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A spatial resolution correction scheme for disturbance profiles in developing zero-pressure-gradient turbulent boundary layers

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Abstract – Constant temperature anemometry (CTA) is still the preferred method in measurement of important quantities in turbulence investigations. One of the main challenges of CTA is the finite length of the sensor often being larger than the smallest eddies present in the flow, which leads to spatial averaging along the sensor. The effect is often an under-estimated fluctuation intensity profile in zero-pressure-gradient (ZPG) turbulent boundary layers (TBL), which leads to the biased estimation of heat- and mass-transfer characteristics of the flow and needs to be corrected. There has been numerous correction schemes, but here we partly follow the scheme proposed by Smits [1] and partly follow an original scheme, to get a better fit to our experimental data obtained in several measurement planes over a flat plate (Fig. 1a). The collapse of the inner-peaks for 6 different spanwise-averaged disturbance profiles is shown in Fig. 1b, and an overview of the experimental cases is summarized in Table 1.

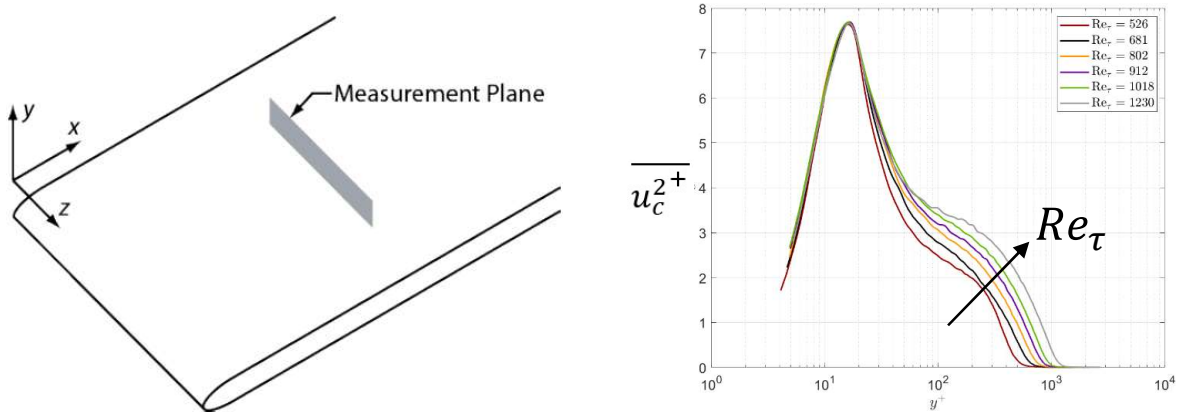

Figure 1. (left) Flat plate schematic, assumed coordinate system and a typical measurement plane. (right) L^+-corrected Streamwise turbulence intensities, $\overline{u_c^{2+}}$ for $Re_\tau = 526$ to 1230.

Experiments are performed in the closed-loop subsonic wind tunnel facility at the Technical University of Denmark (DTU), Department of Mechanics. The experiments were performed over a smooth flat plate with an elliptical leading edge (Fig. 1a) as part of an EU Project, called NATURAL [2], [3]. Single-component, high resolution (both spatial and temporal) velocity profiles were obtained using two hotwires: one acquiring in the boundary layer and one in the freestream, simultaneously. Temperature correction was performed using a

correction procedure suggested by Benjamin and Roberts [4]. Two-dimensional (2D) boundary layer scans were performed at five streamwise locations that are 0.1m apart. Spanwise resolution was 2.5mm, covering a spanwise range of 0.1m, producing a total of 41 profiles per plane. Wall-normal velocity profiles were acquired in an automated fashion using a custom-built LabVIEW program; a modified version of the "Slice" code [5]. The boundary layer sensor came close to the flat plate as much as $y^+ = 4$ for case one, but $y^+ > 5$ for all the other cases, following the recommendations of Zanoun et al. [6]. The post-processing of the data was performed using MATLAB: First, the key parameters for each individual TBL profile was computed by using a robust fitting method proposed by Rodríguez-López et al. [7]. In this fitting procedure, all parts of the TBL profile (i.e. viscous, buffer, log and wake) is used and all five key parameters of the TBL (u_τ, Δy, Π, δ, κ) are optimized where the wall location was estimated within $\Delta y^+ \leq 0.3$ with 85% confidence. A spanwise averaging was performed after the wall location correction, and the fit was performed one last time on the spanwise-average profile to obtain the parameter set (i.e. u_τ, δ, κ) for that case (Tab. 1).

Case	**1**	**2**	**3**	**4**	**5**	**6**
U_o [m/s]	30	30	30	30	30	40
x [m]	0.1	0.2	0.3	0.4	0.5	0.5
Re_x [10^6]	0.2	0.4	0.6	0.8	1.0	1.33
u_τ [m/s]	1.4312	1.3334	1.2811	1.2484	1.2218	1.5716
δ [mm]	5.5336	7.6865	9.4297	10.9964	12.5514	11.7843
κ	0.406	0.3746	0.3742	0.3796	0.3824	0.3681
B	4.768	3.903	3.892	4.047	4.127	3.713
Re_τ	526	681	802	912	1018	1230
L_c [µm]	11	11	12	12	12	10
L^+	114.0	106.2	102.1	99.5	97.4	125.2

Table 1. Parameter overview of the six experimental cases.

A 1.2mm-long DANTEC 55P15 boundary layer probe was used, which is approx. 100 to 125 times longer than the viscous length scale. In order to estimate the true disturbance fluctuation magnitude ($u_c^{2^+}$), various correction schemes were tried on the measured disturbance ($u_m^{2^+}$), but finally we ended up using a partly original (Eqn. 1), and partly modified version of the scheme proposed by Smits [1] (Eqn. 2), which seemed to collapse the inner peaks quite well:

$$\overline{u_c^{2^+}} = \overline{u_m^{2^+}}/[1 - M(L^+, Re_\tau) f(y^+)] \tag{1}$$

$$f(y^+) = \frac{18 + \ln(2)}{y^+ + \ln[\exp(18 - y^+) + 1]} \tag{2}$$

The originality of the current work is the fact that, we were able to observe an Re_τ dependence in the magnitude function M, in the correction equation. Future work will focus on (i) using multiple sensors to measure multiple velocity components, (ii) improving the spatial resolution by collaborating with larger facilities (f.ex. CoLaPipe and CICLoPE) and (iii) validating the above correction scheme by adding more L^+ data points to it. The last point can be achieved using smaller sensors, i.e. subminiature wire sensors (~420µm in length) and nano-scale film sensors (typical ~100µm in length).

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Nomenclature:

U_o	Freestream velocity
u	streamwise velocity
u_τ	friction velocity
u_m	measured velocity fluctuation
u_c	L^+-corrected velocity fluctuation
x	streamwise coordinate
y	wall-normal coordinate
y^+	wall-normal coordinate in viscous scaling
L_c	viscous (inner) length scale
L^+	sensor length in viscous scaling
Re_τ	friction Reynolds number
Re_x	Reynolds number
δ	boundary layer thickness
κ	von Karman constant
B	additive constant