structures, the strip of coarse-grained sandpaper was placed just behind the wire. The facility was equipped with the computer-controlled, 2D traversing system (in streamwise and wall-normal direction). The traverse carriage was driven over a maximum displacement of 180 mm by a servo motor. The uncertainty of the drive step was 0.001 mm with the smallest step equal 0.01 mm. The wall closest position of the hot-wire probe was determined using the mirrored image. Further details of the test section were given in Drozdz *et al.* (2011).

Velocity profiles at the zero pressure gradient region were measured with a single hot-wire anemometry probe of a diameter $d = 3\,\mu$m and length $l = 0.4$ mm (Dantec Dynamics 55P31). Those measurements were supplemented with X-wire probe of wire diameter $d = 5\,\mu$m and length $l = 1.25$ mm (Dantec Dynamics 55P61). The probes were combined with the DISA 55M hot-wire bridge connected to a 14 bit PC card. The acquisition was maintained at frequency 50kHz with 10 seconds sampling records. For the assumed sampling frequency, the non-dimensional inner scale representation was $f^+ \approx 1$. It was consistent with the assumption of Hutchins *et al.* (2009), stating that for the proper anemometer/probe response cutoff must be in the range of $f^+ > 1/3(t^+ < 3)$.

The mean velocity in the core flow was $U_\infty \approx 15$ m/s and the turbulence intensity was $Tu = 0.4\%$. The ambient conditions were carefully controlled during the measurements. The scatter of ambient temperature at the end of the test section did not exceed 0.2°. In the case when the measured temperature was different from temperature during calibration, the temperature correction of CTA voltage was used, Jorgensen (2002). At the same time the free-stream velocity was monitored by means of a Prandtl tube. The scatter of free-stream velocity was found to be around 0.2% of the mean value. The convergence of the flow statistics up to 4th order was checked during preliminary tests. The convergence was achieved after approximately 3.5 s while the acquisition time was equal 10 s.

The calibration was performed *in situ* to eliminate the need for the probe to be moved between the calibration and measurement stage. This removed the risk of probe misalignment between the calibration and the measurement, and improved the overall accuracy of the experiments. For X-wire probe, the calibration of yaw response of hot-wire is required, and in the paper, the approach proposed by Willmarth and Bogar (1977) was applied. For the calibration, the velocity was selected and the yaw angle was changed from -30 to 30 degrees, while the corresponding voltages from wire A and B (E_A and E_B) being recorded. The process was repeated for different velocities, which allowed one to build a voltage-to-velocity conversion map. A typical calibration map is shown in Figure 1.

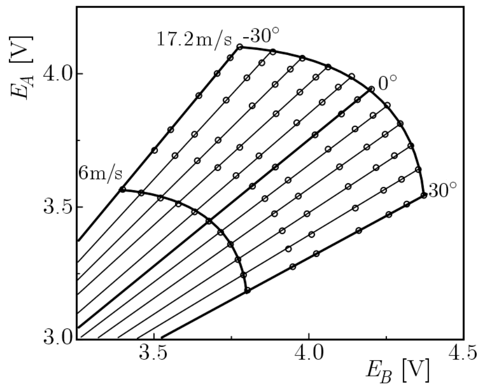

Fig. 1. Calibration results showing calibration points (o), constant flow velocity lines and constant yaw angle lines determined from the calibration points

3. Results

Spatial averaging due to a large length of the single-wire is known to reduce the near wall peak of turbulence intensity (Ligrani and Bradshaw, 1987), but also it could falsify higher order moments, like the skewness and flatness factors (Örlü and Alfredsson, 2010). It could also reduce the frequency of detected burst events as documented by Johansson and Alfredsson (1983). Ligrani and Bradshaw (1987) found two key recommendations for accurate measurements, both became standards for hot-wire design i.e. $l^+ \leqslant 20$ and $l/d > 200$, where l is length of a wire (in the viscous units l^+), while d is wire diameter. To satisfy these conditions, the miniature probe with length of the wire $l = 0.4\,\mathrm{mm}$ and diameter of $d = 3\,\mu\mathrm{m}$ that was characterised by $l/d = 133$ was used. The l/d value did not fulfill the recommendation Ligrani and Bradshaw (1987), however Fig. 2a shows comparison of the fluctuation distributions of the miniature wire probe ($l = 0.4\,\mathrm{mm}$) with the standard wire probe of $l = 1.25\,\mathrm{mm}$ and $d = 5\,\mu\mathrm{m}$. The measurements were performed in the region, where u_τ had value ≈ 0.78, in order to obtain, for the miniature single-wire probe, the value of $l^+ \approx 19$ and to reach the upper limit of Ligrani and Bradshaw (1987) recommendation. It could be noticed that the magnitude of the near wall peak increased by 10% and reached value of $\overline{uu}^+ \approx 8$, which is typical for the analyzed Reynolds number. It is apparent that the increase of the fluctuation level is greater than the level of the estimated uncertainty given in Table 1. The confirmation of the effect of spatial averaging due to longer wire are energy spectra plots recorded at $y^+ \approx 15$ presented in Fig. 2b, where for $l/d = 250$, the drop of energy in the high frequency range is observed.

Another inconsistency in streamwise fluctuation distributions results form using different types of probe. To analyse the problem, the velocity fluctuations from single and X-wire probes were measured in a different position of the test section, where $u_\tau \approx 0.63$, which allow one to get $l^+ \approx 16$ for a single-wire probe and $l^+ \approx 50$ for X-wire probe. It may be noticed that the distribution of $\overline{uu}^+$ (see Fig. 3) obtained by means of the single-wire probe reveals a single peak

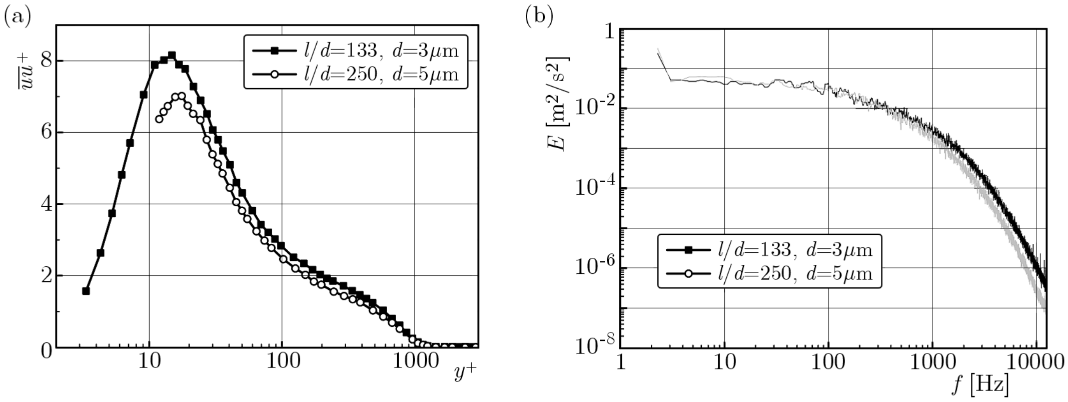

Fig. 2. The comparison of fluctuating components from miniature and standard single-wire probes (a) energy spectra taken for $y^+ \approx 15$ (b)

Table 1. Uncertainty of HWA measurements

Probe	Quantity	Viscous layer	Buffer layer	Log layer	Wake layer
single wire	U	1.5%	5%	2%	2%
	u'	1.5%	5%	1%	20%
X-wire	U	–	1.5%	1.5%	1.5%
	V	–	1.5%	1.5%	1%
	u'	–	3%	1.5%	10%
	v'	–	3%	1.5%	6%

located at $y^+ \approx 15$, which is typical for turbulent boundary layers at zero pressure gradient. However, this peak location is not reached for X-wire probe because of the large size, which not allowed penetration of the boundary layer as close as the single-wire probe. It should also be noticed that the streamwise $\overline{uu}^+$ and $\overline{uu}_x^+$ distributions, respectively for single and X-wire probes, are clearly different. However, computations of the resultant velocity fluctuations in the xy plane i.e. $\overline{uu}_{xy}^+ = \sqrt{\overline{uu}_x^2 + \overline{uu}_y^2}/u_\tau^2$ using the values obtained with the X-wire probe barely show identical shape to the streamwise $\overline{uu}^+$ obtained with the single-wire probe. The slightly higher values of $\overline{uu}_{xy}^+$ obtained from the X-wire probe could be due to influence of the spanwise u_z component, which slightly increases the readings of the X-wire probe, but does not in the case of a single-wire, as the spanwise influence is minor due to the same direction as wire axis. On the other hand, this influence could also be partly attenuated by the larger measuring volume of the X-wire probe. These results indicate that the readings of the single-wire probe are highly influenced by u_y fluctuations which also suggests that the $\overline{uu}^+$ near wall peak have an elevated value by the impact of the u_y component. The influence has to be stronger with the decrease of wire length because the u_y fluctuations are induced only by small-scales (Marusic *et al.*, 2010). In order to confirm this influence on scales from a wider range, the energy spectrum using wavelet transformation was calculated. The analysis was done for all measured points throughout the boundary layer thickness.

In order to obtain the wavelet transformation of each recorded signal, the Mexican Hat wavelet function was used. According to Gordeyev (2000), such a wavelet function is the best choice to perform the analysis of single events in the time signal. Iso-conturs of the wavelet energy spectra E scaled by the square of friction velocity u_τ as a function of the y^+ and time scale $\tau^+ = \tau u_\tau^2/\nu$ are shown in Fig. 4. To remove the effect of convection velocity, the time scale τ was used instead of length scale λ, which was used by Marusic *et al.* (2010). The black cross $(+)$

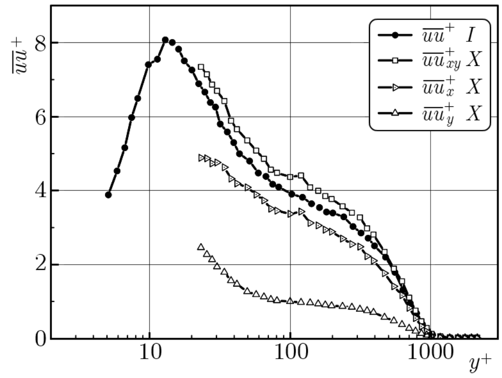

Fig. 3. The comparison of fluctuating components from single and X-wire probes

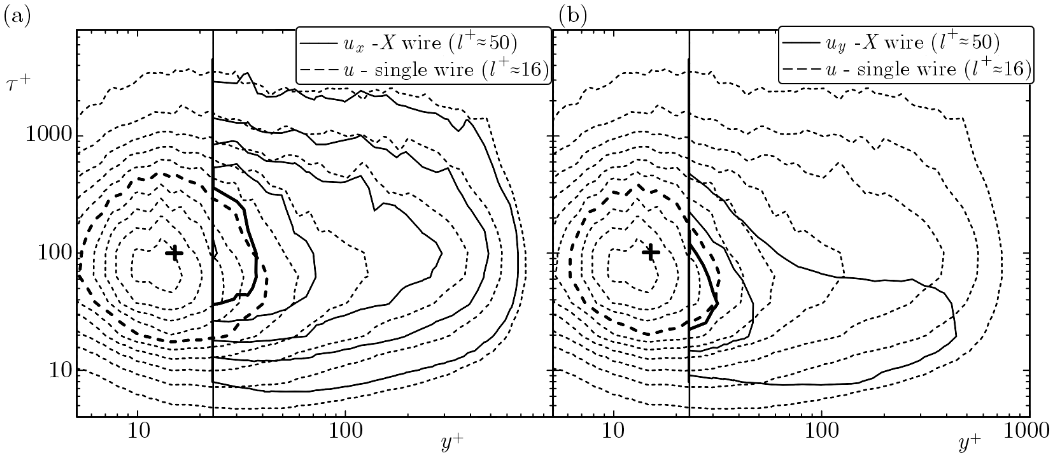

Fig. 4. Iso-contours of the energy spectra E/u_τ^2: effect of the length scale and geometry of the probe: single-wire $l^+ = 16$ (solid); X-wire $l^+ = 50$ (dashed) on streamwise energy (a) and comparison of the streamwise single-wire and wall-normal X-wire energy (b). Contours are from 0 to 2 with the steps equal 0.2

corresponds to the scale and location of the near wall peak of velocity fluctuations. Figure 4 shows the comparison of energy spectra for the single-wire probe with wire length $l^+ \approx 16$ and X-wire probes with wires length $l^+ \approx 50$. Figure 4a presents the comparison of streamwise components, while Fig. 4b shows the comparison of streamwise for the single-wire probe and wall-normal for the X-wire probe components. Dashed lines on both graphs refer to the component measured by the single-wire probe, which is treated as the reference case. The continuous iso-lines for u_x (Fig. 4a) and u_y (Fig. 4b) obtained from the X-wire probe are superimposed for comparison. As the energy iso-lines are drawn to the same scales, the lower values of u_x measured by the X-wire probe are easily visible (see Fig 4a). The more interesting, however, is the maximum shift of the X-wire streamwise energy to higher time scales. For better interpretation, the iso-lines near the maximum of E/u_τ^2 were drawn by thick lines. This phenomenon is observed mainly for a small scales range, that is below $\tau^+ \approx 100$. The similar effects for a single-wire probe with different lengths of the wire were also observed by Hutchins *et al.* (2009). On the other hand (Fig. 4b), the location of the maximum of u_y energy (solid thick line Fig. 4b) is shifted towards smaller scales whoose position can be estimated for $\tau^+ \approx 60$. The displacement of the u_y maximum in relation to u_x maximum is consistent with the study of Marusic *et al.* (2010) and results from the attached eddies hypothesis, where the wall-normal fluctuations will lack a large-scale component at the wall due to the blocking (Townsend, 1956). It is clear therefore that the energy maximum of u_y is shifted towards the smaller scale in comparison to the streamwise component.

Therefore, it must have an impact on the readings of the single-wire probe. It is worth noting that the increased wall-normal component appears in the same time scale as the bursting process (Drozdz and Elsner, 2011) and should result in overestimation of the near-wall peak captured by the single-wire probe.

In order to demonstrate that the u_y component influences the single-wire probe reading, the resultant fluctuation energy $E_{u_{xy}} = \sqrt{E_{u_x}^2 + E_{u_y}^2}$ compared to the single-wire probe fluctuation energy was shown in Fig. 5. It is seen now that $E_{u_{xy}}$ has the maximum (solid thick line) for the scale, which better corresponds to $E_{u_{xy}}$ iso-contours (dashed thick line) obtained for single-wire probe with respect to the results shown in Fig. 4a. The scale energy redistribution confirms that the near-wall peak of fluctuation comes from the increase in the small-scale component of u_y near the wall. These results show that the single-wire measurements give not only u_x fluctuation, but rather the resultant of u_x and u_y velocity components. Furthermore, this indicates that the near-wall peak of fluctuation obtained by the single-wire probe could be overestimated due to the influence of the wall-normal component. Moreover, the criteria for wire length i.e. $l^+ \leqslant 20$ could not be sufficient to properly estimate the streamwise and wall normal fluctuations.

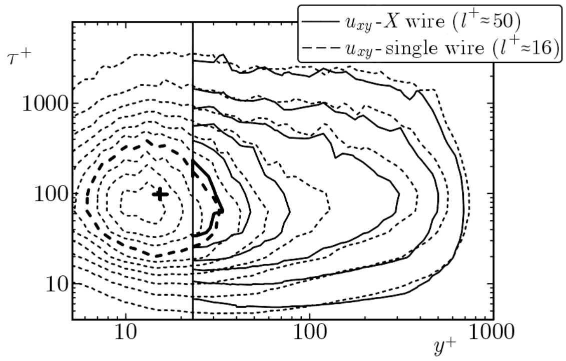

Fig. 5. Iso-contours of the energy spectra $E(u_{xy}) = (E(u)^2 + E(v)^2)^{1/2}$ component across the boundary layer thickness – effect of the probe: X-wire $l^+ = 50$ (solid); single-wire $l^+ = 16$ (dashed). Contours are from 0 to 2 with the steps equal 0.2

4. Conclusions

The results showed that the difference between the streamwise fluctuating component measured with the single and X-wire probes results not only from spatial resolution but also from the influence of the wall-normal fluctuating component, which is usually not considered. It was shown that the vector summing these two components, obtained from the X-wire probe, gives the shape of fluctuation distribution obtained from the single-wire probe. To confirm this influence, the energy spectra using wavelet transformation were calculated. It was shown that the near-wall peak of single-wire fluctuations is the result of both streamwise and wall-normal small-scale components of velocity fluctuations. It implies that the underestimation of the near wall peak of streamwise fluctuating component in X-wire measurements results from not taking into consideration the wall-normal fluctuations, which are obviously taken in the case of the single-wire probe. Moreover, it was shown that the criteria for the wire length, i.e. $l^+ \leqslant 20$, could not be sufficient to properly estimate the streamwise and wall-normal fluctuations.

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